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ORIGINAL PAPER

Effect of an Edible Pectin Coating and Blanching Pretreatments on the Air-Drying Kinetics of Pumpkin (*Cucurbita moschata*)

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Abstract With the aim of making food drying processing data and their evaluation available, this work entails evaluating the air-drying kinetics of fresh pumpkin slices and those pre-treated by applying an edible pectin coating or blanching. The drying kinetics of the fresh, blanched, and pectin-coated pumpkin slices were evaluated at 60 and 70 °C with air velocities of 0.85 and 1.70 m s^{-1}. The effects of the pre-treatments and drying parameters on moisture diffusivity were investigated. Under the drying conditions studied, a constant-rate period was found and the falling-rate period was described by the diffusion equation. In order to take shrinkage into account, shrinkage coefficients were incorporated in an approximate way, using the analytical solution of Fick's equation. The highest constant drying rate values were obtained for the blanched samples, followed by the coated samples and finally the fresh samples. Constant drying rates demonstrated that this period did not significantly influence the estimate of the effective diffusion coefficients. It was shown that the water diffusivity of the coating was high, but only slightly increased the drying time, thus not affecting drying efficiency. Conversely, blanching promoted more water transfer and enhanced drying efficiency. It was concluded that coating and blanching at the temperatures and velocities studied were promising for use as pre-treatments in the drying of pumpkins.

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Keywords Drying rate · Diffusivity · Shrinkage · Fick's equation

Nomenclature

A	Surface area (m^2)
α	Fitting constant (dimensionless)
D_{eff}	Effective diffusion coefficients of water ($m^2 \cdot s^{-1}$)
Bi_M	Mass transfer Biot number (dimensionless)
e	Thickness (m)
k	Drying rate constant (s^{-1}) (Eq. 10 and 12) and (s^{-n}) (Eq. 11)
k_G	Mass transfer coefficient (kg water$\cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$)
m_s	Dry sample mass (kg)
n	Number of terms of the series (Eq. 6); fitting constant (dimensionless) (Eq. 11); and number of observations (Eq. 13);
N_c	Constant flow of evaporated water (kg water$\cdot m^{-2} \cdot s^{-1}$)
P	Mean percent error (%)
R^2	Correlation coefficient (dimensionless)
T	Temperature (°C)
t	Time (s)
V	Volume (m^3)
v	Air velocity ($m \cdot s^{-1}$)
w_0	Water content, w.b. (kg water$\cdot kg^{-1}$ wet matter)
X	Fractional or residual moisture, dry basis (dimensionless)
X	Water content, d.b. (kg water$\cdot kg^{-1}$ dry solids)
X_c	Critical water content (kg water$\cdot kg^{-1}$ dry solids)
$\overline{X}(t)$	Mean fraction of the water mass, d.b. (kg water$\cdot kg^{-1}$ dry solids)
y	Experimental or calculated value
γ_n	Roots of the transcendent equation $tg(\gamma) = 1/\gamma Bi_M$

κ Equilibrium relation at interface between the air and the sample (kg water·kg^{-1} dry solids·Pa^{-1})
ρ_S Solids concentration (kg dry solids·m^{-3})

Subscripts and Superscripts

0 Initial state
c Critical
cal Calculated
d.b. Dry weight basis
eq Equilibrium
exp Experimental
w.b. Wet weight basis

Introduction

Pumpkins (*Cucurbita moschata*), widely cultivated in Brazil, are important sources of carotenoids, mainly α-carotene and β-carotene. In addition to their great pro-vitamin A activity, the carotenoids are antioxidant agents (Rodriguez-Amaya et al. 2008) and thus involved in the prevention of cancer, macular degeneration, heart diseases, and other degenerative diseases (Krinsky 1993). Dried pumpkin has shown high nutritional content even though some losses occur during drying process (Lago-Vanzela et al. 2013). Pumpkins are also important sources of dietary fiber. Enriched fiber products were obtained from *C. moschata* Duchesne ex Poiret which were found to have a remarkable hydration capacity and adequate values of glucose retention (de Escalada Pla et al. 2007).

Consumer demand for processed foods that preserve their original properties has increased. In industrial terms, this requires the development of operations that minimize the adverse effects of food processing (Nijhuis et al. 1998). The drying process provides many advantages with respect to food stability at room temperature for long periods of time. However, degradation of the food quality during drying is one of the greatest problems encountered in the design and control of drying processes, due to the physical, chemical, and biochemical alterations caused by this process (Mujumdar 1997). Freeze drying provides a better quality product but is expensive in terms of capital costs and operating costs (Mujumdar and Law 2010). Que et al. (2008) compared pumpkin flour from hot-air drying (70 °C for 54 h) with freeze dried flour. Freeze-drying significantly reduced the browning and preserved the redness of pumpkin flours, besides presenting a higher oil absorption capability, lower bulk density, and higher porosity. However, total antioxidant activity was higher for air-dried pumpkin flour, which was attributed to Maillard products or their intermediates having potent antioxidant activity, a consequence of the long time exposure to high temperature.

Many studies have been carried out to improve the physical and nutritional quality of the dried products. Convective predrying followed by vacuum-microwave drying to finish the process allowed an increase in energy savings in comparison to convective drying and also enhanced antioxidant capacity in dried garlic (Calín-Sánchez et al. 2014). Other studies have proposed models to predict shrinkage or collapse of the plant tissue during drying as these properties have a direct impact on the quality attributes of the final products (Khalloufi et al. 2012). Moreover, as the maximum drying temperatures used in foods are generally insufficient to inactivate the enzymes related to nutritional losses, the application of heat blanching to the vegetable matter before drying fruits and vegetables has been frequently used. This procedure aims to interrupt enzymatic activity, avoiding undesirable changes in the sensory and nutritional properties that could occur during the drying process and subsequent storage, thus improving the quality of the dehydrated product (Chantaro et al. 2008; Wolfe and Liu 2003; Ong et al. 2012).

The coating of food pieces with edible films has also been studied as a treatment prior to drying, contributing to nutrient retention by decreasing contact of the vegetable matter with oxygen during the drying process, as observed by Lago-Vanzela et al. (2013) who used starch coatings on pumpkins and obtained enhancement in carotene retention. However, these biopolymers can affect the drying efficiency and their choice must be based on their gas and water permeabilities, which vary with moisture content (Cuq et al. 1995). Edible coatings formed from polysaccharide materials such as low methoxylated pectin, present good oxygen barrier properties especially under low moisture conditions (Cuq et al. 1995; Gontard et al. 1996). Garcia et al. (2014) demonstrated that pectin-based coating applied on papayas can protect part of the vitamin C contained in the fruit during drying. Besides this role of controlling gas exchange, these coatings can also act as carriers for compounds of interest such as aromatic, antimicrobial, or nutritional substances. Despite the papaya slices coated with pectin plus ascorbic acid have shown some vitamin losses during drying, the coating has still provided good content of vitamin C after drying and 30 days of storage (Canizares and Mauro 2015).

