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Hot Air Drying Kinetics of Thin Layers of Prickly Pear Fruit Paste

(Kinetik Pengeringan Udara Panas pada Lapisan Nipis Pes Buah Pir Berduri)

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ABSTRACT

Hot air drying of thin layers of a paste from prickly pear fruit (without seeds) to obtain a chewy product was studied. The effect of air temperature (50 to 80°C) and sample thickness (4, 6, and 8 mm) on drying kinetics was analyzed. Drying curves were obtained, and drying data were fitted to Lewis, Henderson & Pabis, Peleg and Page mathematical models. The models were compared by two statistical parameters (coefficient of determination and reduced chi-squared). The drying rate curves showed that the layers of the paste were characterized by a single-falling-rate period. Water loss during drying was described by Fick's equation and effective diffusivity, ranging between 0.75 and 7.05×10^{-9} m^2s^{-1} *depending on drying conditions. Activation energy was calculated from Arrhenius equation, being 34.51, 29.86, and 25.31* $kJmol^{-1}$ *for layers of 4, 6, and 8 mm thickness, respectively. The Page model fitted adequately the drying process of thin layers of the paste from prickly pear fruit.*

Keywords: Hot air drying; mathematical modeling; moisture diffusivity; prickly pear fruit

ABSTRAK

Pengeringan secara udara panas mengeringkan lapisan nipis pes buah pir berduri (tanpa biji) untuk mendapatkan produk kenyal telah dikaji. Kesan suhu (50 hingga 80°C) dan ketebalan sampel (4, 6 dan 8 mm) terhadap kinetik pengeringan telah dianalisis. Kadar lengkung pengeringan diperoleh dan data pengeringan telah dipadankan dengan model matematik Lewis, Henderson & Pabis, Peleg dan model matematik Page. Model tersebut telah dibandingkan oleh dua parameter statistik (pekali penentuan dan pengurangan khi kuasa dua). Kadar lengkung pengeringan menunjukkan bahawa lapisan pes dicirikan oleh tempoh kadar-tunggal-jatuh. Kehilangan air semasa pengeringan ditunjukkan oleh persamaan Fick's dan daya keresapan yang berkesan, merangkumi antara 0.75 dan 7.05×10^{-9} m^2s^{-1} *bergantung pada syarat pengeringan. Tenaga pengaktifan dihitung daripada persamaan Arrhenius, 34.51, 29.86 dan 25.31* $kJmol^{-1}$ *untuk lapisan bertebal 4, 6 dan 8 mm secara turutan. Model Page sepadan dengan proses pengeringan lapisan nipis pes buah pir berduri.*

Kata kunci: Buah pir berduri; kadar penyerapan kelembapan; model matematik; pengeringan udara panas

INTRODUCTION

The greatest genetic diversity of prickly pear in the world belongs to Mexico, in the semi-arid regions of the country. Prickly pear fruit (*Opuntia* spp.), member of Cactaceae family, is characterized by a thick pericarp with small prickles, colors from yellow to purple, and juicy pulp full of seeds (Sáenz 2000; Zito et al. 2013). From the nutrimental view point, prickly pear fruit contains ascorbic acid (0.02 - 0.04%), fibre (0.02-3.15%) and some essential amino acids like methionine and phenylalanine (El Gharras 2011; Herrera-Hernández et al. 2010; Ozcan & Juhaimi 2011; Piga et al. 2003; Sharma et al. 2014). The caloric value of its pulp is 209.34 kJ/100 g, comparable to other fruits such as pear, apricot and orange (Felker et al. 2002; Herrera-Hernández 2010). The prickly pear pulp is mainly composed by 85% of water and 10-15% of carbohydrates (Gurrieri et al. 2000). These characteristics, together with low acidity values and its high sugar content (even 16%) leads to its typical sweet flavor (Joubert 1993; Piga et al. 2003; Sepulveda & Saenz 1990).

