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The impact of convective drying on the color, phenolic content and antioxidant capacity of noni (*Morinda citrifolia* L.)

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Abstract

The effect of thin-layer drying temperature on color, phenolic content and antioxidant capacity of noni slices was investigated. Noni slices were air-dried at 50, 60 and 70 °C under natural convection conditions. Drying curves were fitted to thin-layer drying models in order to evaluate the drying characteristics of the product. In addition, an unsteady-state diffusion equation was numerically solved considering both product shrinkage and a variable mass Biot number in boundary condition to accurately estimate water diffusivity in a process with external resistance to mass transfer. Results revealed that the Aghbashlo model accurately reproduced the experimental behavior. As expected, water diffusivities, corrected for shrinkage, increased with the use of higher drying temperatures, with values in the range of 1.80-3.19 to $\times 10^{-9}$ m^2/s. On the other hand, while drying caused a reduction in product lightness (24-31%) and total phenolic content (20-28%), the antioxidant capacity of dried noni was high (82-93% DPPH inhibition), which is advantageous for the further storage or processing of this fruit.

Keywords: antioxidants; natural convection; noni drying.

Practical Application: Dehydrated noni slices can be ground to obtain a powder which has many possible applications. It can be incorporated into ground beef in order to stop the oxidation of fat and can be incorporated into herbal tea blends to increase their antioxidants content. They can also be used as antioxidant supplements in animal diets, where they may act as growth promoters.

1 Introduction

The noni (*Morinda citrifolia* L.) has gained an increasing research interest due to its possible benefits to human health, including anti-inflammatory and anti-cancer activities (Chan-Blanco et al., 2006). Although the use of noni for human consumption has become very controversial in recent years, since on the one hand several authors (Kadiri et al., 1999; Collins, 2009; Serafini et al., 2011; Alencar et al., 2013) have conducted experiments in vivo use of this fruit and have reported a nephrotoxic and genotoxic effect, other authors have evaluated the pharmacological activity of *M. citrifolia* by in vivo and clinical trials and found among other anti cancer effect (Kamiya et al., 2010) agent hepatoprotective (Lin et al., 2013), anti dyslipidemia (Mandukhail et al., 2010), immune stimulator (Krishnaiah et al., 2012), anthelminthic activity (Brito et al., 2009) and anti inflammatory (Fletcher et al., (2013). Given these contradictory highlighted in some countries have banned its use, while the vast majority is still used for the treatment of various diseases. These properties have been related to different phytochemicals such as phenolics, rutin and scopoletin, which are mainly responsible for its high antioxidant capacity (Lin et al., 2014).

The accelerated maturation of this fruit, where the pulp softens and dissolves, makes its fresh ingestion difficult; therefore, commercialization and consumption generally require noni to be processed into juice or juice drinks (Gironés-Vilaplana et al., 2015). However, recent studies have highlighted the importance of studying the use of other noni products, such as purees, as possible novel food ingredients (West et al., 2011), thus driving the search for processing or conservation methods that can facilitate noni storage or integration into other technological processes (Fabra et al., 2011).

Convective drying is one of the most important preserving technologies used in the food industry. This process is often used to decrease the chemical, enzymatic and microbiological reactions occurring in fruits and vegetables, representing a feasible and economical way to extend their shelf-life. However, a main drawback of drying is its undesirable effects on product quality indices, such as color changes and degradation of bioactive compounds, which depends of the severity on drying conditions (Rodríguez et al., 2013) and may lead to a reduced consumer acceptance (Larrosa et al., 2015). Pacheco-Aguirre et al. (2014), Taghian Dinani et al. (2014) and Rodríguez et al. (2013) have used either empirical or mechanistic models to describe water transfer during convective drying of foodstuffs. Empirical models include exponential or Page's equations (Taghian Dinani et al.,

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2014). Nevertheless, while these models can satisfactorily describe the experimental behavior, they are not generalizable to other process conditions. To the best of the authors' knowledge, no studies have been published regarding the drying of noni slices and the characterization of water diffusivity in this product. Thus, the objective of this study was to characterize the thin-layer drying of noni slices at different temperatures and evaluate the effect of this process on the color, phenolic compounds and antioxidant capacity of the product.