Biological materials with high water content can present a constant drying rate while their surfaces are covered with a thin layer of water, which is assumed to be completely unbound moisture (Treybal 1980). After this period, the drying rate will decrease and the value that marks the transition between the constant and falling rate periods is called the critical moisture content (Fortes and Okos 1980; Zhao et al. 2013). Both the constant and falling drying rates were observed in the microwave dehydration of chilies (Liu et al. 2014; Zhao et al. 2013), although in general a constant rate period is not found for plant foods (Zhao et al. 2014; Esturk 2012) or is neglected when the diffusivity is estimated.

It is important to have models that simulate the drying curves under different conditions in order to improve the control of the drying parameters, and for this purpose, theoretical,

empirical, and semi-empirical models are used (Guiné et al. 2011). Although empirical models are suitable for engineering applications in the food industry, in general they cannot be applied under conditions that are different from those used to determine the model parameters (Ah-Hen et al. 2013). One of the most well-known theoretical models is based on Fick's Law and applies the theory of water diffusion in the liquid or vapor form in order to interpret food and agricultural product drying processes. Nevertheless, the diffusion coefficient is effective, since the diffusivity of water depends on the concentration, porosity, and tortuosity of the material (Fernando et al. 2011). Fick's equation is generally used as an integrated analytical solution, but has been found inadequate for highly deformable materials. If one considers shrinkage of the material, this implies a numerical solution to the equation. However, some authors have used simplified alternatives to calculate the diffusivity based on an analytical solution, incorporating the shrinkage into the equation in an approximate way, via the characteristic dimension as a function of the water content. This procedure was shown to be adequate to fit the experimental data in the osmotic dehydration of pumpkin in sodium chloride solutions (Mayor et al. 2006), in the osmotic dehydration of pineapple in sucrose solutions under some specific conditions (Ramallo et al. 2004), in the osmotic dehydration of pumpkin in sucrose solutions, and in the drying of fresh and osmotic dehydrated pumpkin (Garcia et al. 2007).

However, coating materials and thermal treatments can affect drying efficiency. Aiming for a better comprehension of the transport phenomena and to evaluate the effects of assumptions over the modeling, the present research proposed:

- to investigate the effects of the edible pectin coating and blanching pretreatments on the air-drying kinetics of pumpkin slices;
- to evaluate the influence of the constant drying rate period on the estimated diffusivities, based on the Fick's Law.

Material and Methods

Materials

Mature pumpkins (*C. moschata*) of the cultivar Rajada Seca Melhorada in the mature stage and weighing between 30 and 50 kg were acquired at the São José do Rio Preto Supply Center (CEAGESP, São José do Rio Preto, SP, Brazil) and stored at room temperature.

Low methoxylated amidated pectin (Grindsted Pectin LA 210; degree of methoxylation of 0.34; degree of amidation of 0.17; Danisco, Cotia, SP, Brazil) for industrial use was used in the coating procedure, and the calcium chloride used was of United States Pharmacopeia (USP) food grade and hydrated ($CaCl_2 \cdot 2H_2O$, Synth, Labsynth, Diadema, SP, Brazil).

Equipment

The drying experiments were carried out in a fixed bed dryer (Fig. 1) equipped with a centrifugal fan (CV3600, Ibram, São Paulo, SP, Brazil) with a 2 CV motor, a drying chamber with a cross-sectional area of 9.61×10^{-2} m^2, and the air velocity adjusted by a frequency inverter (ML-7.0/200-240, WEG, Jaguará do Sul, SC, Brazil) connected to the motor of the fan. The frequency inverter was previously calibrated and regularly checked with a vane anemometer (LCA 6000, Airflow, Buckinghamshire, UK). A semi-analytical balance (BG4000, Gehaka, São Paulo, SP, Brazil), with a precision of 0.01 g and capacity for 4.0 kg, was connected to the dryer, which had an RS232 interface for transmitting the data to a computer, where the weights were recorded over time at each second. The samples were also weighed before and after drying in another semi-analytical balance with a precision of 0.01 g and capacity for 2.0 kg (BG2000, Gehaka, São Paulo, SP, Brazil) installed near the equipment. Air diffusers contribute to homogeneity of airflow. A valve that permits recycling the hot air drying was regulated in such a way that allowed stable conditions for the continuous weighing up to a maximum air velocity of 1.7 m·s^{-1} and approximately 70 % of recycle. Small humidity changes through the trays were detected from the evaporated water flux, the airflow rate, and the absolute humidity of the air, inside and outside of the dryer. The air properties were determined using a psychrometric chart, considering the local pressure of 717 mm Hg (São José do Rio Preto, São Paulo, Brazil). A program compatible with the electronic spreadsheets of Microsoft Excel was used. A digital microprocessed controller with a PT 100 type probe was used to control the temperature (N489D, Novus, Porto Alegre, RS, Brazil), and the plate of the balance was substituted by a structure constructed to support three metal mesh trays. The air flow was incident parallel to the samples (Fig. 1).

Sample Preparation and Pre-treatments

The pumpkins were cut into three portions in a transversal direction to their axis and the ends cut off. Each piece was then cut longitudinally into four parts and two opposite parts of each piece were peeled and seeded. The part of the pumpkin closest to the center was removed since this was composed of spongy tissue, and the remaining piece was sliced (3.7×10^{-3} m thickness) using an electric vegetable cutter. The transversal area of the slices was approximately 34×10^{-4} m^2. The slices were immediately placed into a plastic bag to avoid moisture loss to the environment and also to mix them in order to make a random selection of the samples.