Prickly pear is usually consumed fresh, but some other uses have been explored in both traditional and industrial processes (Stintzing & Carle 2005). Andress and Harrison (1999) reported products from dried puree of fruits called 'fruit leathers'. These are made by drying a very thin layer of fruit puree and other ingredients, such as citric acid and pectin, to produce a chewy snack (Orrego et al. 2014). Often, the product is targeted at health food markets, labeled as 'pure', 'sun dried', or 'rich in vitamins'. Diverse reports include studies of fruits dried in thin layer, such as jackfruit (Okilya et al. 2010), papaya (Chan & Cavaletto 1997), grapes (Maskan et al. 2002), mango (Azeredo et al. 2006), apple (Quintero et al. 2012), apricot (Sharma et al. 2013), and kiwifruit (Vatthanakul et al. 2010). 'Fruit leathers' offer diverse advantages, among them easy to eat, convenient to pack, few storage troubles, and cheap transport and distribution (McHugh et al. 1996; Moyls 1981).

Diverse empirical and semi-empirical models have been reported in order to describe the drying behavior of agricultural products. From a phenomenological viewpoint, diffusion has been employed to describe the moisture transfer during drying for homogeneous materials. Assuming diffusion-based moisture migration, negligible shrinkage, and constant drying temperature, the solution of Fick's second law for a semi-infinite slab is (Crank 1975):

$$M = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp\left[-\frac{(2n+1)^2 \pi^2}{4L} D_{eff} t \right] . (1)$$

where *MR* is the moisture ratio (dimensionless), M is the moisture content (kg waterŸkg dry solids^{-1}) after t (s) of drying, M_e is the equilibrium moisture content (kg waterŸkg dry solids^{-1}) of the process at a given temperature and a determined thickness of sample, M_0 is the initial moisture content (kg waterŸkg dry solids^{-1}) of the sample, L is the thickness of the thin layer (m), D_{eff} is the effective moisture diffusivity (m^{2}s^{-1}) and t is the drying time (s). The equilibrium moisture content was assumed equal to zero (McMinn et al. 2005).

Nevertheless, to the best of the authors' knowledge, there are not reports about formulation or studies of drying of prickly pear leathers. This chewy product could be of interest in the industry, in order to get stable products for prickly pear, which is a temporary fruit. Additionally, hot air drying represents a cheap and easy process for fruit preservation. Thus, the objectives of the present work were to evaluate the effect of air temperature (a processing parameter) and sample thickness on the drying kinetics of prickly pear fruit paste, disposed in thin layer; and to find suitable mathematical models for the drying curves for further applications, for example, processing optimization.

MATERIALS AND METHODS

PRICKLY PEAR PASTE ELABORATION

Prickly pear fruits from *Opuntia ficus-indica,* variety 'Roja pelona', at commercial maturity stage (maturity index=62.2, which was calculated by the ratio soluble solids/titratable acidity=11.83/0.19), were obtained from a plantation located at the region of Dolores Hidalgo, Guanajuato, Mexico. Fruits were washed in water and then manually peeled. The pulp was homogenized into a blender (Oster, Mexico) and filtrated, in order to separate the juice from the seeds and insoluble solids. The resulting juice was preserved under frozen storage (-18°C) until needed. The prickly pear peel previously obtained was dried in a convective oven (100°C, 24 h) and ground to obtain flour. Prickly pear juice (11.83% of total soluble solids, TSS) was concentrated in a laboratory rotary vacuum evaporator (Yamato RE 500 model, Yamato Scientific America Inc. Orangeburg, NY) to 30±1% of TSS. Prickly pear fruit paste was prepared by blending concentrated juice, prickly pear peel flour (4%), and citric acid (0.15%).

HOT AIR DRYING PROCESS

The paste was spread into thin layers on steel trays coated by Teflon (0.25 m × 0.25 m) and drying in a laboratory hot air dryer. The dryer was designed and built in the University; it works with an electric resistance of 2000 W, equipped with a fan of 170 W and 233 m^3/h of air flow. The dryer has a chamber where sample is placed. Drying was conducted with two independent variables: drying temperatures (50, 60, 70 and 80ºC) and thickness (4, 6 and 8 mm).

