Received: 27 May 2019 | Revised: 27 September 2019 | Accepted: 6 October 2019

DOI: 10.1111/jfpe.13304

ORIGINAL ARTICLE

Journal of Food Process Engineering | WILEY

Effect of Refractance Window on dehydration of osmotically pretreated apple slices: Color and texture evaluation

Yossebann Hernández[1] | Cristian Ramírez[1,2] | Jorge Moreno[3] | Helena Núñez[1] | Oscar Vega[4,5] | Sergio Almonacid[1,2] | Marlene Pinto[1] | Lida Fuentes[2] | Ricardo Simpson[1,2]

[1]Departamento de Ingeniería Química y Ambiental, Universidad Técnica Federico Santa María, Valparaíso, Chile

[2]Centro Regional de Estudios en Alimentos Saludables (CREAS), CONICYT-Regional GORE Valparaíso Proyecto R17A10001, Valparaíso, Chile

[3]Departamento de Ingeniería en Alimentos, Universidad del Bío-Bío, Chillán, Chile

[4]BIOALI Research Group, Department of Food, Faculty of Pharmaceutical Sciences and Food, Universidad de Antioquia, Medellín, Colombia

[5]Corporación Universitaria Americana, Medellín, Colombia

Correspondence
Cristian Ramírez, Departamento de Ingeniería Química y Ambiental, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile.
Email: cristian.ramirez@usm.cl

Funding information
CONICYT, Grant/Award Numbers: 1160761, 1191280, 1181270

Abstract

The objective of this research was to explore the advantages of apple slices dehydration (cv. Granny Smith) using a Refractance Window (RW) with and without osmotic dehydration as pretreatment and compared with conventional hot-air drying considering the quality attributes such as color and texture. For pretreatment, the apple slices were osmotically dehydrated and coupled to a moderate electric field (9.3 V/cm) using a sucrose solution (45°Brix) at 40°C until an A_w = 0.95 was achieved. Then, apple slices (with and without pretreatment) were dehydrated using RW at 55, 75, and 95°C and compared with conventional hot-air drying at 55°C as a control. The results showed that with dehydration using RW, both with and without pretreatment at 95°C, it was possible to achieve a similar quality of apple slices when compared with conventional hot-air drying at 55°C, but with a significant reduction in processing time. Additionally, the dehydration process using RW presented anomalous diffusion behavior on apple slices with an $\alpha > 1$.

Practical applications

Refractance Window (RW) is a technology used for dehydration of fruit and vegetables slices and pulp based on the refractance properties of wet materials. RW has reported promising results in processing time reduction as compared with conventional dehydration methods. In addition, the quality of the end products by RW is higher as compared with conventional drying methods. In this research, we have showed that the final product (dehydrated apple slices) using RW attained quality values (color and texture) similar to those obtained with osmotic dehydration (OD) coupled with moderate electric field (MEF)/hot-air drying. However, the time spent by RW (50 min) was much lower than OD coupled with MEF/hot-air drying (240 min). Then, the main advantage of RW is the capacity to dehydrate fruit and vegetables materials using temperatures around 100°C, which allow both, reduce processing time and also attain high-quality retention.

1 | INTRODUCTION

Drying is a preservation process used in the food industry to extend shelf life and, as a secondary effect, minimize transportation and storage costs. However, the fruit attributes, thermal sensitivity and the impact of heat on product quality means that new alternatives are always being explored (Vega-Mercado, Góngora-Nieto, & Barbosa-Cánovas, 2001). Refractance Window (RW) was patented by Magoon