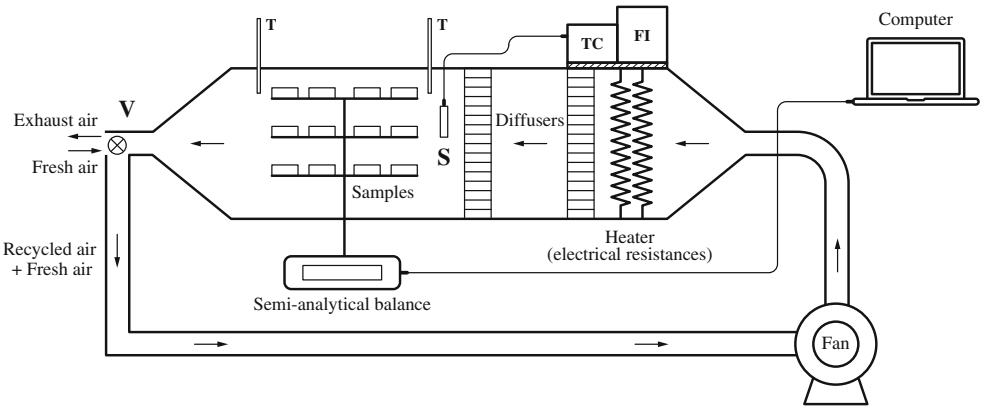

Fig. 1 Schematic diagram of the dryer. *FI*, frequency inverter; *TC*, temperature controller; *S*, PT 100 sensor; *T*, thermometer; *V*, valve

Two separate pre-treatment processes were applied: blanching and coating with pectin.

Heat blanching of the pumpkin samples was carried out in São José do Rio Preto, SP, Brazil (local pressure of 717 mm Hg), by immersing in boiling water (98.3 °C) for 1 min. Batches of approximately 4×10^{-1} kg, contained in a perforated basket, were blanched in 20 l of boiling water and then cooled in running water at room temperature for the same period of time. The slices were dried with absorbent material to remove excess moisture from the surface. The coating consisted of a 2 % low methoxylated pectin solution prepared at 70 °C with constant stirring and then cooled to 40 °C before applying to the samples. The slices were immersed in this solution for 60 s, and then in a 1 % calcium chloride solution for 30 s in order to promote gelation of the pectin coating. The slices were then rinsed in distilled water (10 s).

Convective Drying Kinetics

The drying trials of the treated and fresh pumpkin slices were carried out at 60 and 70 °C with air velocities of 0.85 and 1.70 m s^{-1}. The pumpkin slices were placed between two metallic screens to avoid deformation during drying. The samples were distributed in three trays (Fig. 1) with an approximate mass of 2×10^{-1} kg, and the system recorded the loss of sample weight every second.

Analytical Methods

Total Solids Determination

A gravimetric method was used to determine the solids content of approximately 3 g of sample dried to constant weight in a vacuum oven at 60 °C and 10 kPa. This analysis was carried out in quintuplicate for the fresh, blanched, and coated samples, and in triplicate for the dried samples.

Reducing and Total Sugar Content

The total and reducing sugar contents of the fresh and blanched samples were determined in triplicate by the oxidation-reduction titration (AOAC 1970).

Determination of the Thickness

The density of 36 mm diameter plugs of the fresh, blanched, and coated samples was determined by the volume displacement method, using a glass pycnometer made from a 20-ml burette soldered to an approximately 100-ml glass flask substituting the tip, and to an open-topped recipient (approximately 100 ml) with a sintered glass stopper. The apparatus was partially filled with toluene up to a specific mark, closed, and inverted to read the calibration. For each measurement, the pycnometer was filled with toluene up to the calibration mark; the previously weighed samples were placed in the upper recipient, closed, and inverted to read the new volume. The difference between the two readings represented the sample volume. The thickness was determined from the known area and volume.

Mathematical Models

Constant Drying Rate Period

When a moist, solid food is exposed to an air current at fixed velocity, temperature, and relative humidity, its temperature adjusts to the drying conditions until reaching a stationary state. If the food enters this regime, the drying rate will be constant while these conditions remain. Few foods present such a period, and when they do, it tends to be for a relatively short time as compared to the other drying periods. The drying rates were evaluated from the graphs of the rate of water mass evaporated as a function of the water content. The mass transfer flow was calculated from Eq. (1):

$$N_c = -\frac{m_s}{A(t)}\frac{\Delta X}{\Delta t} \quad (1)$$

where N_c is the constant flow of evaporated water (kg water·m^{-2}·s^{-1}), m_s is the mass of dry solids (kg dry matter), ($\Delta X/\Delta t$) represents the variation in moisture (kg water·kg^{-1} dry matter·s^{-1}), $A(t)$ is the surface area (m^2) for heat and mass transfer where evaporation occurs, and the area changes as a function of time (t). Thus the constant drying rate period could be identified, where the flow did not vary with the water content.

Falling Drying Rate Period

In the drying of fruits and vegetables, the majority of the process occurs during the falling drying rate period. In the present trials, Fick's second law was used to describe the drying process in the falling period, presented below in its general form:

$$\frac{\partial X}{\partial t} = D_{\text{eff}} \nabla^2 X \tag{2}$$

where X is the fraction of the water mass on a dry weight basis (kg water·kg^{-1} dry matter), D_{eff} is the effective diffusion coefficient (m^2·s^{-1}), and t the drying time (s).

The water content of the original sample was considered to be homogenous, as also that of the blanched and coated samples.

$$X = X_0, \qquad t = 0 \tag{3}$$

If the external resistance during drying is not considered in the boundary conditions, the concentration at the interface will be represented by the water content of the sample in equilibrium with the drying air, as follows:

$$X = X_{\text{eq}}, \qquad t \geq 0 \tag{4}$$

In the central plane of the slice, the concentration gradient is nil.

$$\left.\frac{\partial X}{\partial z}\right|_{z=0} = 0, \qquad t \geq 0 \tag{5}$$

Since the phenomenon of migration is complex, the effective diffusivity includes all the effects that could interfere with this phenomenon. In addition, if external resistance is not considered, diffusion coefficients also encompass this effect and their values might be lower than those which would be found if the model had shared the control between the internal and external resistance. The solid is considered to be an infinite plane sheet with both surfaces exposed to the drying air and the effective water diffusivity is assumed constant. The effect of the temperature gradient on the inside of the sample is considered to be negligible. Thus the analytical solution is as follows in the integrated form (Crank 1975), that is, in terms of the mean concentration in the plane sheet at time t:

$$\mathbf{X} = \frac{\overline{X}(t) - X_{\text{eq}}}{X_0 - X_{\text{eq}}} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left[-(2n-1)^2 \frac{\pi^2 D_{\text{eff}}\, t}{e^2}\right] \tag{6}$$

where $\mathbf{X}$ is the mean residual moisture, non-dimensional, $\overline{X}(t)$ is the mean fraction of the water mass (d.b.) found in the plane sheet at time t, X_0 and X_{eq} are the fractions of the water mass (d.b.), where 0 represents the initial time ($t = 0$) and eq the equilibrium, and e is the sample thickness (m), and n is the number of terms of the series. In the integrated analytical solution for a plane sheet (Eq. 6), four terms were used in series, which was sufficient for their convergence.