2 Materials and methods

2.1 Plant material and drying conditions

Whole noni fruits in the green-yellow maturity stage were obtained from a local market in Distrito Federal, México. Noni fruits were washed, sanitized with chlorinated water (150 ppm, 5 min), dried with a cloth and then longitudinally cut with an electrical meat slicer into 0.2 cm thick slices without removing the peel. The resulting samples (50 g) were placed in a wire mesh with 0.5 cm^2 openings in the middle section of a natural convection oven (Memmert DO6836, Germany) and dried at one of these 50 (300 min), 60 (240 min) or 70 °C (200 min). The moisture content of the product was expressed as the dimensionless free moisture fraction Ψ (the removable water portion remaining in the product). Meanwhile, shrinkage was determined by measuring changes in product thickness with a micrometer during additional tests conducted under the same conditions described above. The initial moisture content was determined by oven-drying the product at 100 °C for 24 hours. The dried product was placed in hermetic bags protected from light at -18 °C until further analysis.

2.2 Color, total phenolic compounds and antioxidant capacity measurement

Color was determined as the average of six measurements using a colorimeter (Konica-Minolta C-400) and expressed in the CIE Lab color space. The parameters chroma (*C*) and hue angle (*H*) were calculated.

The total phenolic content (TPC) and antioxidant capacity in fresh and dried samples were determined using the extraction and quantification methodologies described by Yang et al. (2010) using the Folin-Ciocalteau reagent, and expressed as milligrams of gallic acid equivalents (GAE)/g dry matter (dm). Antioxidant capacity (AC) was tested using the DPPH free radical scavenging assay with a metanol solution (0.025 g/L). The results were reported as the percentage inhibition of DPPH activity.

2.3 Thin-layer drying models

Five common thin-layer drying models - Newton, Page, modified exponential, two-terms exponential and Aghbashlo models with 1 to 4 adjustable constants - were tested for their ability to accurately reproduce the experimental moisture evolution of noni slices. These equations were fitted to experimental drying curves to identify the parameters *a*, *b*, k_1 and k_2.

2.4 Unsteady-state diffusion model

Model development

The Equations 1, 2, 3 and 4 describes the water transfer between solid and gas phases in an air-drying process:

$$\frac{\partial(c_s X)}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial(c_s X)}{\partial z}\right) \quad for \quad t>0 \quad and \quad 0 \le z \le L \tag{1}$$

$$-D\frac{\partial(c_s X_i)}{\partial z} = \frac{h_m}{v}(H_i - H) \quad for \quad t>0 \quad and \quad z = L \tag{2}$$

$$-D\frac{\partial(c_s X)}{\partial z} = 0 \quad for \quad t>0 \quad and \quad z=0 \tag{3}$$

$$X = X_0 \quad for \quad t=0 \quad and \quad 0 \le z \le L \tag{4}$$

The Figure 1 illustrates the location of the boundary conditions.

In this study, mass transfer in the radial direction was considered negligible since the noni peel, which was not removed, provided an increased resistance to mass transfer. If product