MOISTURE LOSSES DURING DRYING PROCESS

For determination of drying curves, moisture losses were recorded at intervals of 10 min during whole drying process (8 h) by an electronic balance (Citizen CT 600H, Northglenn, CO) with a sensitivity of 0.01 g. Moisture content of the paste was determined by drying; 5 g of sample was exposed in a convective oven at 100ºC for 24 h.

MATHEMATICAL MODELS

For this research, four empirical models were employed to fit the drying experimental data. Empirical models are presented in Table 1.

TABLE 1. Mathematical models for fitting drying of thin layers of prickly pear fruit

Model	Equation
Lewis	MR = exp(-kt)
Henderson and Pabis	MR = a exp(-kt)
Peleg	$M_t = M_o - t/(k_1 + k_2 t)$
Page	MR = exp(-kt^n)

STATISTICAL ANALYSIS

For the validation of drying kinetics, the correlation coefficient (r^2) was chosen for selection of the best mathematical model. As a second index, the goodness of fitting was determined by reduced chi-squared (χ^2). Reduced Chi-squared, χ^2, can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{calc,i})^2}{N - n} \qquad (2)$$

where $MR_{calc,\ j}$ is the calculated moisture ratio for observation i, $MR_{exp,\ i}$ is the experimental moisture ratio for observation j; N is the number of observations; and n is the number of constants in the drying method.

RESULTS AND DISCUSSION

Effect of air temperature on drying behavior and drying rate
The drying time required for reducing the moisture content of the prepared prickly pear fruits paste to levels of 5-9% (w.b.) varied from 280 min to 520 min, depending on the drying temperature. This low level of 5-9% moisture

content was established in order to observe the whole drying process; some fruit leathers are produced drying to a value of 14.79% of moisture content (jackfruit leathers, by Okilya et al. 2010) or even 25% of moisture content, such as apple leathers (Quintero-Ruiz et al. 2012). The typical characteristic drying curves for prickly pear fruit paste of 6 mm thickness during the process are shown in Figure 1(a). The relationship between the moisture ratio and drying time is nonlinear, with a large decreasing at the beginning and followed by a falling rate period at all temperatures. Similar trends were obtained for thickness of 4 and 8 mm. Figure 1(b) displays the effect of sample thickness on drying rate at 60ºC. The decreasing in sample thickness reduced the drying time for all the studied temperatures. The drying time is reduced due to shorter distance for the moisture for the center to the surface in the sample, as it was reported by Maskan et al. (2002) for hot air and sun drying operations.

CALCULATION OF THE EFFECTIVE MOISTURE DIFFUSIVITY AND ACTIVATION ENERGY

The drying rate was calculated from the slopes in the plot of moisture content versus drying time. Figure 2(a) shows the drying rate against moisture content at 50, 60, 70 and 80ºC. The initial drying rate was high, followed by a decreasing, as the sample is reaching the dried state. Drying rates increased with decreasing in thickness and increasing temperature (Figure 2(b)). The drying of prickly pear fruit paste was characterized mainly by a falling rate period. Das et al. (2013), Lahsasni et al. (2004) and Maskan et al. (2002) also reported this behavior during the drying of others biological products.

During the falling rate period, the process is internally controlled, with diffusion being the main mechanism for moisture transfer. Thus, diffusion was governing moisture movement during drying of thin layers of prickly pear fruit paste.