In addition, if we wish to evaluate external resistance, the boundary condition (Eq. 4) must be substituted by an interface condition written as a function of partial pressure of water. Internal and external resistances can be expressed by the mass transfer Biot number, Bi_{M}, as follows (Fontaine and Ratti 1999):

$$Bi_{\text{M}} = \frac{k_{\text{G}}(e/2)}{\rho_s D_{\text{eff}} \kappa} \tag{7}$$

where k_{G} (kg water·m^{-2}·s^{-1}·Pa^{-1}) represents the convective mass transfer coefficient of water in the gas phase and can be estimated from correlations of dimensionless groups (Treybal 1980), κ (kg water·kg^{-1} dry solids·Pa^{-1}) represents an equilibrium relationship at the interface, between the air and the sample (Fontaine and Ratti 1999), ρ_S is the solids concentration (kg dry solids·m^{-3}), and e is the slice thickness (m). If internal and external resistances are considered for the surface boundary condition, the analytical solution of the Fick's equation (Eq. 2) in the integrated form (Crank 1975) becomes

$$\mathbf{X} = \frac{\overline{X}(t) - X_{\text{eq}}}{X_0 - X_{\text{eq}}} = 2 \sum_{n=1}^{\infty} \frac{Bi_{\text{M}}^2}{\gamma_n^2 \left(\gamma_n^2 + Bi_{\text{M}}^2 + Bi_{\text{M}}\right)} \exp\left[-\gamma_n^2 \frac{D_{\text{eff}}\, t}{(e/2)^2}\right] \tag{8}$$

where γ_n are the roots of the transcendent equation $tg(\gamma) = 1/\gamma Bi_{\text{M}}$.

If Eq. (8) was applied, fitting will be improved because of the two fitting parameters. However, the integrated analytical solution needs constant parameters and κ varies considerably during drying. Hence, it will be more appropriate to use numerical solutions to solve these equations.

The effective diffusion coefficient was calculated based on the analytical solution for the already integrated Fick's equation (Eq. 6). A simplified procedure that incorporated shrinkage in an approximate way in the equation via the characteristic dimension as a function of water content (Garcia et al. 2007) was applied according to the following method. The values for the thicknesses of the samples were determined

from the volumetric variation in the water obtained from the drying curve in each experiment, considering that shrinkage occurred in the same proportion for each of the dimensions of the solid according to Eq. (9).

$$\frac{e}{e_0} = \sqrt[3]{\frac{V}{V_0}} \tag{9}$$

where e is the thickness at time t, e_0 is the thickness at time $t=0$, V is the volume at time t, and V_0 is the volume at time $t=0$.

Therefore, the thickness reduction was described as a function of the water content. Such an approximation is admissible when one considers that the variation in volume is proportional to the volume of water evaporated during drying. This assumption seems suitable for pumpkin since the value for density is near unity, suggesting low porosity (Garcia et al. 2007).

Empirical Models

Simple empirical drying models suitable to thin-layer drying were also applied to evaluate the drying kinetics of the pumpkin slices, namely the Newton (Eq. 10), the Page (Eq. 11), and the Henderson-Pabis model (Eq. 12) Ertekin and Yaldiz (2004).

$$\mathbf{X} = \frac{\overline{X}(t) - X_{eq}}{X_0 - X_{eq}} = \exp(-k\,t) \tag{10}$$

$$\mathbf{X} = \frac{\overline{X}(t) - X_{eq}}{X_0 - X_{eq}} = \exp(-k\,t^n) \tag{11}$$

$$\mathbf{X} = \frac{\overline{X}(t) - X_{eq}}{X_0 - X_{eq}} = a \times \exp(-k\,t) \tag{12}$$

where k is the drying rate constant, (s^{-1}) or (s^{-n}), and n and a are fitting constants (dimensionless).

Statistical Methods

Equations (6), (10), (11), and (12) were fitted to the experimental results using the software ORIGIN v. 6.0 (Microcal Software 1997), which fits non-linear functions. Four terms of the series of Eq. (6) were used, sufficient for convergence of the solution. The fitting efficiency was based on the coefficient of determination of the fit (R^2) and the mean relative error (P%), as defined by Eq. (13) (Lomauro et al. 1985):

$$P(\%) = \frac{100}{n}\sum_{1}^{n}\frac{\left|y^{exp} - y^{calc}\right|}{y^{exp}} \tag{13}$$

where y^{exp} represents the experimental value, y^{calc} the calculated value, and n the number of observations.

The data were statistically analyzed by an analysis of variance (ANOVA) and Tukey's test at a 5 % significance level.

Results and Discussion

Convective Drying Kinetics

Figure 2a shows the water content (non-dimensional, dry weight basis) as a function of drying time for the fresh and pre-treated samples at a temperature of 60 °C and drying air velocity of 0.85 m s^{-1}. It can be seen that the blanched samples were the quickest to dry, followed by the fresh samples and finally the coated ones. As shown in Fig. 2a, the same behavior was repeated for the other experiments with the other combinations of drying temperature and air velocity. Figure 2b–d shows the water content (non-dimensional, dry weight basis) as a function of drying time for the fresh, blanched, and coated pumpkin slices, respectively under the other conditions. These curves compare the influence of temperature and air velocity on the drying of the pumpkin slices, and show that the drying time decreased with increase in air velocity and temperature. Only a 10 °C difference significantly changed the rates and times of pumpkin drying. Guiné et al. (2011) verified that the drying time of pumpkin cylinders diminished 75 % for a change in temperature from 30 to 70 °C.

Constant Drying Rate Period

A constant-rate period was detected in all the drying assays for approximately the first 20 min. Table 1 shows the constant evaporated water flux of the blanched, pectin-coated, and fresh pumpkin slices for trials (1) and (2). A reasonable reproducibility was obtained for the three treatments (Table 1).

Figure 3 illustrates the drying rates of the fresh, blanched, and coated samples dried at 70 °C and 1.7 m s^{-1}.