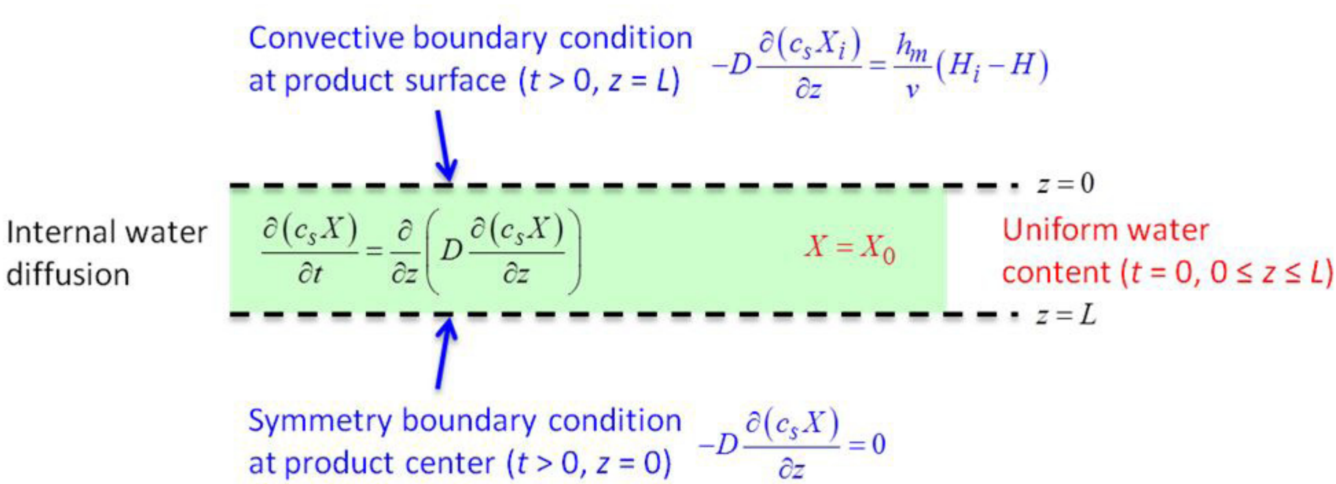

Figure 1. Schematic view of product and model components.

shrinks, the characteristic length for diffusion (and product domain) changes along process, that is $L = L(t)$. In Equation 5 the variable transformation, can be used to express the original moving boundary problem as a fixed boundary problem:

$$\partial\xi = \frac{1}{L(t)}\partial z \tag{5}$$

The dimensionless group $Bi_m(t)$ is the mass Biot number and its value determines the dominant mechanism for mass transfer during drying, for example, internal diffusion or external convection.

The calculation of $Bi_m(t)$ during simulation requires the knowledge of models for $K(t)$, $L(t)$ and h_m, as this last variable is also a function of product dimensions, and consequently of drying time. $L(t)$ can be determined in advance from drying experiments; however, the true relationship between H_i and X_i, required to evaluate $K(t)$, is very complex and depends upon psychometric properties and sorption isotherm of the product, while h_m can be determined from empirical correlations based on dimensionless groups such as Reynolds, Schmidt and Sherwood numbers.

The fact that both $L(t)$ and $Bi_m(t)$ are bounded functions during drying implies that $\phi(t)$ is also bounded. The following exponential equation is proposed to describe the behavior of $\phi(t)$ (Equation 6):

$$\phi(t) = (\beta - \alpha)\exp\left(-\kappa t^n\right) + \alpha \tag{6}$$

Modeling of shrinkage data

In this study, the following relationship is proposed to relate dimensional changes of the product with drying time and temperature:

$$\frac{L(t)}{L_0} = (1-\Delta)\exp\left(-kt^n\right) + \Delta \tag{7}$$

$$k = k_0 \exp\left(\frac{E_S}{R(T+273.15)}\right) \tag{8}$$

In Equations 7 and 8 the temperature effect is included in the shrinking rate constant k with an Arrhenius-type equation.

Model solution

Equations 3-5 were numerically solved by using the method of lines (MOL) with central finite differences for space derivatives. The dependency of water diffusivity on drying temperature was included in Equation 3 by considering the Arrhenius-type model in Equation 9:

$$D(T) = D_0 \exp\left(\frac{E_D}{R(T+273.15)}\right) \tag{9}$$

The MOL produced the following ordinary differential equation (ODE) system (Equation 10) with t as the independent variable (for $j = 1,2,......,N$):

$$\frac{du_j}{dt} = \frac{D(T)}{\left[L(t)\right]^2}\left[\frac{u_{j+1} - 2u_j + u_{j-1}}{(\Delta\xi)^2}\right] \tag{10}$$

Moisture content in nodes outside boundaries ($u_j + 1$ for $j = N$ or $u_j - 1$ for $j = 1$) can be calculated by applying boundary conditions. Therefore Equations 11 and 12 are expresses as:

$$u_{j+1} = u_{j-1} - 2\Delta\xi L(t)\phi(t)u_j \quad for \quad j = N \tag{11}$$

$$u_{j-1} = u_{j+1} \quad for \quad j = 1 \tag{12}$$

The resulting ODE system was integrated with the initial condition and $N = 100$ using the Matlab R2012, a routine ode15s based on a variable order method (MathWorks Inc., Natick, MA, USA). Mean moisture content of the product was calculated from the numerical integration of local values using the trapezoidal rule according to the formula:

$$U = \int_0^1 u d\xi \Big/ \int_0^1 d\xi = \int_0^1 u d\xi \tag{13}$$

A simple expression to evaluate Equation 13 is given by Equation 14:

$$U = \frac{u_1\Delta\xi}{2} + \Delta\xi\sum_{j=2}^{N-1} u_j + \frac{u_N\Delta\xi}{2} \tag{14}$$

Parameter estimation for water diffusivity and mass Biot number models

Shrinkage data were initially fitted to determine the model constants Δ, E, k_0 and n. Thereafter, drying data for all temperatures were used to simultaneously estimate the parameters D_0, F, α, β, k and v by iteratively solving the ODE system jointly with the mean moisture content equation.