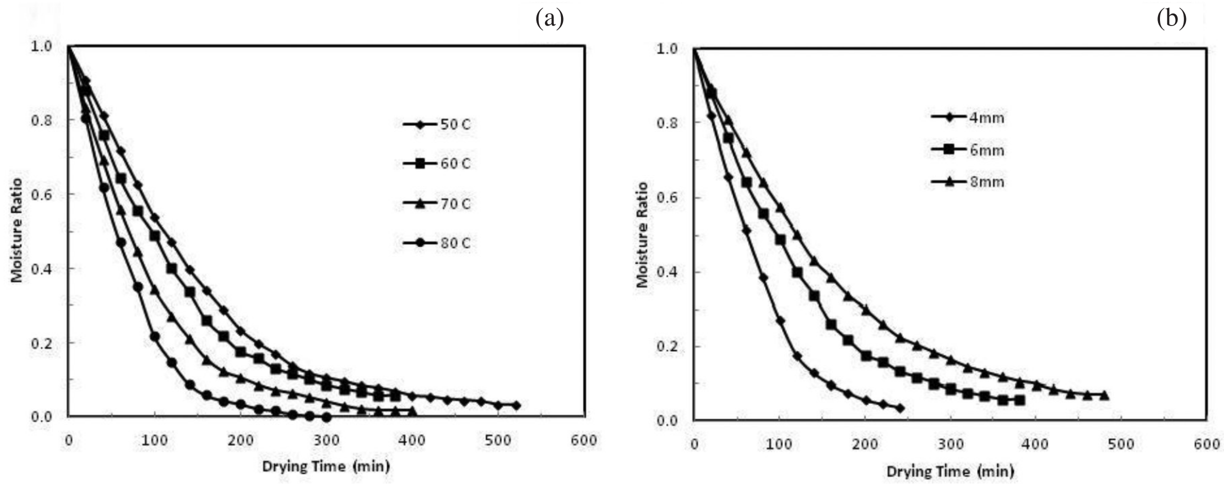

FIGURE 1. Drying time curves required for reducing the moisture in thin layers of prickly pear fruit. (a) Different drying temperatures at 6 mm thickness, and (b) Different sample thickness at 60°C

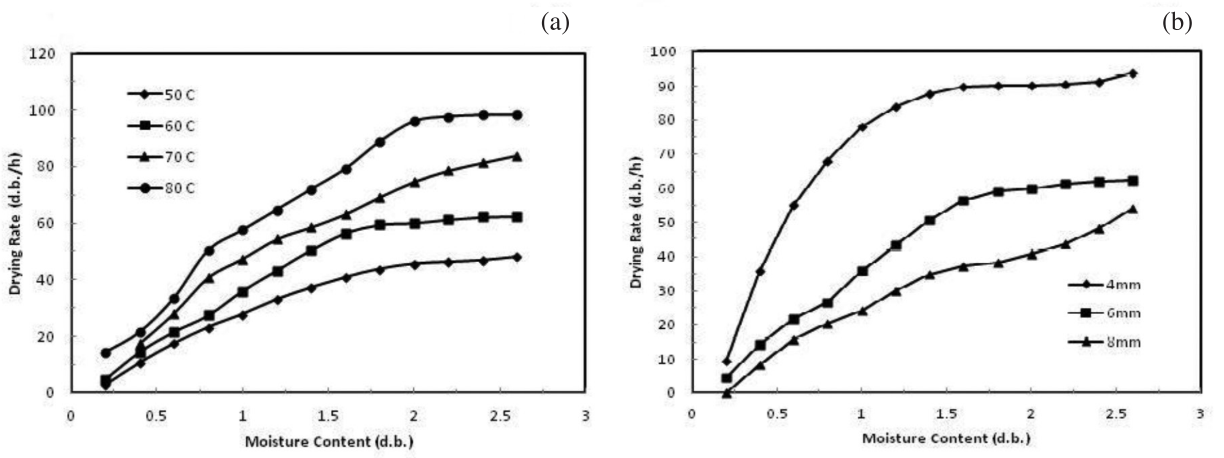

FIGURE 2. Drying rate at different temperatures and thickness of thin layers of prickly pear fruit. (a) Different drying temperatures at 6 mm thickness, and (b) Different sample thickness at 60°C

Figure 3(a) shows the drying rates curves for different temperatures at a fixed thickness, while Figure 3(b) shows the drying curves for different thicknesses at the fixed temperature of 60ºC. $R^2>0.98$ were found for all drying temperatures and sample thickness, indicating good fit of the mathematical models evaluated.

The calculated values of D_{eff} for the drying of prickly pear fruit leathers at different thicknesses and temperatures are shown in Table 2. Both air temperature and thickness affected the D_{eff}. The values of D_{eff} for prickly pear fruit leather ranged from 0.75 to 7.05 × 10^{-9} m^2s^{-1} depending on drying conditions. The highest value of D_{eff} was obtained at the highest air temperature with the thickest layer. D_{eff} values were higher than other reported coefficients, such as 3-37.6 × 10^{-11} m^2s^{-1} for hot air drying of grape leathers at temperatures between 55 and 75ºC (Maskan et al. 2002).