(1986) and developed by MCD Technologies, Inc. (Tacoma, WA) as a technique for the efficient dehydration of heat-sensitive foods. This technique features an internal food temperature of less than 70°C and short drying times that are dependent on the thickness of the product. Essentially, the food material to be dried is placed on a transparent plastic film (Mylar) floating on hot water and is exposed to infrared radiation at 95–97°C. The thin plastic film is transparent to infrared radiation and a window for thermal radiation from hot water to wet material is formed (Kudra & Mujumdar, 2009; Nindo, Feng, Shen, Tang, & Kang, 2003; Nindo & Tang, 2007; Ochoa-Martínez, Quintero, Ayala, & Ortiz, 2012; Ortiz-Jerez, Gulati, Datta, & Ochoa-Martinez, 2015; Raghavi, Moses, & Anandharamakrishnan, 2018). RW has demonstrated high retention of product quality (color, vitamins, and antioxidants) when compared with other conventional methods (including freeze-drying). Experiments using vegetable and fruit purées, such as carrots, strawberries, and asparagus (Abonyi et al., 2002; Nindo, Sun, Wang, Tang, & Powers, 2003; Nindo & Tang, 2007; Nindo, Tang, Powers, & Bolland, 2004), indicate the good maintenance of total antioxidant activity and metabolites, such as carotenes and ascorbic acid, when compared with other conventional drying methods. In addition, the RW technique exhibits a high potential for the drying of fruit and vegetable slices. The reduction in drying time with the use of continuous RW drying compared with other techniques have been reported for mango slices (Ochoa-Martínez et al., 2012) and especially for foods such as purées (Abonyi et al., 2002; Nindo, Sun, et al., 2003). The mango slices dried with RW exhibited increased diffusivities when compared with samples dried with air. Additionally, 2 mm slices dried with RW exhibited the highest effective diffusivity, with fewer signs of deterioration (Ochoa-Martínez et al., 2012).

Dried apples are an attractive format for a commercial product, and different novel drying processes have been assessed to maximize the retention of quality. For example, Sacilik and Elicin (2006) studied the drying characteristics of apple slices in a convective hot-air dryer as a single layer with thicknesses ranging from 5 to 9 mm and drying air temperatures of 40, 50, and 60°C. The results showed that the moisture content and drying rate were affected by the drying air temperature and slice thickness. Nowak and Lewicki (2004) studied the effects of apple slices dried with infrared energy and convection under equivalent conditions. The results showed that the processing time can be reduced by up to 50% when the heating is performed with infrared energy.

To reduce the loss in quality due to the dehydration process, the application of pretreatments has been widely studied, with osmotic dehydration (OD) being one of the most popular methods due to its low complexity and cost (Prosapio & Norton, 2017). OD is a countercurrent mass transfer process where the food sample is put into a hypertonic solution formed by a solute (commonly sugar), which flows from the hypertonic solution into the food tissue, whereas water flows from the food tissue into the hypertonic solution (Ahmed, Qazi, & Jamal, 2016; Ciurzynska & Lenart, 2010; Simpson et al., 2015). The driving force for water removal from the food is the difference in concentrations between the hypertonic solution and the food material (Rahman, 2008). The OD process has been applied to various fruits such as strawberries (Moreno et al., 2012), mangoes (Torres, Talens, Escriche, & Chiralt, 2006), pineapples (Lombard, Oliveira, Fito, & Andrés, 2008), pears (Moreno et al., 2011), and apples (Moreno et al., 2011; Simpson et al., 2015), as well as to vegetables such as peppers (Ozdemir, Ozen, Dock, & Floros, 2008), potatoes (Khin, Zhou, & Perera, 2006), and tomatoes (Derossi, Severini, Del Mastro, & De Pilli, 2015).

On the other hand, moderate electric field (MEF) is a technology based on the passing of an electric current through a food material, in which the main objective is not to induce the heating of the sample but to produce microstructural changes at the cellular level. The electric field produces changes in the permeability due to the formation of pores in the cell membrane, a phenomenon called electroporation (Moreno, Espinoza, Simpson, Nuñez, & Gianelli, 2016; Simpson et al., 2015; Vorobiev & Lebovka, 2012). Simpson et al. (2015), in a study of the OD of apples coupled with MEF, using electric fields between 9 and 17 V/cm, observed that with the application of MEF, the sucrose diffusion into apple tissue increased when the electric field was increased. This result can be attributed to the higher values of the effective diffusion coefficient obtained.