2.5 Data analysis

Numerical procedures, nonlinear regression (based on ordinary least squares) and 95% confidence intervals (95% CI) were calculated with the Matlab software and its Statistics Toolbox 8.0 (Matlab R2012a, MathWorks Inc., Natick, MA, USA).

The generalized determination coefficient (R^2) in the Equation 15 and root mean square error ($RMSE$) in the Equation 16 were used to determine the fitness quality of proposed models:

$$R^2 = \frac{\sum_{i=1}^{N_{obs}}\left(\Psi_{\exp,i} - \bar{\Psi}_{\exp,i}\right)^2 - \sum_{i=1}^{N_{obs}}\left(\Psi_{\exp,i} - \bar{\Psi}_{\mathrm{mod},i}\right)^2}{\sum_{i=1}^{N_{obs}}\left(\Psi_{\exp,i} - \Psi_{\mathrm{mod},i}\right)^2} \tag{15}$$

$$RMSR = \sqrt{\frac{\sum_{i=1}^{N_{obs}}\left(\Psi_{\exp,i} - \Psi_{\mathrm{mod},i}\right)^2}{N_{obs} - p}} \tag{16}$$

One-way analysis of variance and Tukey's pairwise comparisons were performed to test differences between fresh and dried samples ($p < 0.05$) with the software Minitab 15 (Minitab Inc., USA).

3 Results and discussions

3.1 Experimental drying behavior and thin-layer models

Experimental drying curves of noni slices are shown in Figure 2, while the corresponding drying rate data are plotted in Figure 3. As expected, the use of higher temperatures led

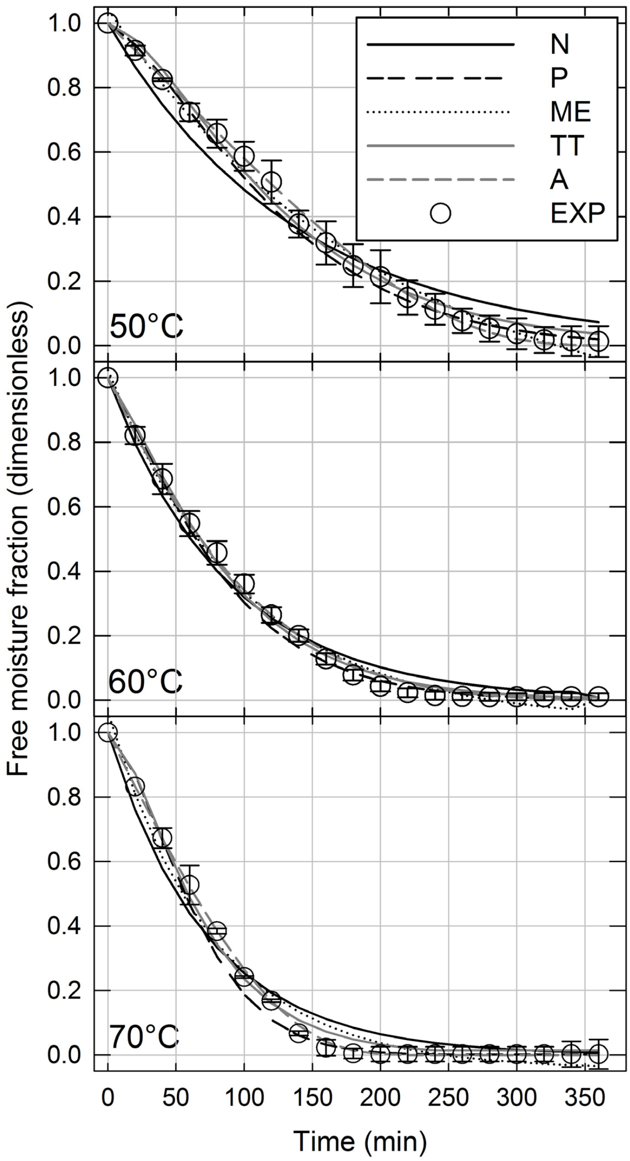

Figure 2. Comparison between thin-layer drying models (lines) and experimental data (dots) of noni slices processed at different air temperatures. N = Newton; P = Page; ME = Modified exponential; TT = Two-term exponential; A = Aghbashlo.