EFFECT OF TEMPERATURE ON DIFFUSIVITY AND MODELING OF THE DRYING CURVES

The Arrhenius- type equation was employed to calculate the activation energy (E_a) for the diffusion drying process of prickly pear leathers:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (3)$$

The calculation of activation energy is common in the drying process to evaluate the effect of the temperature on the diffusivity coefficient (Doymaz & Pala 2003; Maskan et al. 2002). Figure 4(a) shows ln D_{eff} versus T^{-1}, the linear relationship indicates Arrhenius dependence. The values of E_a were 34.51, 29.86, and 25.31 kJ mol^{-1} for prickly pear fruit leather with 4, 6, and 8 mm thickness, respectively. E_a increased when thickness decreased. This trend has been also reported by Maskan et al. (2002), who found E_a values of 10.3 to 21.7 kJ mol^{-1} in drying of grape leathers with thickness from 0.71 to 2.86 mm. Small thickness affects more the diffusivity in comparison with samples of longer thickness, because of a smaller variation in temperature during the drying (Lee & Hsieh 2008).

The parameters obtained from the linear plot of each model for different drying conditions are included in Table 3. The models were evaluated with the coefficient of regression (r^2) and chi-square (χ^2), resulting in values within the range of 0.8855 to 0.9993 and 41.5 × 10^{-4} to 0.076 × 10^{-2}, respectively. Page model gave higher coefficient of regression (r^2) values (0.991-0.9993) over the others models. Thus, the Page model could sufficiently define the air drying of prickly pear fruit in thin layers. Page models has been reported as the best model to describe drying process in other layers of vegetables, by Madamba et al. (1996) for garlic slices, Dandamrongrak

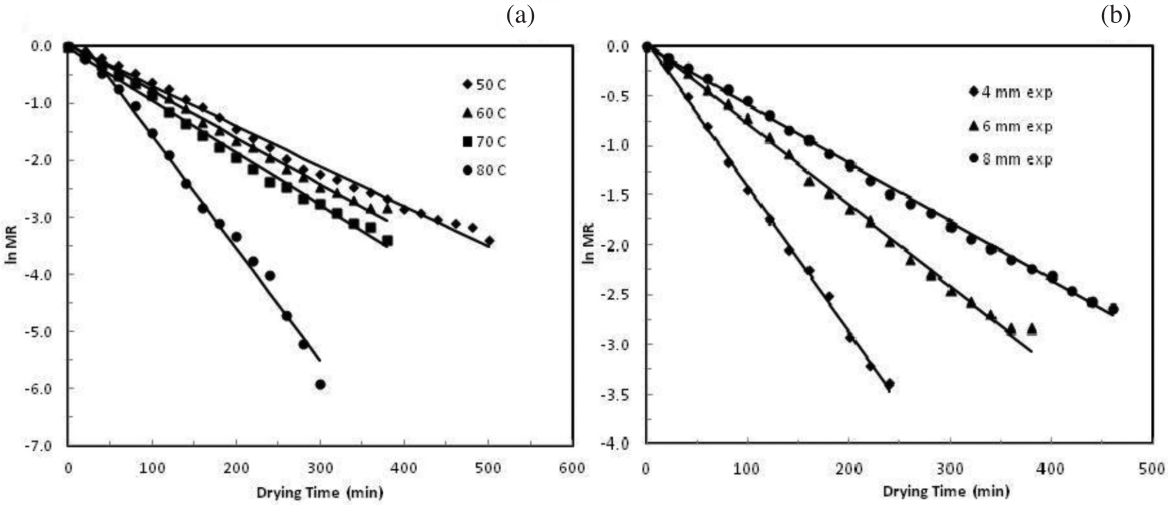

FIGURE 3. Semi logarithmic plots by drying time in thin layers of prickly pear fruit. (a) Different drying temperatures at 6 mm thickness, and (b) Different sample thickness at 60°C