The influence of temperature and air-velocity on the constant flow of evaporated water for each treatment can be observed in Table 1. When the drying temperature was raised from 60 to 70 °C, this 10° variation resulted in an average increase in the flux of approximately 22 %, and when the velocity was doubled from 0.85 to 1.7 m·s^{-1}, the fluxes increased by an average of nearly 26 %.

The highest constant flows were found for the blanched samples (Table 1) and attributed to the damaged tissue and to the reduction in soluble solids content, both caused by blanching in boiling water. As shown on Table 2, after blanching, the total sugar contents were always lower than in the fresh pumpkin because the sugars leave the disrupted tissue near the surface. High constant flows were also found in the samples coated with pectin. Although the liquid water present on the food surface during the constant drying rate period is assumed to be entirely unbound (Treybal 1980), this

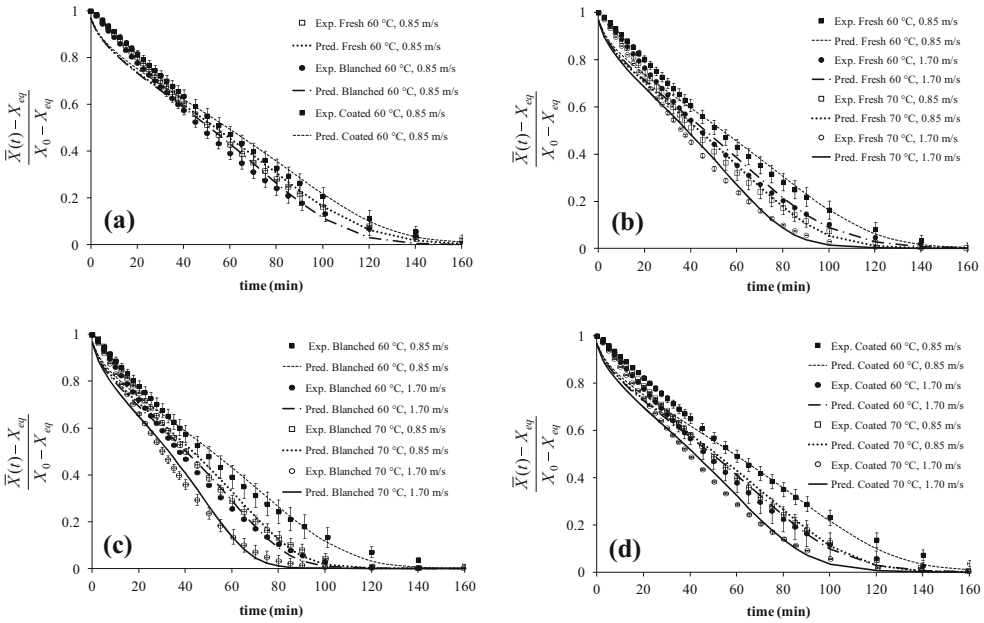

Fig. 2 Comparison between the experimental (*Exp.*) and predicted (*Pred.*) values (Eq. 6) for the water content as a function of the drying time. **a** Fresh, blanched, and coated samples at 60 °C and 0.85 m·s^{-1}; **b** fresh samples; **c** blanched samples; **d** coated samples, under the various drying conditions. Mean of two trials

liquid contains some solutes that influence the vapor pressure, which is therefore lower than the saturated vapor pressure for pure water. Consequently, differences were observed between the evaporated water fluxes of each treatment at the same air velocity and temperature, especially when comparing blanched or coated samples with fresh samples, as more soluble solids were expected to be found on the wet surface of the latter samples.

The external resistance effects can also be observed by comparison of the constant evaporated water flows at 0.85 and 1.7 m·s^{-1} velocities (Table 1). As mentioned above, when the air velocity was doubled, flows increased in approximately 22 % for the fresh pumpkins, 30 % for the blanched ones, and 24 % for the pectin-coated ones.

The critical moisture content was determined at the end of the constant rate period. The water contents of the samples before each drying experiment and the respective critical moisture contents (X_c) are shown in Table 3. The critical moisture, in general, is increased by increasing the drying rate and the thickness of the solid (Treybal 1980). Despite the differences between replicates, the critical moisture tended to increase from the fresh to the blanched tissue and finally to the thicker samples that were the coated ones. In addition, both blanching and edible coating treatments increased the water contents of the samples, the former because of the water that diffuses from the boiling water to the samples and the soluble solids that leave the samples during this treatment, and the latter because of the high moisture level of the pectin-based coating. The critical moisture means the transition between the constant and falling rate periods. Thus, to determine the water diffusivity in the exclusively falling rate period, the effective diffusivities were calculated from the critical moisture values.

Table 1 Constant flow of evaporated water (N_c) for fresh, blanched, and coated pumpkin slices as a function of temperature and air-drying velocity for the two trials, and the mean ± sd (standard deviation) for the different drying conditions

Drying conditions			Fresh		Blanched		Coated	
T (°C)	v (m·s^{-1})	Trial	$N_c \times 10^5$ (kg·m^{-2}·s^{-1})	mean ± sd	$N_c \times 10^5$ (kg·m^{-2}·s^{-1})	mean ± sd	$N_c \times 10^5$ (kg·m^{-2}·s^{-1})	mean ± sd
60	0.85	1	30.03	28.56 ± 2.07	34.61	32.10 ± 3.54	33.75	32.40 ± 1.91
		2	27.10		29.60		31.05	
60	1.7	1	34.96	34.80 ± 0.23	42.99	43.07 ± 0.12	40.63	40.35 ± 0.40
		2	34.63		43.15		40.07	
70	0.85	1	36.98	35.32 ± 2.35	40.95	40.48 ± 0.66	38.48	38.80 ± 0.44
		2	33.66		40.01		39.11	
70	1.7	1	43.30	43.47 ± 0.24	52.42	51.42 ± 1.41	47.51	47.83 ± 0.45
		2	43.64		50.42		48.15	