to shorter drying times, with the required time to reach the equilibrium moisture content reduced from 380 (at 50 °C) to 200 min (at 70 °C). Comparable results have been obtained with other products such as thyme, with a drying time decrease from 495 (at 40 °C) to 120 min (at 60 °C) (Doymaz, 2011), and chard leaves, which showed drying times reduced from 195 (at 50 °C) to 22 min (at 105 °C) (Alibas, 2006). According to Pacheco-Aguirre et al. (2014), if the process is diffusion-controlled, then the drying rate exhibits a continuous decrease since the drying start or shortly after an initial preheating period where an initial drying rate rise can be observed. However, the drying rate plot of noni slices was inconsistent with this behavior, only exhibiting a clear falling-rate period when $\Psi < 0.3$, highlighting an initial resistance to mass transfer at the product surface expected from the natural convection conditions.

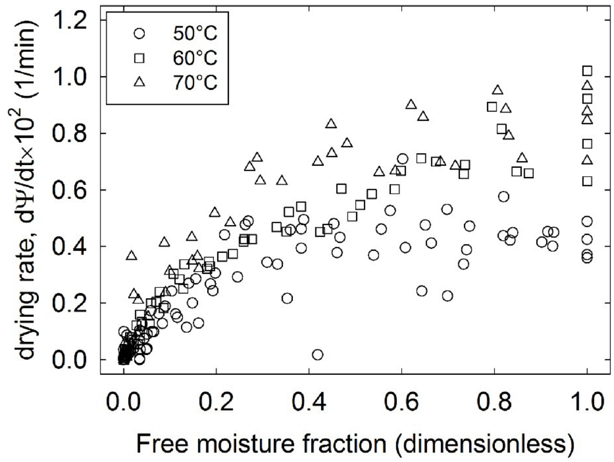

Figure 3. Drying rate of noni slices at different drying temperatures under natural convection.

The summary statistics for thin-layer drying models are shown in Table 1. All models showed a satisfactory reproduction of experimental behavior ($R^2 > 0.93$). Overall, the Newton's model (a.k.a. first order exponential) had the lowest R^2 values (0.938-0.983) and highest *RMSE* ($7.8\text{-}16.0 \times 10^{-2}$). On the other hand, Aghbashlo's model achieved the best description of drying data with its highest R^2 (> 0.998) and lowest *RMSE* ($< 1.75 \times 10^{-2}$). This model was first proposed for drying carrots at 50, 60 and 70 °C, also achieving the best fit (Aghbashlo et al., 2009).

3.2 Water diffusivity corrected for product shrinkage

Shrinkage data obtained during convective drying of noni slices are plotted in Figure 4. As shown in this figure, the use of higher drying temperatures produced faster product shrinkage. Nonlinear regression parameters for shrinkage model formed by Equations 7 and 8 are summarized in Table 2. According to the parameters Δ and n, drying of noni slices resulted in samples with about 24% of their original thickness regardless of drying temperature, with a marked deviation from the first order exponential behavior (Figure 4). Shrinkage model was specifically developed to describe current data and to the best of the authors' knowledge it has not been reported in any other study. Thus, a direct comparison of all model parameters with those reported in other works is not fully achievable. The only parameter that can be compared is Δ as it is related with the final shrinkage degree. In this case, noni has a shrinkage degree slightly lower to that found in other vegetables such as chayote ($\Delta = 0.1135$) and potato ($\Delta = 0.1733$) (Ruiz-López et al., 2012; Ortiz-García-Carrasco et al., 2015).

Experimental drying curves of noni slices were used to simultaneously evaluate parameters for water diffusivity and mass Biot number. According to Table 3, a diffusion model was able to accurately describe the drying curves ($R^2 > 0.98$). Statistical analysis revealed that all constants were significant ($p < 0.05$), thus the model is structurally identifiable with current data (*i.e.*, its parameters can be uniquely estimated). In addition, parameter η was not significantly different from one (95% CI = 0.8472/1.2213). Thus, η was removed from the

Table 1. Nonlinear regression parameters of thin-layer drying models.

