INFLUENCE OF THICKNESS ON THE DRYING OF PAPAYA PUREE (*Carica papaya L.*) THROUGH REFRACTANCE WINDOW™ TECHNOLOGY

INFLUENCIA DEL ESPESOR EN SECADO DE PURÉ DE PAPAYA (*Carica Papaya L.*) POR TECNOLOGÍA DE VENTANA DE REFRACTANCIA®

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ABSTRACT: The aim of this study was to evaluate the influence of sample thickness (2, 3 and 4 mm) on the drying kinetics, water activity (a_w) and color (ΔE) of papaya puree slices processed through Refractance Window™ technology (RW™). Additionally, the water diffusion coefficient (D_{eff}) was evaluated taking into account the shrinkage effect. The experimental values of moisture were fitted using Newton's and Midilli's models. The results showed that the lower the thickness, the faster the drying, the lower the values of a_w and the higher the ΔE. The samples reached 0.0652, 0.1132 and 0.2624 g water/ g dry solid in 60 min for 2, 3 and 4 mm slices, respectively. Midilli's model was the most appropriate to predict the experimental curves of papaya drying through RW™. D_{eff} decreased at a lower thickness and its order of magnitude was of 10^{-10} m^2/s.

KEYWORDS: drying, papaya, refractance window, diffusion coefficient, mathematical modeling.

RESUMEN: El objetivo de este trabajo fue evaluar la influencia del espesor de las muestras (2, 3 y 4 mm) sobre las cinéticas de secado, actividad de agua (a_w) y color (ΔE) de rodajas de puré de papaya procesadas por tecnología de ventana de refractancia™ (RW™). Adicionalmente se evaluó la difusividad del agua (D_{eff}) teniendo en cuenta el encogimiento. Los datos de humedad se ajustaron mediante los modelos de Newton y Midilli. Los resultados mostraron que a menor espesor el secado fue más rápido, los valores de a_w fueron menores y los ΔE superiores. Las muestras alcanzaron 0.0652, 0.1132 y 0.2624 g agua/ g sólido seco en 60 min para rodajas de 2, 3 y 4 mm, respectivamente. El Modelo de Midilli fue el más apropiado para predecir las curvas de secado de papaya por RW™. D_{eff} disminuyó a menor espesor y su orden de magnitud fue de 10^{-10} m^2/s.

PALABRAS CLAVE: secado, papaya, ventana de refractancia, coeficiente de difusión, modelamiento matemático.

1. INTRODUCTION

Papaya is a tropical fruit which originated from Mexico and Central America, and it is a good source of vitamins (C, A, B1, B2 and carotenoids) [1, 2]. Papaya is highly perishable, mainly due to its high moisture content (between 80 and 85% wb), so it is important to find alternatives for its preservation and/ or processing [3-5].

Drying is one of the most commonly-used processes for food preservation due to the significant reduction of water activity and consequently, the reduction of microbiological activity and physical and chemical changes during storage of the product [6]. During drying, foods undergo changes in volume, shape, porosity and density that can cause shrinkage or structural collapse, thus affecting the quality of the final product [7]. Therefore, changes in volume should be considered for the modeling of mass transfer during a drying process [7-8].

Several methods of food drying have been developed (spray drying, tray drying, freeze drying, among others) but none provide economical and high quality products [9]. Freeze drying is considered one of the best food processing methods to produce high-quality dehydrated food, but it is a costly and time-consuming process.

Refractance Window™ (RW™) is an innovative drying technology developed by MCD Technologies Inc. (Tacoma, Washington, USA), featuring short drying times, low energy consumption, and high-quality of products [10]. This technology is used for drying of fruit puree, where the puree is spread on a plastic belt that moves over a reservoir of hot water (temperature below the boiling point), with infrared radiation from the water passing through the belt and causing the drying of the material [11].

As RW™ is a relatively novel technology, there are not many scientific publications related to the influence of puree thickness, and water temperature, on product characteristics [9-16].

The aim of this study was to evaluate the influence of samples thickness (2, 3 and 4 mm) on the drying kinetics, water activity (a_w) and color (ΔE) of papaya puree slices dried through the RW™ technique. Additionally, the water diffusion coefficient was evaluated, taking into account the shrinkage effect.