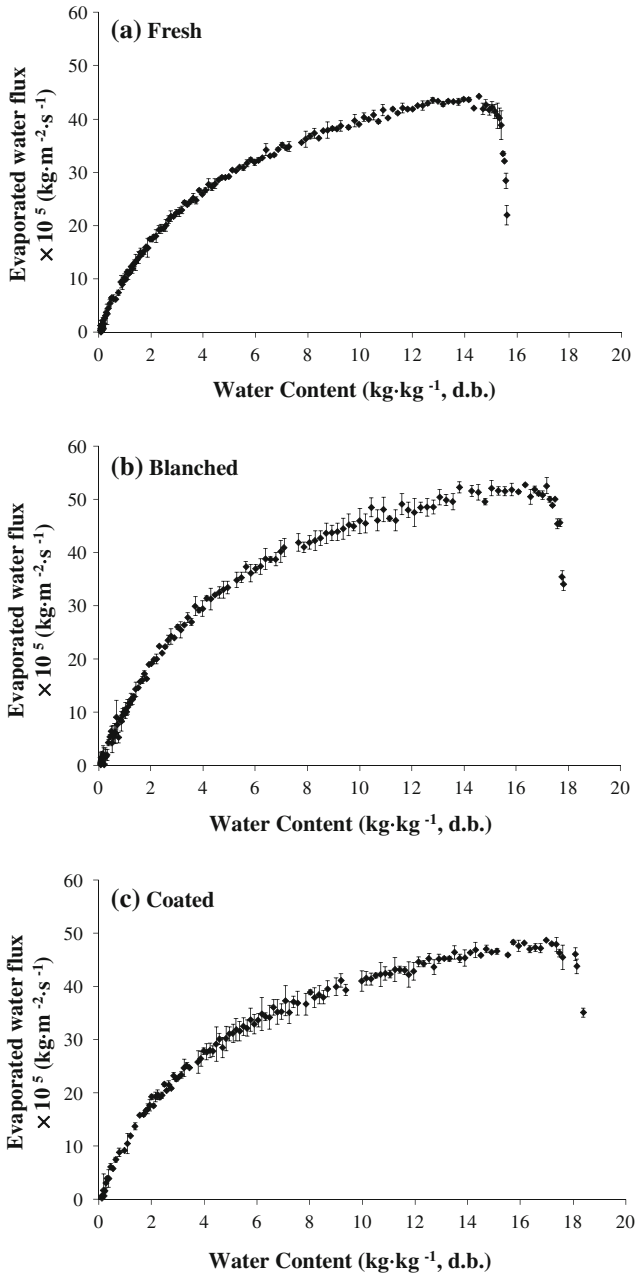

Fig. 3 Evaporated water flux of the **a** fresh; **b** blanched; and **c** coated pumpkin slices dried at 70 °C and 1.7 m·s^{-1} as a function of water content (d.b.). Mean of two trials

Falling Drying Rate Period

The falling drying rate was described based on Fick's second law. To determine the effective diffusivity, Eq. 6 was fitted to the drying data. It is important to point out that the mean initial thicknesses determined by the volume displacement method were different between the trials with fresh (3.70×10^{-3} m), blanched (3.74×10^{-3} m), and coated (4.40×10^{-3} m) samples. Table 4 shows the diffusivities, coefficients of determination (R^2), and relative errors, P (%), as a function of temperature and air-drying velocity.

The diffusivities were determined in two different ways: ignoring the constant rate period, that is, determining the diffusivity over the whole drying curve as from $t_0 = 0$ min, and considering the falling rate period as from the critical moisture content, which corresponded to approximately 20 min of drying time ($t_0 \cong 20$ min). To determine the water diffusivity in the exclusively falling rate period, that is, as from the critical moisture content, X_0 was substituted by X_c in the residual moisture (dimensionless), the thicknesses were also calculated from the critical moisture, and then, Eq. (6) was fitted to these values. This procedure resulted in greater coefficients of diffusion than those calculated considering the whole drying period. However, differences between the diffusivities calculated with and without the constant rate period were lower than 7.2 % and not significant at the 5 % level for all treatments, as can be seen in Table 4 for the fresh, blanched, and coated treatments. Each drying experiment was repeated twice, and in general, trials (1) and (2) showed good reproducibility for the three treatments (Table 4).

A comparison between the treatments for each temperature and velocity condition showed no significant difference between the diffusion coefficients for the fresh and blanched samples, even though the diffusivity of the water in the blanched samples was always slightly higher than that in the fresh samples. This was associated with tissue damage caused by blanching, as well as with the loss of sugars during this treatment, from the samples to the boiling water (Table 2) and consequent decrease in the equilibrium moisture, as low molecular mass carbohydrates such as sucrose and reducing sugars have higher capacity to retain water than cellulosic compounds and proteins, which, together with the sugars, are the major pumpkin components (Molina Filho et al. 2011).

Conversely, coated samples presented the greatest diffusion coefficients, with or without constant-rate consideration. This suggests that the water diffusivity is significantly higher in pectin than in pumpkin, thereby contributing to the greater effective diffusivity value. Leiva Díaz et al. (2009) dried an apple pectin gel and applied a model where the drying curve was divided into high- and low-moisture zones. At 60 °C, the authors found a higher water diffusion coefficient in the high-moisture region (18.04×10^{-10} m^2·s^{-1}) than in the low-moisture zone (1.69×10^{-10} m^2·s^{-1}). This fact was corroborated by sorption isotherms of pectins, which show a high capacity to retain water at high moisture levels (Panchev et al. 2010).

Although the diffusion coefficients of the coated samples were generally greater than those of the other samples, the drying curves showed longer drying times to reach the same water content because of the greater initial thickness and water content of these samples (Fig. 2a). The initial thickness of the coated samples was, on average, 4.40×10^{-3} m, almost 20 % greater than the mean thickness of the other treatments (3.70 and 3.74×10^{-3} m). Thus, although on one hand the diffusivity

Table 2 Mean ± sd (standard deviation) for the reducing and non-reducing sugar contents and total sugar contents, before and after blanching of the pumpkin slices (kg·100 kg^{-1} dry matter)

Drying conditions			Fresh (before blanching)			Blanched		
T (°C)	v (m·s^{-1})	Trial	Reducing sugar (kg·100 kg^{-1} dry matter)	Non-reducing sugars (kg·100 kg^{-1} dry matter)	Total sugars (kg·100 kg^{-1} dry matter)	Reducing sugars (kg·100 kg^{-1} dry matter)	Non-reducing sugars (kg·100 kg^{-1} dry matter)	Total sugars (kg·100 kg^{-1} dry matter)
60	0.85	1	20.44 ± 0.40	31.14 ± 0.35	51.58	18.12 ± 0.03	27.54 ± 0.34	45.66
		2	18.86 ± 0.37	28.73 ± 0.32	47.59	16.08 ± 0.028	24.44 ± 0.30	40.52
60	1.7	1	44.15 ± 0.24	12.74 ± 2.14	56.89	37.02 ± 0.35	12.41 ± 0.52	49.43
		2	21.11 ± 0.41	32.15 ± 0.36	53.25	18.21 ± 0.031	27.67 ± 0.34	45.88
70	0.85	1	37.23 ± 0.08	17.63 ± 0.12	54.87	32.37 ± 0.45	14.80 ± 0.99	47.17
		2	20.21 ± 0.23	34.52 ± 0.02	54.74	17.05 ± 0.45	31.84 ± 0.78	48.89
70	1.7	1	36.12 ± 0.67	13.62 ± 0.82	49.74	31.46 ± 0.29	14.19 ± 0.30	45.64
		2	22.68 ± 0.40	31.18 ± 0.47	53.86	18.47 ± 0.21	28.46 ± 1.03	46.93

of the water in the coatings was high, on the other hand the increase in thickness and in water content due to the coating resulted in a reasonable increase in the drying time of these samples.