Model	Temperature	Parameters				R^2	$RMSE \times 10^2$	$x^2 \times 10^2$
		$k^1 \times 10^2$	$k^2 \times 10^2$	a	b			
Newton	50	1.0400	-	-	-	0.9687	12.2141	1.5747
	60	1.5100	-	-	-	0.9826	7.8061	0.6452
	70	2.4800	-	-	-	0.9378	15.9855	2.7683
Page	50	0.1036	-	1.3999	-	0.9965	2.9648	0.0982
	60	0.3986	-	1.2386	-	0.9969	2.5284	0.0719
	70	0.1366	-	1.5443	-	0.9950	3.7219	0.1637
Modified exponential	50	0.6307	-	1.1843	-0.1170	0.9939	3.6552	0.1586
	60	0.7106	-	0.9246	-0.0798	0.9900	7.1628	0.6158
	70	0.7826	-	1.2564	-0.1800	0.9902	11.3226	1.5384
Two-term exponential	50	0.7826	-0.6770	1.0923	-0.0007	0.9870	2.8819	0.0928
	60	1.1768	-0.6832	1.0450	-0.0007	0.9949	2.1216	0.0506
	70	1.4548	-0.0863	1.0775	-0.0015	0.9880	3.0949	0.1132
Aghbashlo	50	0.4206	-0.2256	-	-	0.9988	1.7358	0.0337
	60	0.9277	-0.1369	-	-	0.9988	1.7192	0.0332
	70	0.8528	-0.3586	-	-	0.9996	1.0953	0.0148

Table 2. Nonlinear regression parameters of shrinkage model.

Parameter	Value
k_0 (s^{-N})	1919.27
E_s (J/mol)	71530
n (dimensionless)	2.0992
Δ (dimensionless)	0.2383
R^2	0.9663

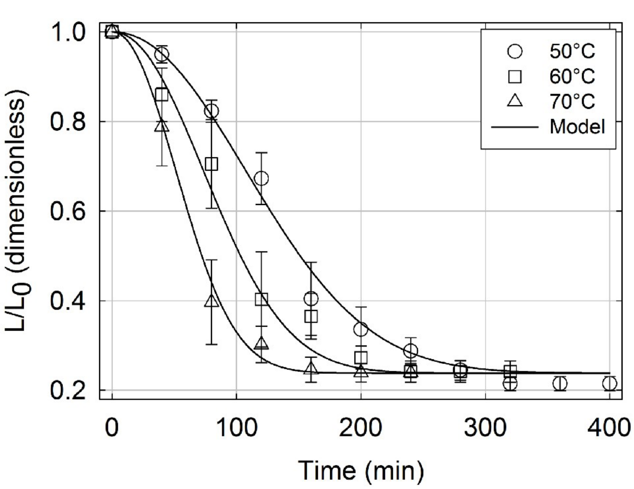

Figure 4. Shrinkage characteristics of noni slices at different drying temperatures.

original model (*i.e.*, the parameter was set to unity) and the nonlinear regression procedure was repeated.

The model with $\eta = 1$ retained the fitting characteristics of the original six-parameter equation and all constants were also significant ($p < 0.05$). As expected, the use of higher drying temperatures promoted higher water mobility in the food system ($p < 0.05$). According to estimated constants for Equation 9, water diffusivities at drying temperatures of 50, 60 and 70 °C had the values 1.80×10^{-9}, 2.42×10^{-9} and 3.19×10^{-9} m^2/s, respectively. Water diffusivities, corrected for product shrinkage, were comparable to literature data for other vegetable products such as carrots (2.58×10^{-10} to 1.72×10^{-9} m^2/s, 60-90 °C), mango (2.61×10^{-10} to 1.30×10^{-9} m^2/s, 40-70 °C) and potato (3.55×10^{-10} to 1.92×10^{-9} m^2/s, 40-85 °C) in which shrinkage was also considered (Zielinska & Markowski, 2010). A high airflow rate is often used in drying experiments to favor a diffusion-controlled process (Pacheco-Aguirre et al., 2014; Ortiz-García-Carrasco et al., 2015). However, as natural convection conditions were used in noni drying experiments, an important resistance to mass transfer at the product surface was anticipated and later confirmed with the drying rate plot (Figure 5). Mass Biot was calculated in the range of 0.11-0.56, which corresponds to a process controlled by the rate of water removal at the product surface, and is consistent with drying conditions and sample thickness. These results are similar to those found by other authors under natural convection conditions (Białobrzewski, 2007; Rahman & Kumar, 2007). For example, Rahman & Kumar (2007) found that Biot number for mass transfer varied from 0.05 to 1.00 during drying of potato samples (60 °C, cylinders with length of 0.05 m and thicknesses of 0.005, 0.008, 0.010 and 0.016 m, and circular slices with diameter of 0.05 m and thickness of 0.01 m). On the other hand, Białobrzewski (2007) highlighted that a third kind boundary condition was necessary to accurately describe mass transfer during drying of celery roots. All these authors concluded that external resistance to mass transfer cannot be ignored during natural convection air-drying.