TABLE 2. Values of effective diffusivity (D_{eff}) for drying of prickly pear fruit leather (r^2 values in parentheses)

Sample Thickness (mm)	Effective diffusivity ($x10^{-9}$), (m^2s^{-1})			
	50°C	60°C	70°C	80°C
4	0.754 (0.993	0.887 (0.997)	1.124 (0.988)	1.715 (0.985)
6	1.716 (0.991)	1.989 (0.993)	2.226 (0.993)	4.787 (0.989)
8	2.587 (0.996)	3.227 (0.997)	4.067 (0.988)	7.052 (0.990)

TABLE 3. Results of non-linear regression obtained from different thin-layer drying models

Model	T (°C)	Sample thickness (mm)	Model constants	r^2	X^2
Lewis model	50	4	k = 0.0109	0.9796	39.79×10^{-4}
		6	k = 0.0068	0.9851	6.297×10^{-4}
		8	k = 0.0046	0.9962	0.549×10^{-4}
	60	4	k = 0.0176	0.9879	28.10×10^{-4}
		6	k = 0.0091	0.9911	8.4×10^{-4}
		8	k = 0.0058	0.9981	1.28×10^{-4}
	70	4	k = 0.0143	0.9985	2.22×10^{-4}
		6	k = 0.0076	0.9919	3.29×10^{-4}
		8	k = 0.0073	0.9971	1.58×10^{-4}
	80	4	k = 0.0254	0.9784	35.8×10^{-4}
		6	k = 0.0177	0.9888	41.5×10^{-4}
		8	k = 0.0118	0.9910	18.57×10^{-4}
Henderson and Pabis model	50	4	a = 0.8945; k = -0.0114	0.9768	12.02×10^{-3}
		6	a = 1.0605; k = -0.0066	0.9834	0.888×10^{-3}
		8	a = 1.0313; k = -0.0179	0.9959	0.101×10^{-3}
	60	4	a = 1.0697; k = -0.0179	0.9852	1.91×10^{-3}
		6	a = 1.0214; k = -0.0090	0.9897	0.645×10^{-3}
		8	a = 1.0211; k = -0.0057	0.9956	0.231×10^{-3}
	70	4	a = 1.0216; k = -0.0144	0.9984	0.165×10^{-3}
		6	a = 1.0061; k = -0.0077	0.9919	0.373×10^{-3}
		8	a = 1.1216; k = -0.0072	0.9893	3.532×10^{-3}
	80	4	a = 1.1272; k = -0.0261	0.9784	2.87×10^{-3}
		6	a = 1.3665; k = -0.0192	0.9888	11.09×10^{-3}
		8	a = 1.2868; k = -0.2521	0.9910	6.279×10^{-3}
Peleg model	50	4	k_1 = 42.853; k_2 = 0.2072	0.8855	2.892×10^{-2}
		6	k_1 = 50.071; k_2 = 0.9630	0.9630	15.61×10^{-2}
		8	k_1 = 72.053; k_2 = 0.2406	0.9932	0.137×10^{-2}
	60	4	k_1 = 22.682; k_2 = 0.2479	0.9381	3.530×10^{-2}
		6	k_1 = 39.069; k_2 = 0.2453	0.9541	1.732×10^{-2}
		8	k_1 = 55.844; k_2 = 0.2457	0.9840	0.467×10^{-2}
	70	4	k_1 = 16.211; k_2 = 0.2957	0.9397	1.754×10^{-2}
		6	k_1 = 37.484; k_2 = 0.2687	0.9983	0.076×10^{-2}
		8	k_1 = 57.712; k_2 = 0.2154	0.9847	3.063×10^{-2}
	80	4	k_1 = 10.000; k_2 = 0.3051	0.9673	5.375×10^{-2}
		6	k_1 = 17.709; k_2 = 0.2843	0.9459	2.648×10^{-2}
		8	k_1 = 25.119; k_2 = 0.2832	0.9616	1.194×10^{-2}
Page model	50	4	k = 0.0029; n = 1.2460	0.9910	4.483×10^{-4}
		6	k = 0.0039; n = 1.0961	0.9927	3.190×10^{-4}
		8	k = 0.0040; n = 1.0219	0.9993	0.299×10^{-4}
	60	4	k = 0.0059; n = 1.2128	0.9974	30.80×10^{-4}
		6	k = 0.0048; n = 1.1176	0.9924	10.53×10^{-4}
		8	k = 0.0050; n = 1.0288	0.9982	0.964×10^{-4}