2. MATHERIALS AND METHODS

2.1. Raw material and experimental design

Papaya fruits were obtained at a local market (Cali-Colombia) and were selected with uniform soluble solids content (10 - 12º Brix). These were prime-quality samples, according to the Colombian Technical Standard NTC 1270 [17]. The fruits were washed, peeled (using a stainless steel knife) and cut into two pieces to remove the seeds. The fruit puree was obtained with a food processor (Oster, 3167, USA). Preformed plastic molds were used to obtain puree slices of 2, 3 or 4 mm of thickness and 30 mm in diameter.

The slices were dried in a prototype designed to reproduce the RW™ principle (Figure 1). This consists in a tank filled with water (length: 0.6 m, width: 0.4 m, depth: 0.1 m), where a polyester membrane (Mylar™ type - transparent to infrared radiation) slides over the water surface at a speed of 0.001 m/min. The water was recirculated at a rate of 2.74 L/min in order to recover the unused heat. The water temperature was set up at 70°C.

A completely randomized design was carried out considering the thickness of the puree slices (2, 3 and 4 mm) and the drying time (0, 10, 20, 30, 60, 90, 120 and 180 min) as the experimental factors. The response variables were moisture content (*MC*), water activity (a_w), total color difference (ΔE), apparent density (ρ_{at}), and volume (V). Experiments were conducted in triplicate.

2.2. Physicochemical analysis

The *MC* was determined by drying the samples in a vacuum oven until constant weight at 60°C (AOAC, 1980) [18]. The a_w was measured with a dew-point hygrometer (Decagon, AquaLab CX-1, USA) with a sensitivity of 0.0001.

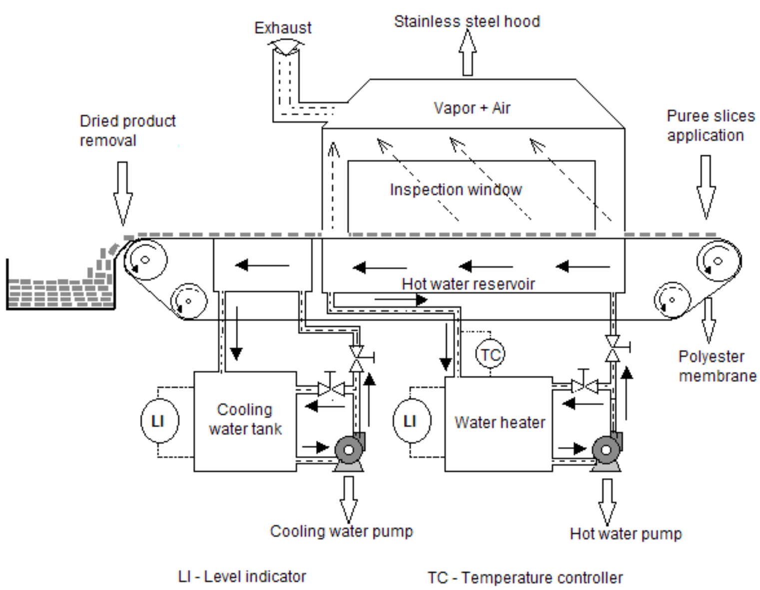

Figure 1. Schematic diagram of a pilot scale RW™ dryer

The color was measured between 400-780 nm, employing a spectrocolorimeter (Hunter-Lab, ColorFlex, USA) and using as standard the illuminant D65 and the 10º observer in order to obtain the color coordinates CIE-L*a*b*. ΔE was determined through (1):

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

The ρ_{at} of the samples was determined by means of the volume displacement method, using a pycnometer and distilled water at 20±0.3°C as the displacement medium. The V of the slices was calculated from ρ_{at} data.

2.3. Mathematical modeling

The drying kinetics were fitted using Newton's (2) and Midilli's (3) models, widely used for modeling moisture ratio (*MR*) in biological materials [19-21].

$$MR = \exp(-kt) \quad (2)$$

$$MR = a\exp(-k(t^n)) + bt \quad (3)$$

where k, a, n and b are parameters of the models and t is the drying time.

MR is defined in accordance with (4).