3.3 Color, total phenolic compounds and antioxidant capacity of fresh and dried product

Color measurements, total phenolic compounds (TPC) and antioxidant capacity (AC) of dried noni slices are shown in Table 4. No significant differences were found in the color parameters a*, b*, hue and chroma between fresh and dried samples. However, the lightness L* of dried slices decreased between the 24 and 31% compared with the fresh product, a result similar to that reported for red pepper oven-dried at 50 and 70 °C (Arslan & Özcan, 2011). The decrease in lightness

Table 3. Nonlinear regression parameters of the diffusion model considering product shrinkage and external resistance to mass transfer.

Set	$D_0 \times 10^5$ (m^2/s)	E_D (J/mol)	α (1/m)	β (1/m)	$\gamma \times 10^4$ ($1/s^N$)	η (dimensionless)	R^2
1	3.302 (3.247/3.357)	26326.5 (25094.1/27558.9)	55.781 (29.813/81.749)	46.935 (26.701/67.168)	3.604 (1.351/5.8567)	1.034 (0.847/1.221)	0.985
2	3.276 (2.544/4.007)	26351.1 (26044.3/26657.9)	55.997 (49.295/62.699)	46.578 (38.627/54.529)	2.943 (1.715/4.1712)	Set to 1, not fitted	0.985

Table 4. Color parameters, total phenolic content and antioxidant capacity of fresh and dried noni slices*.

Variable	Fresh	Drying temperature (°C)			p
		50 °C	60 °C	70 °C	
L*	60.42 ± 6.2[a]	45.79 ± 2.5[b]	45.30 ± 5.4[b]	41.94 ± 4.8[b]	0.0093
a*	3.98 ± 3.5[a]	4.62 ± 1.1[a]	3.29 ± 1.3[a]	4.38 ± 0.8[a]	0.6532
b*	14.12 ± 5.0[a]	14.99 ± 2.1[a]	12.49 ± 1.1[a]	15.66 ± 1.9[a]	0.2943
Hue	181.30 ± 1.1[a]	181.27 ± 0.1[a]	181.31 ± 0.1[a]	181.30 ± 0.0[a]	0.2711
Chroma	14.65 ± 4.7[a]	15.68 ± 2.1[a]	12.91 ± 1.3[a]	16.25 ± 1.9[a]	0.2185
TPC (g GAE/g dm)	31.67 ± 1.6[a]	25.28 ± 1.1[b]	22.76 ± 3.0[b]	22.97 ± 2.3[b]	0.0000
AC (% DPPH inhibition)	93.25 ± 0.5[a]	93.56 ± 0.8[a]	91.97 ± 1.0[a]	82.52 ± 1.8[b]	0.0000

*Data expressed as mean ± standard deviation of three independent experiments. Values in a column followed by the same lowercase letter indicate no significant difference between fresh or dried samples according to Tukey's test ($p < 0.05$). TPC = total phenolic content, AC = antioxidant capacity

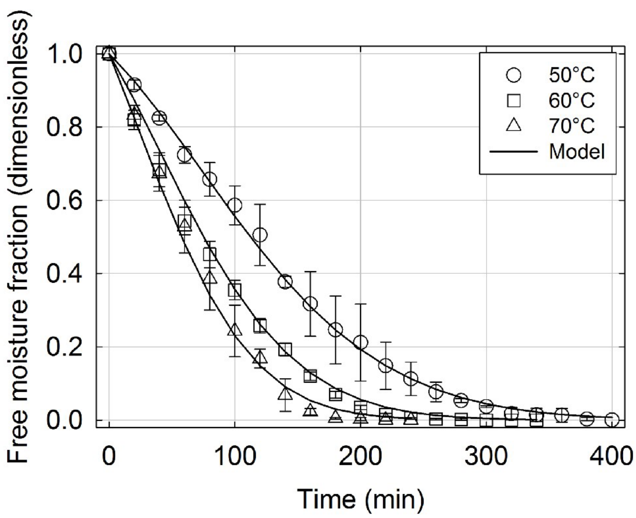

Figure 5. Comparison between the diffusive model with external resistance to mass transfer (lines) and experimental data (dots) of noni slices processed at different air temperatures.