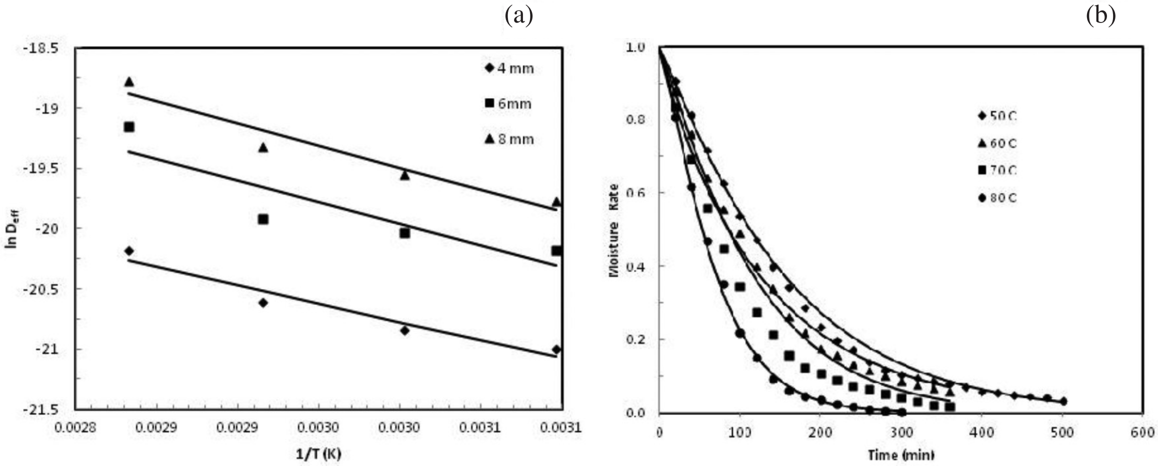

FIGURE 4. Effect of temperature and modeling of the drying curves in thin layers of prickly pear fruit. (a) Arrhenius-type relationships between effective diffusivity and temperature for different sample thicknesses and (b) Experimental data and adjustment to Page model for thin layer (6 mm thickness) of prickly pear fruit

et al. (2002) for bananas with various pretreatments, and Lahsasni et al. (2004) in bits for prickly pear fruit. The correlation coefficient has been a goodness test for selecting the best model to validate drying curves, employed by Dandamrongrak et al. (2002). The r^2 value should be higher and χ^2 values should be lower to establish the best drying condition (Demir et al. 2004; Goyal et al. 2006; Pangavhane et al. 1999; Togrul & Pehlivan 2002).

Figure 4(b) shows the fit of the Page model to the experimental data of 6 mm sample thickness of prickly pear fruit thin layers at different temperatures. There was a good correlation between predicted and observed values. Similar results were obtained for the 4 and 8 mm prickly pear fruit layer thickness at different drying temperatures. Increasing sample thickness and low drying temperatures resulted in longer drying time. The thickness had more effect on the drying time than the drying temperature.

CONCLUSION

Drying rate increased with the increase in drying air temperature, which reduced the drying time of thin layer of prickly pear fruit paste. Hot air drying of prickly pear fruit leathers took place in a falling rate period, and the Page model was suitable to describe the drying behavior in the temperature range of 50 to 80ºC. The values of diffusivity (0.75 to 7.05 × 10^{-9} m^2s^{-1}) followed Arrhenius-type temperature dependence. Both drying air temperature and sample thickness had pronounced influences on diffusivity values. The values of activation energy for moisture diffusion (25.31-34.51 kJ mol^{-1}) were markedly affected by the sample thickness of prickly pear fruit leather. The results will be useful to implement an effective, simple and cheap drying process for the expanding prickly pear industry

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