The coefficients of determination for the fit (R^2) with values above 0.85 Vega-Gálvez et al. (2007), and the values for relative error below 10 % (Lomauro et al. 1985), corresponded to an acceptable fit of the model. In previous work with pumpkins (Garcia et al. 2007), a diffusion model with volumetric shrinkage incorporated in the same manner as in the present work showed a good fit. The authors observed that considerations related to the initial dimensions can result in diffusivities that are several times larger. They also compared their results with values predicted by Rovedo et al. (1997), who applied a rigorous approach with consideration of the shrinkage and concluded that the simplified method could be useful in predicting diffusivities with reasonable accuracy.

A similar procedure was applied by Perez and Schmalko (2009). The authors, investigating the drying of fresh and blanched pumpkins, considered the characteristic dimensions as dependent on the water content in the integrated analytical solution. They also considered the diffusion coefficient to vary with the temperature and water content, solving the problem numerically, but did not obtain a good fit, probably due to the complex equation system.

The fit of Eq. 6 to the data obtained was generally less efficient for the blanched samples than for the fresh and coated samples, probably because this pre-treatment makes the thickness and form of the slices less regular, due to damage caused by heat blanching in boiling water.

A temperature of 70 °C with an air velocity of 1.7 m s^{-1} corresponded to the worst fit of the diffusion equation, which could be associated with very fast drying of the sample surface, resulting in the formation of some drier, more rigid areas in an irregular way.

Drying efficiency was affected by the air velocity of 0.85 m·s^{-1}, as can be seen in Fig. 2, where the drying curves corresponding to this condition show slower rates because of the influence of the external resistance. This can also be

Table 3 Mean ± sd (standard deviation) for the initial water content (w.b.) and critical moisture content (d.b.), given in kg water·100 kg^{-1} of wet and dry matter, respectively, for the fresh, blanched, and coated samples in the two trials under different drying conditions

Drying conditions			Fresh		Blanched		Coated	
T (°C)	v (m·s^{-1})	Trial	w_0 (kg·100 kg^{-1} wet matter)	X_c (kg·100 kg^{-1} dry solids)	w_0 (kg·100 kg^{-1} wet matter)	X_c (kg·100 kg^{-1} dry solids)	w_0 (kg·100 kg^{-1} wet matter)	X_c (kg·100 kg^{-1} dry solids)
60	0.85	1	94.01 ± 0.05	12.47	95.26 ± 0.08	16.84	94.74 ± 0.07	14.46
		2	93.59 ± 0.02	11.88	94.66 ± 0.04	14.44	93.30 ± 0.17	11.94
60	1.7	1	93.30 ± 0.02	10.80	94.84 ± 0.02	13.36	95.57 ± 0.03	16.82
		2	93.02 ± 0.12	10.45	95.28 ± 0.03	13.78	93.68 ± 0.23	10.54
70	0.85	1	94.17 ± 0.04	11.87	95.49 ± 0.02	15.72	95.70 ± 0.05	17.44
		2	93.37 ± 0.09	10.59	93.39 ± 0.02	10.81	94.36 ± 0.06	13.54
70	1.7	1	94.36 ± 0.06	12.66	95.12 ± 0.01	12.60	94.87 ± 0.03	13.59
		2	92.86 ± 0.49	9.67	94.37 ± 0.23	11.25	95.07 ± 0.02	13.63

Table 4 Effective diffusion coefficients of the water, coefficients of determination (R^2), relative errors, P (%), and mean ± sd (standard deviation) for the fresh, blanched, and coated pumpkin slices as a function of temperature and air-drying velocity, considering the constant rate period (20 min) or not (0 min)

Drying conditions				Fresh				Blanched				Coated			
T (°C)	v (m·s^{-1})	Trial	t_0 (min)	D_{eff} ×10^{10} (m^2·s^{-1})	R^2	P (%)	Mean ± sd	D_{eff} ×10^{10} (m^2·s^{-1})	R^2	P (%)	Mean ± sd	D_{eff} ×10^{10} (m^2·s^{-1})	R^2	P (%)	Mean ± sd
60	0.85	1	0	1.34	0.984	6.54	1.28 ± 0.09^{aA}	1.39	0.985	7.88	1.32 ± 0.10^{aAB}	1.74	0.981	6.26	1.68 ± 0.08^{aB}
60	0.85	2	0	1.22	0.978	6.36		1.25	0.982	6.48		1.63	0.976	5.86	
60	0.85	1	20	1.42	0.986	5.94	1.35 ± 0.09^{abA}	1.41	0.983	7.98	1.35 ± 0.08^{abA}	1.81	0.982	5.61	1.75 ± 0.09^{abB}
60	0.85	2	20	1.29	0.981	5.44		1.30	0.984	6.04		1.68	0.976	5.49	
60	1.70	1	0	1.56	0.989	7.26	1.57 ± 0.00^{bcA}	1.75	0.991	13.88	1.72 ± 0.06^{cAB}	2.05	0.987	7.68	1.98 ± 0.10^{abB}
60	1.70	2	0	1.57	0.990	7.08		1.68	0.989	11.81		1.91	0.987	5.47	
60	1.70	1	20	1.64	0.989	7.00	1.65 ± 0.01^{cdA}	1.83	0.992	13.48	1.76 ± 0.09^{cdA}	2.14	0.986	7.70	2.04 ± 0.14^{bA}
60	1.70	2	20	1.66	0.990	6.63		1.70	0.989	11.33		1.94	0.985	5.35	
70	0.85	1	0	1.64	0.991	8.35	1.59 ± 0.07^{bcA}	1.63	0.990	13.00	1.69 ± 0.08^{bcA}	1.97	0.987	7.65	1.95 ± 0.03^{abB}
70	0.85	2	0	1.54	0.989	7.21		1.74	0.991	8.95		1.93	0.988	6.44	
70	0.85	1	20	1.72	0.992	7.52	1.68 ± 0.05^{cdA}	1.74	0.990	13.06	1.79 ± 0.08^{cdeAB}	2.08	0.988	7.32	2.04 ± 0.05^{bB}
70	0.85	2	20	1.64	0.990	6.65		1.85	0.992	8.56		2.00	0.987	6.16	
70	1.70	1	0	1.84	0.992	11.75	1.89 ± 0.07^{deA}	2.14	0.988	23.42	2.08 ± 0.08^{deA}	2.41	0.991	10.29	2.39 ± 0.02^{cB}
70	1.70	2	0	1.94	0.992	10.58		2.03	0.986	18.47		2.37	0.992	9.77	
70	1.70	1	20	1.94	0.993	10.42	2.01 ± 0.10^{eA}	2.21	0.988	23.14	2.13 ± 0.11^{eA}	2.52	0.991	9.78	2.50 ± 0.02^{cB}
70	1.70	2	20	2.07	0.993	9.40		2.05	0.987	17.31		2.49	0.993	8.87	