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (4)$$

where X_t is the moisture content at a given time, X_e is the equilibrium moisture content and X_0 is the initial moisture content (g water/g dry solid). However, *MR* was simplified to (5), taking into account that the RW™ equipment used for the experiments does not control the relative humidity of air in contact with the material [21-23].

$$MR = \frac{X_t}{X_0} \quad (5)$$

The analytical solution of Fick's second law was used in order to determine the effective diffusion coefficient (D_{eff}), considering the geometry of a semi-infinite sheet with thickness l and assuming that the drying process is controlled by internal moisture diffusion in an axial direction. The analytical solution is given by (6) [24], which is valid only for the falling rate drying period.

$$\frac{X_t - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left[-(2n+1)^2\frac{\pi^2 D_{eff}\, t}{l^2}\right] \quad (6)$$

To take shrinkage into account, the sample thickness must be considered as a function of time *l(t)*(7)[25]:

$$l(t) = \frac{m_t}{\pi R^2 \rho_{at}} \quad (7)$$

where m_t is the mass at a given time (g), ρ_{at} is the apparent density at a given time (g/cm^3) and R is the ratio of the papaya slices, equivalent to 0.015 m. D_{eff} values were calculated with and without considering shrinkage.

2.4. Statistical Analysis

The order of the experiments and the effect of thickness on the response variables were determined by means of the Minitab statistical program (version 15.1.20.0, 2007), for a significance of 0.05 and a confidence interval of 95% ($p<0.05$). Regressions to estimate the parameters of Newton's and Midilli's models were performed, using the Polymath 5.0 (version 5.1, 2000) statistical software. The fitting quality of the experimental data to the models was assessed using the correlation coefficient (R^2), reduced Chi-square (χ^2), and the Root Mean Square Error (RMSE). These statistical parameters were calculated using equations (8), (9) and (10) [26], respectively. The highest values of R^2 and the lowest values of χ^2 and RMSE were taken as the optimum criteria.

$$R^2 = \frac{\sum_{i=1}^{N}\left(\overline{MR_{pre}} - MR_{pre,i}\right).\sum_{i=1}^{N}\left(\overline{MR_{exp}} - MR_{exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(\overline{MR_{pre}} - MR_{pre,i}\right)^2\right].\left[\sum_{i=1}^{N}\left(\overline{MR_{exp}} - MR_{exp,i}\right)^2\right]}} \quad (8)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (9)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad (10)$$

where N is the number of observations, z is the number of model parameters, MR_{exp} is the experimental moisture ratio, and MR_{pre} is the predicted moisture ratio.

3. RESULTS AND DISCUSSION

3.1. Moisture content (*MC*)

The initial *MC* of papaya puree was 8.2262 ± 0.4519 g water/g dry solid. The *MC* decreased faster at a lower thickness; the samples of 2 mm reached 0.0652 g water/g dry solid in 60 min, while those of 3 and 4 mm reached 0.1132 and 0.2624 g water/g dry solid, respectively. Figure 2 shows *MC* variation of papaya samples during the drying time.

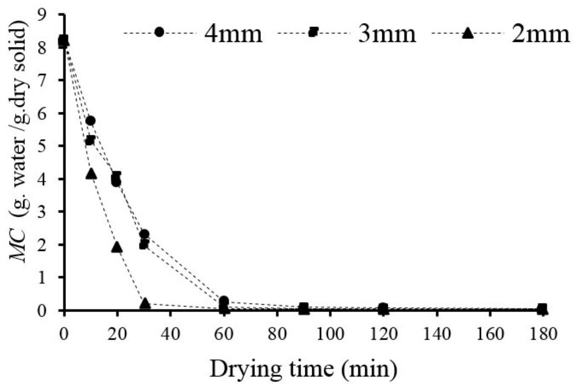

Figure 2. Curves of moisture content during drying of papaya puree at 70°C for samples of 2, 3, and 4mm.

Thinly sliced samples dried faster due to the reduced distance the water travels in order to be extracted [27]. Similar results were observed during drying of mango [16] and orange [28] by RW™, and during convective drying of eggplant [29], papaya and garlic [30]. According to Geankoplis (1993) [31], the drying time is directly proportional to the weight of dry solid, which increases with the increasing of thickness. The ANOVA (Analysis of Variance) showed a significant effect ($p<0.05$) of thickness and drying time on *MC* of papaya samples.

3.2. Water activity (a_w)

Thickness affected the a_w of the samples significantly (Figure 3). Findings showed that the lower the thickness, the lower the value of a_w, at a specific time. Similar results were obtained during drying of mango using the RW™ technique [16].

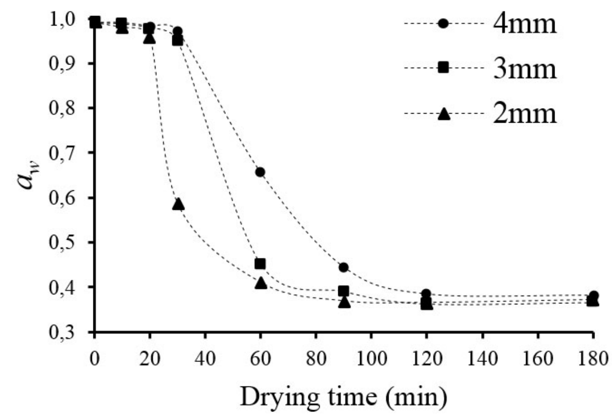

Figure 3. Effect of sample thickness on water activity (a_w) of papaya puree during RW™ drying at 70°C.