The objective of this research was to explore the advantages of apple slices dehydration (cv. Granny Smith) using a RW with and without OD as pretreatment and compared with conventional hot-air drying considering the quality attributes such as color and texture.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Apples (cv. Granny Smith) were obtained from a local market and stored at 2°C until its use. Apples were used within 2 days of purchase, the initial moisture was 0.90 g of water/g of sample, total soluble solid was 10.7 ± 1.1 g sucrose/100 g of sample and A_w was 0.9808 ± 0.0032. Apples were rinsed, peeled, and cut into slices of 4.00 mm thick and 40.00 mm in diameter using a cork borer. Samples were obtained exclusively from the parenchymatic tissue (Ramírez, Troncoso, Muñoz, & Aguilera, 2011). After cutting, all slices were immersed in an aqueous, antibrowning, solution containing 3% (wt/wt) ascorbic acid and 1.5% (wt/wt) citric acid for 3 min in order to prevent enzymatic browning.

2.2 | Pretreatment: OD of apple slices coupled with a MEF

The OD solution at 45°Brix was selected based on preliminary study performed in our laboratory, considering that at this sugar concentration and coupled with 9.3 V/cm, a higher effective diffusion coefficient during OD was obtained. The osmotic solution was prepared by dissolving 675 g of sucrose (commercial sugar), 0.5 g of potassium sorbate, for use as a preservative, and 1.27 g of calcium chloride, used to increase the conductivity of the solution. The ratio of the OD solution to the apple slices was 11:1 (wt/wt) to prevent and minimize the

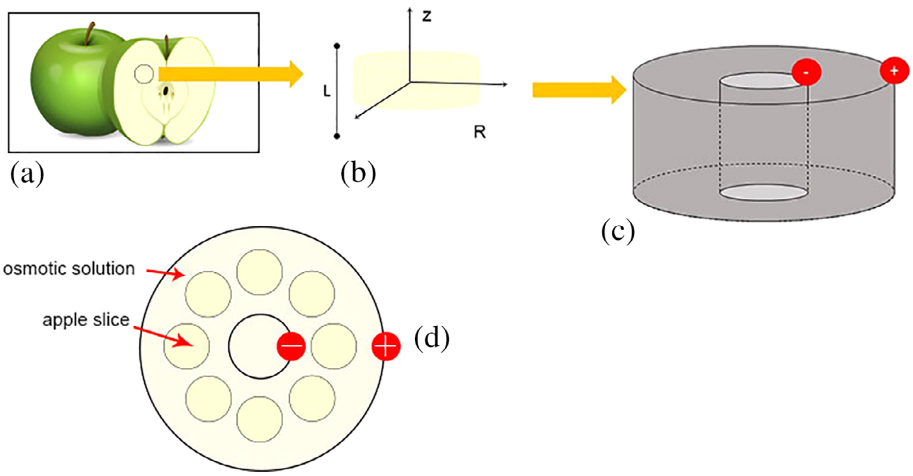

FIGURE 1 Sampling and experimental device

change in concentration of the solution during the experiment. In total, approximately 140 g of apples (approximately 35 slices) were used in each experiment. The samples were immersed in a cylindrical cell made of stainless steel with a plastic bottom. The cell was formed by two concentric cylinders (3.7 cm and 19 cm diameter) connected to a generator by means of two electrodes (Figure 1). The osmotic solution was subjected to an alternating current of 60 Hz and 70 V, which generated a MEF of 9.3 V/cm, where conditions were chosen based on previous tests performed by Simpson et al. (2015). The cell was immersed in a regulated thermal bath (BS-21 Jeio Tech, Korea) with the objective of holding the medium temperature at 40°C throughout the experiment. The temperatures of the solution and the samples were measured using Type T thermocouples (Copper-Constantan). An OM-320 data-logger (OMEGA Engineering, Stamford, CT) was employed to simultaneously monitor the temperature, voltage, and current. The OD pretreatment had a duration of 80 min, which was the time required to get a water activity of 0.95 into the apple slices. Then, the samples followed the dehydration process with either hot-air or RW.