The same low letter in the same column means no significant difference between drying conditions. The same capital letter in the same line means no significant difference between treatments

observed in Table 4, whose diffusivities determined by air speed of 0.85 m·s^{-1} at the same temperatures were around 20 % lower than those determined by 1.70 m·s^{-1} (Table 4). To evaluate the external resistance through the Biot mass number, κ was estimated using a water concentration range from the sorption curves determined for pumpkins (Molina Filho et al. 2011). This permitted an evaluation of the Biot number magnitude from a correlation for flat plate that considers low mass transfer rates (Treybal 1980). However, high values were found for all experimental conditions. Even though the Biot numbers reflected a low external resistance, the observed differences between the diffusion coefficients showed that this estimation was not correct, probably because the κ values do not represent well the transient phenomena, the ratio between moisture and water vapor pressure changes during drying, and the air not flowing perfectly parallel to the slices. In addition, Eq. 8 could be solved for several Biot numbers, optimizing the fitting; however, the same problems will arise because Biot number changes during the process, which would demand a numerical solution. Fontaine and Ratti (1999) have proposed a short-cut method to predict drying kinetics of biological materials, in which the Biot mass numbers were very high when pieces of fruit were dried with air flowing at velocities of 1 and 2 m·s^{-1}. Therefore, in the present work, a careful study of this parameter and numerical approaches would be necessary to better elucidate the dependence of the drying kinetics with hot-air streams.

Empirical Models

Finally, Newton, Page, and Henderson-Pabis models were fitted to the experimental data and the constants of the equations are shown in Table 5. The Page model showed the best results, whose fitting efficiency was higher than those obtained by the Fick's model. These models are very useful for predicting drying time when the sample size and the drying surface area exposed to the airflow are similar to those used to find the constants of the equation, as they incorporate the sample geometry (Canizares and Mauro 2015).

Conclusions

Treatments applied prior to air drying, and the temperatures and air velocities of drying affected the kinetics of this process. The highest evaporated water constant fluxes were obtained for the blanched samples, followed by the coated samples and finally the fresh samples. The high fluxes for blanched samples were attributed to thermally damaged tissue and a reduction in the soluble solids content, both caused by blanching. The diffusivities did not follow the same behavior, since the coated samples presented the largest values, followed by the blanched samples and the fresh samples. The diffusivities of the pectin-coated samples were high because of the added polysaccharide with high water content, but their thickness and water content slightly increased the drying time in comparison to the fresh and blanched samples. The blanched samples dried faster than the fresh and coated samples. In the falling rate period, the highest drying rates corresponded to the higher temperatures and air velocities. The values obtained for diffusivity in the exclusively falling rate period resulted in slightly higher diffusion coefficients than those calculated considering the whole drying period. However, the differences between them were shown not to be significant, and thus it is reasonable to neglect the constant drying rate period for materials of plant origin. Drying air velocity at 0.85 m·s^{-1}

Table 5 Parameters determined according to the Newton, Page, and Henderson-Pabis models, coefficients of determination (R^2) and mean relative error, P (%), for the fresh, blanched, and coated pumpkin slices as a function of temperature and air-drying velocity

Drying conditions			Newton			Page				Henderson-Papis			
Treatment	T (°C)	v (m·s^{-1})	$k \times 10^4$(s^{-1})	R^2	P (%)	$k \times 10^5$(s^{-n})	n	R^2	P (%)	$k \times 10^4$ (s^{-1})	a	R^2	P (%)
Fresh	60	0.85	2.19	0.974	10.30	2.09	1.29	0.998	2.48	2.40	1.06	0.984	7.67
	60	1.70	2.78	0.973	19.34	2.36	1.31	0.998	4.92	3.05	1.07	0.983	15.04
	70	0.85	2.84	0.971	23.28	2.11	1.33	0.998	5.95	3.14	1.07	0.982	18.17
	70	1.70	3.59	0.969	59.09	2.14	1.36	0.998	13.55	3.96	1.08	0.980	47.18
Blanched	60	0.85	2.35	0.976	11.57	2.47	1.28	0.998	2.96	2.57	1.06	0.985	8.76
	60	1.70	3.34	0.971	44.90	2.38	1.34	0.997	12.47	3.67	1.08	0.980	36.36
	70	0.85	3.16	0.965	44.65	1.57	1.38	0.998	11.02	3.52	1.09	0.977	35.42
	70	1.70	4.21	0.971	81.62	2.43	1.37	0.998	14.68	4.63	1.09	0.980	64.89
Coated	60	0.85	1.99	0.977	7.95	2.33	1.26	0.998	2.15	2.17	1.05	0.986	5.96
	60	1.70	2.46	0.978	11.59	3.10	1.26	0.998	3.28	2.66	1.05	0.985	9.16
	70	0.85	2.45	0.972	15.71	2.09	1.31	0.997	4.79	2.69	1.06	0.981	12.39
	70	1.70	3.18	0.971	36.98	2.31	1.33	0.998	10.12	3.50	1.08	0.981	29.64

showed an influence on the mass transfer control that was shared between internal and external resistances. At the temperatures and velocities studied, coating and blanching did not significantly affect the drying kinetics, and thus these procedures are promising for use as pre-treatments for pumpkin drying.

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