After 60 min of drying, samples of 2 and 3 mm reached values of a_w below 0.6, but 2 mm samples reached the lowest value (0.41); these results indicate the growth restriction of pathogenic microorganisms such as fungi, yeasts, and bacteria [32]. After 90 min of drying, these samples present values of a_w below 0.4, which are characteristic of highly stable food during storage [33]. This result is relevant for the preservation of papaya because of its high susceptibility to mold growth [34]. The ANOVA evidenced a significant effect ($p<0.05$) of thickness and drying time on the a_w of papaya samples.

3.3. Color

Figure 4 presents the values of ΔE of papaya samples during the drying process. For the three sample thicknesses investigated, it can be observed that ΔE increases until about 60 min of drying and subsequently stabilizes. This behavior shows the ability of RW™ technique to self-regulate and protect the characteristics of the puree at low moisture content [35]. The influence of thickness on ΔE is also observed, obtaining a higher value for the samples of lower thickness. This result is due to the fact that thinner samples reach higher internal temperatures which causes further degradation of the papaya carotenoids (licopene, ß-criptoxanthin, ß-carotene). Ahmed et al. (2002) [36] report that the change in color of papaya puree is a direct consequence of the change in the carotenoids; the authors also point out that the color change reaction has first order kinetics, where the rate constant depends on the temperature and follows the Arrhenius relationship.

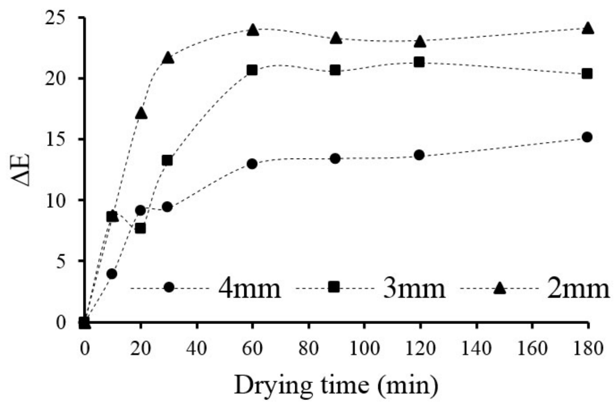

Figure 4. Changes in color (ΔE) of papaya puree during RW™ drying at 70°C for 2, 3, and 4 mm samples.

The ANOVA showed that thickness and drying time had a significant influence ($p<0.05$) on the ΔE of papaya puree slices.

3.4. Mathematical modeling of drying kinetics

Table 1 shows the estimated kinetic parameters of Newton and Midilli's models, including criteria to evaluate the fitting quality.

Table 1. Values of kinetic parameters k for each drying curve.

Model	Constants and statistical parameters	Thickness (mm)		
		2	3	4
Newton	k x10^2(min^{-1})	7.5617	4.3694	4.0548
	R^2	0.9960	0.9948	0.9979
	RMSE	0.0307	0.0365	0.0254
	χ^2 x 10^3	1.0781	1.5200	0.7391
Midilli	k x10^2(min^{-1})	3.2951	2.7516	2.0203
	n	1.2980	1.1426	1.2193
	a	0.9981	0.9895	0.9957
	b x 10^5	2.7640	-0.8387	2.8440
	R^2	0.9984	0.9955	0.9995
	RMSE	0.0191	0.0333	0.0108
	χ^2 x 10^3	0.7293	2.2122	0.2322

It is observed that the parameter k increases at a lower thickness of the samples, having a higher value for the samples of 2 mm with 7.5617x10^{-2} (min^{-1}). The variable k is often temperature dependent, consequently, an increase in k is related to an increase in drying temperature [37]. Generally, higher drying temperatures resulted in steeper curves and shorter drying times [38]. In this study, the temperature was constant (70ºC), therefore, this behavior is probably due to the fact that thinner samples reached higher temperature at their geometrical center as a result of the smaller mass per unit of surface area.

Both proposed models showed a good fit of the experimental values, nevertheless, Midilli's model was the one with the best fit (Figure 5) corresponding to the highest values of correlation coefficient and the lowest values of χ^2 and RMSE.