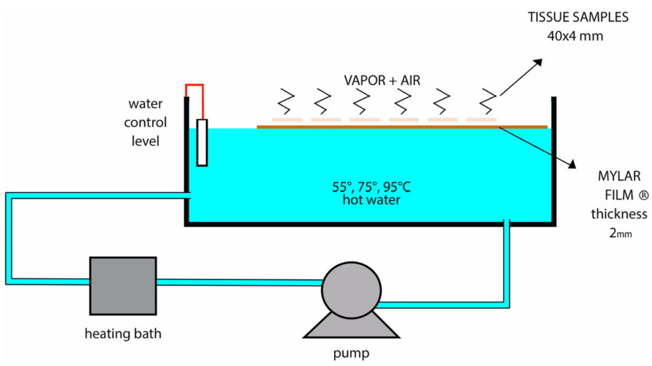

FIGURE 2 Schematic representation of Refractance Window (RW) setup

2.3 | Dehydration processes

2.3.1 | Conventional dehydration process: Hot-air drying

Hot-air drying was defined as the control dehydration process. Approximately 48 g of apple were dried in a laboratory tunnel drier (1.83 m long × 11 cm in diameter) with an axial air flow provided by a fan located at the beginning of the tunnel. The drying chamber included three trays (8 cm wide and 9 cm long). The drying was carried out with air at 55 ± 1°C and an average air rate of 2.23 m/s, conditions chosen based on preliminary tests. The air flow rate was measured with a portable anemometer (TSI VelociCalc Plus model 8360; MN). Each test was conducted with 12 samples evenly distributed on each tray in a single layer.

The changes in weight of the samples during the drying process were measured using a digital balance (Precisa model XB 620M; Dietikon, Switzerland) with a 0.001-g precision and water activity was determined using a 4T AQUALab (Decagon Devices, Inc., Pullman, Washington). Both measures were recorded along with the drying time. The drying process was performed until the samples achieved an A_w of 0.4. The drying experiments were performed in triplicate.

2.3.2 | Refractance Window

A RW drier was mounted in a 60-L thermoregulated bath (MERMMERT, WNB22 model; Germany), which was filled with distilled water. A sheet of plastic film (Mylar, polyethylene terephthalate), 2 mm thick, was placed over the bath in direct contact with the water, yielding a drying surface of 150 × 470 mm^2, which allowed for the drying of 30 samples per batch (Figure 2). A 4-cm gap between the thermobath boundaries and the Mylar sheet montage was used to purge air bubbles produced by high temperatures. To maintain permanent contact between the hot water and the Mylar, an automatic water level control system was used (Franco et al., 2019).

Three different temperatures, 55 ± 1, 75 ± 1, and 95 ± 1°C, were applied in the case of RW, which were defined based on preliminary studies. All experimental work was performed in the laboratory under standard conditions (25°C and 75% relative humidity). The sampling intervals used to measure the weight changes were 0, 20, 40, 60, 80, 100, 120, 150, 180, 240, 300, 360, and 390 min. Sample weights were measured using a digital balance with a 0.001-g precision (Precisa model XB 620M; Dietikon). The drying process was performed until the samples achieved an A_w of 0.4. Drying experiments were performed in triplicate.

2.4 | Mathematical modeling

2.4.1 | Fick's second law model

The mathematical models of hot-air drying and RW were based on the analytical solution of Fick's second law, as proposed by Crank (1975), for an infinite slab and represented by Equation (1) as follows:

$$\mathrm{MR}_t = \frac{W_t - W_e}{W_0 - W_e} = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2} e^{\left(\left(-(2i-1)^2\ \pi^2\ D_{\mathrm{eff}}\ t\right)/\left(4L^2\right)\right)} \quad (1)$$

where MR corresponds to the moisture ratio, W_t is the moisture content at any time t (g water/g dry basis), W_e is the moisture content at equilibrium (g water/g dry basis), W_0 is the initial moisture content (g water/g dry basis), D_{eff} is the effective diffusion coefficient (m^2/s), L is the half thickness of the slice (m), and t is the drying time (s). The value of W_e was obtained by checking the asymptotical value of the moisture profile. In that case, the analysis is made over a long period of time (MR > 0.6), Equation (1) can be simplified as follows:

$$\mathrm{MR}_t = \frac{8}{\pi^2} e^{\left(\left(-D_{\mathrm{eff}} \times \pi^2 \times t\right)/\left(4L^2\right)\right)} \quad (2)$$

D_{eff} was obtained by fitting the MR data with Equation (2) by minimizing the sum of the square error using the Solver tool included in Excel (Microsoft Office 365, Redmon, WA).