during drying is related to the generation of brown pigments derived from the Maillard reactions and non-enzymatic processes. In this study, the TPC in fresh and dried noni ranged from 22.76 to 31.67 mg GAE/g dm, which are higher than the levels obtained by Yang et al. (2010) (about 18 mg GAE/g dm) in noni juice and powder. The higher TPC value in this study may be related to the presence, in our sample, of noni seeds which also contain phenolic compounds (Singh & Singh, 2013). As shown in Table 4, TPC concentration decreased ($p < 0.05$) with drying temperature (about 20 to 28%). The reduction in TPC in dried, as compared to fresh product observed in this study is comparable to that obtained by Chong et al. (2013) in apple (9-63%), pear (13-65%), papaya (7-69%) and mango (7-71%) subjected to combined drying methods. The losses in TPC during dehydration may be due to the binding of polyphenols to other compounds or to chemical structure modifications which may complicate extraction and quantification by current methods (Miranda et al., 2010). Regarding noni drying, Yang et al. (2007) reported no loss of phenolic compounds during the first 4 hours of drying ripe noni pulp at 50 °C and 65 °C. Differences between our findings and those mentioned above may be due to differences in fruit pretreatment, maturity stage and drying conditions.

In the case of the AC, the lowest value was obtained at 70 °C, while there was no significant difference between fresh and dried products at 50 and 60 °C ($p < 0.05$). These results are comparable to those reported by Katsube et al. (2009), where a lower AC (measured by DPPH) was obtained in air-dried leaves at 70 °C.

Despite the reduction in phenolic compounds present in this work, DPPH radical inactivation is still considered high (82-93%) according to the index classification of Hassimotto et al. (2005), in which inhibition values higher than 70% indicate a good activity. In this case, the observed antioxidant capacity may be attributed to the presence of other phenolic or nonphenolic compounds, or to other thermo-tolerant compounds with high antioxidant capacity such as the α-tocopherol present in the fruit seeds (Singh & Singh, 2013).

4 Conclusions

The results of this study demonstrated that both empirical and theoretical models can be used to produce an accurate description of noni drying; however, the diffusion model with convective boundary can be applied for future predictions under different drying conditions without needing to assume a dominant mass transfer mechanism. According to numerical results and statistical analysis, the experimental conditions used here were characteristic of drying processes with external (convection) resistance to mass transfer. Under the studied conditions, dried noni retained most of its functional properties which is advantageous for the further storage or processing of this fruit.

Nomenclature

a, b, k_1, k_2 parameters for thin-layer drying models

Bi_m mass Biot number (dimensionless)

c_s volumetric concentration of dry solids (kg dry solids/m^3 product)

D effective diffusivity of water in food (m^2/s)

D_0 pre-exponential factor for water diffusivity model (m^2/s)

E_D activation energy for water diffusivity model (J/mol)

E_S activation energy for shrinkage rate model (J/mol)

H air humidity (kg water/kg dry air)

h_m convective mass transfer coefficient (m/s)

k shrinkage rate constant (1/s^N)

k_0 pre-exponential factor for shrinkage rate model (1/s^N)

L characteristic length for moisture diffusion (m)

m_p product mass (kg)

n shrinkage behavior constant (dimensionless)

N number of nodes in numerical solution

n_{obs} number of experimental observations

p number of fitted parameters

R ideal gas constant (8.314 J/mol·K)

R^2 generalized determination coefficient

RMSE root mean square error

t drying time (s)

T drying temperature (°C)

u, U free moisture fraction (dimensionless): local and average, respectively

v humid volume of drying air (m^3 humid air/kg dry air)

X moisture content (dry basis) (kg water/kg dry solids)

z axial coordinate for mass transfer (m)

Greek letters

Δ resulting fraction of the initial characteristic length for diffusion at the end of the drying process

η interface behavior constant (dimensionless)

ξ axial coordinate for mass transfer (dimensionless)

Subcripts

0 at the beginning of drying process

e at equilibrium

exp experimental

i at air-product interface

mod model

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