Some researchers have found that Midilli's model accurately characterized the drying behavior of different foods, as in apple drying with infrared rays [19] and red pepper drying by combining hot air and ultrasound [21].

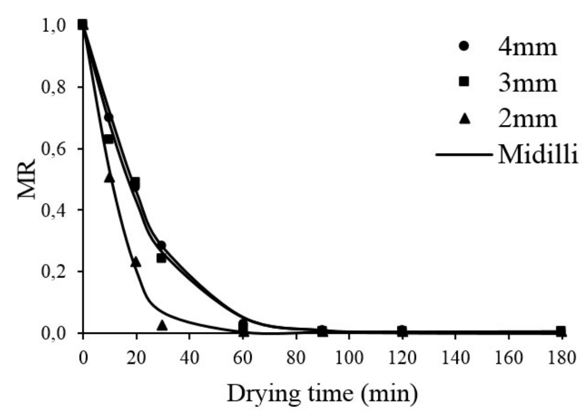

Figure 5. Experimental and calculated drying curves for papaya puree slices of 2, 3 and 4 mm using Midilli's model.

3.5. Effective diffusion coefficient (D_{eff})

D_{eff} was calculated for the first falling rate drying period using the first term of the analytical solution of Fick's second law, which was the most significant. For this calculation, shrinkage or volume change (see Figure 6), of the slices as a function of drying time was considered, which was calculated from ρ_{at} (values not shown). According to the results, thickness influenced volume change during drying; specifically, the thicker the sample, the smaller the changes (4 mm samples showed the highest values of V).

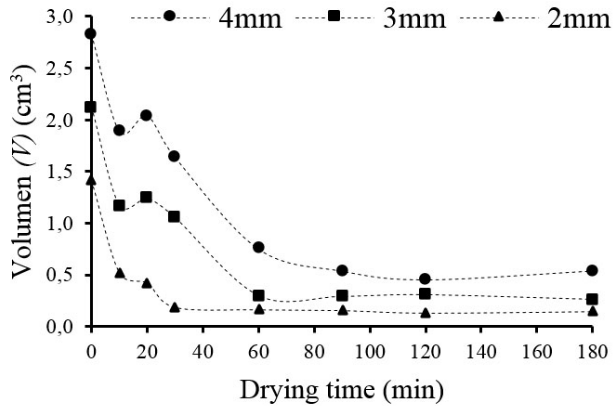

Figure 6. Changes in volume (V) for papaya puree slices of 2, 3 and 4 mm of initial thickness during RW™ drying.

Table 2 shows the influence of thickness and volume change on D_{eff} of papaya puree slices during drying, which have a similar magnitude order to those reported in drying of papaya by convection [39] and treatment by osmotic dehydration [5].

Table 2. Mean effective diffusion coefficient for papaya slices of 2, 3 and 4 mm of thickness

Thickness (mm)	D_{eff} x 10^{10} (m^2/s)	D_{eff}^* x 10^{10} (m^2/s)	Δ(%)
2	4.2592	0.4005	90.60
3	4.7724	1.3813	71.06
4	7.6811	3.1663	58.78

Δ: Difference between the diffusion coefficients without considering shrinkage (D_{eff}) and considering shrinkage (D_{eff}^*).

It can be seen that D_{eff} and D_{eff}^* are higher when puree thickness increases, because the thicker samples exhibit less shrinkage for a fixed time (Figure 6), thus, significantly facilitating diffusion. Similar results were obtained in convective drying of papaya slices [30], mango drying by RW™ [16], and sun and convective drying of grape products [27].

Table 2 also shows that the diffusion coefficient values corrected by volume (D_{eff}^*) were lower than the uncorrected values (D_{eff}), since food shrinkage modifies the distance required for the movement of water molecules [40]. The diffusion coefficient is overestimated between 58.78 and 90.60%, when volume correction is not taken into account.

4. CONCLUSION

Thickness of papaya puree significantly influenced drying kinetics, water activity and the color of the product; the lower the thickness, the faster the drying, the lower the a_w and the higher the ΔE. Midilli's model was the most appropriate to predict the experimental drying curves of papaya puree processed by RW™. The diffusion coefficient was higher when not considering shrinkage. These findings show that the RW™ technique is highly suitable for papaya drying; it makes it possible to dry the product reaching a low moisture content in shorter times, reducing the a_w to values below 0.4 and preserving a similar color.

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