2.4.2 | Anomalous diffusion model

The drying process was also analyzed with the anomalous diffusion model based on fractional calculus (Simpson et al., 2015; Simpson, Jaques, Nuñez, Ramírez, & Almonacid, 2013). Basically, for one dimension, the model is represented by Equation (3) as follows:

$$\frac{\partial^\alpha W}{\partial t^\alpha} = D_{\mathrm{eff}} \frac{\partial^\beta W}{\partial x^\beta} \quad (3)$$

where W corresponds to food water content (g water/g dry basis), D_{eff} corresponds to the effective diffusion coefficient (m^β/s^α), α is related to anomalous waiting times between jumps, and β is related to anomalous jump lengths.

If the food matrices space component β converges to 2 and the temporal component has a fractional order (Simpson et al., 2013), Equation (3) can be represented as follows:

$$\frac{\partial^\alpha W}{\partial t^\alpha} = D_{\mathrm{eff}} \frac{\partial^2 W}{\partial x^2} \quad (4)$$

Then, the solution for the anomalous diffusion model is presented as Equation (5):

$$\mathrm{MR}_t = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2} E_\alpha\left(-D_{\mathrm{eff}}\left(\frac{(2i-1)\ \pi}{2L}\right)^2 t^\alpha\right) \quad (5)$$

where E_α corresponds to a Mittag-Leffler function (Simpson et al., 2013). When considering the long drying time, Equation (5) can be simplified as follows:

$$\mathrm{MR}_t = \frac{8}{\pi^2} E_\alpha\left(-D_{\mathrm{eff}}\left(\frac{\pi}{2L}\right)^2 t^\alpha\right) \quad (6)$$

If the parameter over time α converges to the unit and the Mittag-Leffler function converges to the exponential function, Equation (6) can be simplified as follows:

$$\mathrm{MR}_t = \frac{8}{\pi^2} e^{\left(-D_{\mathrm{eff}}(\pi/2L)^2 t^\alpha\right)} \quad (7)$$

The α value indicates the transport mechanism that is dominating the mass transfer process. Then, if $0 < \alpha < 1$, the diffusion mechanisms can be assumed to be subdiffusive. In contrast, if $\alpha > 1$, the mechanisms can be considered to be superdiffusive. If α converges to the unit, the anomalous diffusion model converges to Fick's second law.

2.4.3 | Temperature dependence of D_{eff} based on the Arrhenius model

The dependence of D_{eff}, for the time fractional diffusion, on the temperature used during RW was correlated using ln(D_{eff}) with the reciprocal of the absolute air temperature (T) by applying the Arrhenius model (Ramírez, Astorga, Núñez, Jaques, & Simpson, 2017) as follows:

$$\ln(D_{\mathrm{eff}}) = \ln(D_0) - \frac{E_a}{R}\left(\frac{1}{T}\right) \quad (8)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s^α), E_a is the activation energy (kJ/mol), R is the gas constant (kJ/mol K), and T is the absolute temperature (K).

2.5 | Determination of quality attributes and properties

The moisture content, water activity, total soluble solids, hardness, and color of samples were measured at the beginning and at the end of the drying processes.

For the apple tissue, the initial moisture content was 0.90 g of water/g of sample and was determined according to the Association of Official Analytical Chemists by drying fresh apple at 60°C under vacuum conditions for 24 hr until the samples reached a constant weight (AOAC, 2000). The water activity (A_w) was measured using a 4T AQUALab hygrometer (Decagon Devices, Inc., Pullman, WA) during the drying time.

Total soluble solids were quantified according to the method described by Moreno et al. (2011) using a refractometer (Hanna Instrument, model HI-96801; RI). The soluble solids were analyzed in triplicate.

The hardness of the apple slices was analyzed at room temperature (20 ± 1°C) using a CT3-4500 texture analyzer (Brookfield AMETEK, Middleboro, MA) with a load cell capacity of 50 kg. In a deformation test, five samples (total height 20 mm) were compressed with a plate probe (50 mm diameter) at a speed of 5 mm/s. One compression cycle was applied and the texture profile parameter (hardness) was defined as the maximum force required to compress 50% of the sample height and calculated as the peak force of the first compression of the product. The results are expressed in Newton (*N*), and the experiments were performed with five replicates.

Color change measurements (ΔE) at the surface of apple slices were measured using a colorimeter (CR-300, Konica Minolta, Japan) and expressed according to the CIELAB scale (L^*, a^*, and b^*) with coordinates obtained using a D65 illuminant with observer 2°. The measurement was performed in five samples randomly selected with three positions per sample. The total color difference (ΔE) in fresh, pretreated, and dehydrated samples was calculated using Equation (9) (Gnanasekharan, Shewfelt, & Chinn, 1992).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{9}$$

The browning index (BI) of dehydrated apple slices was calculated according to Equation (10) (Djekic et al., 2018).

$$\mathrm{BI} = \frac{100(x-0.31)}{0.17}; \quad \text{where} \quad x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \tag{10}$$

2.6 | Microstructural analysis

Dehydrated samples were directly mounted in aluminum plates and held using a double sticky carbon tape. Structural analysis was conducted using a Carl Zeiss EVO MA 10 scanning electron microscope (Carl Zeiss SMT, Ltd., UK) at 10 kV accelerating voltage and at pressure of 6×10^{-6} mbar.

2.7 | Statistical design and analysis

Tests of the significance of the results between different drying conditions and methods were performed using analysis of variance (ANOVA) with a CI of 95% using STAT-GRAPHIC Centurion XVI software (Statistical Graphic Corporation, version 16.0.07, Rockville, MD).

3 | RESULTS AND DISCUSSION

3.1 | Effect of pretreatment on physicochemical properties of apple slices

The moisture content of pretreated apples diminished from 86.54 ± 0.35 to 69.44 ± 4.06 g/100 g of sample, and A_w was reduced from 0.9808 ± 0.0032 to 0.9516 ± 0.0049 (a value considered as a target of the pretreatment). Apple slice hardness was reduced from 421.70 ± 7.90 to 365.22 ± 7.55 N after pretreatment, and this reduction may be explained by the application of MEF, which causes the cell walls to be altered and perforated due to an electropermeabilization mechanism (Moreno et al., 2011, 2013). Total soluble solid values increased from 10.7 ± 1.1 to 31.9 ± 0.5 g sucrose/100 g of sample. In qualitative terms, the color change value was ΔE = 2.9 ± 1.2 using MEF (9.3 V/cm), which was lower than the values (ΔE = 6.7 ± 0.7) reported by Moreno et al. (2013) for osmotically dehydrated apples coupled with ohmic heating at a higher electric field (13 V/cm). The differences in color change can be explained due to the direct relation of the electric field—in a range of 9 at 17 V/cm—on the sucrose diffusion into apple tissue (Simpson et al., 2015).

3.2 | Effect of pretreatment drying processes

Changes in the moisture ratio (MR) and water activity for untreated and pretreated apple slices under hot-air dehydration are presented in Figure 3a,b, respectively. Figure 3a shows that untreated and pretreated samples exhibited differences in MR profiles until 150 min. After that, no significance differences were observed ($p < .05$). As depicted in Figure 3b, the processing time required to obtain the target of A_w = 0.4 was 280 min for untreated samples and 180 min for pretreated samples. The reduction in processing time may be explained as an effect of electroporation, which sensitized the samples and made them more susceptible to drying (Moreno et al., 2016).

The drying curves for untreated and pretreated apple slices dried under RW at 55, 75, and 95°C are presented in Figure 3. Specifically, the drying process and A_w measured for RW at the three temperatures are presented in Figure 4a,b, respectively. As shown in Figure 4a, the time required to obtain an MR value of 0.2 was significantly affected by the drying temperature. Specifically, untreated samples dehydrated at 55°C required approximately 270 min, whereas only 50 min was required for the same sample dehydrated at 95°C. For pretreated samples, the drying time was reduced when the process was performed at either 75 or 95°C (Table 1).

The analysis of A_w changes during the RW drying process (Figure 4b) showed that the time required to achieve an A_w of 0.4 was increased as the drying temperature decreased. Thus, the drying times were 50, 95, and 270 min at drying temperatures of 95, 75, and 55°C,

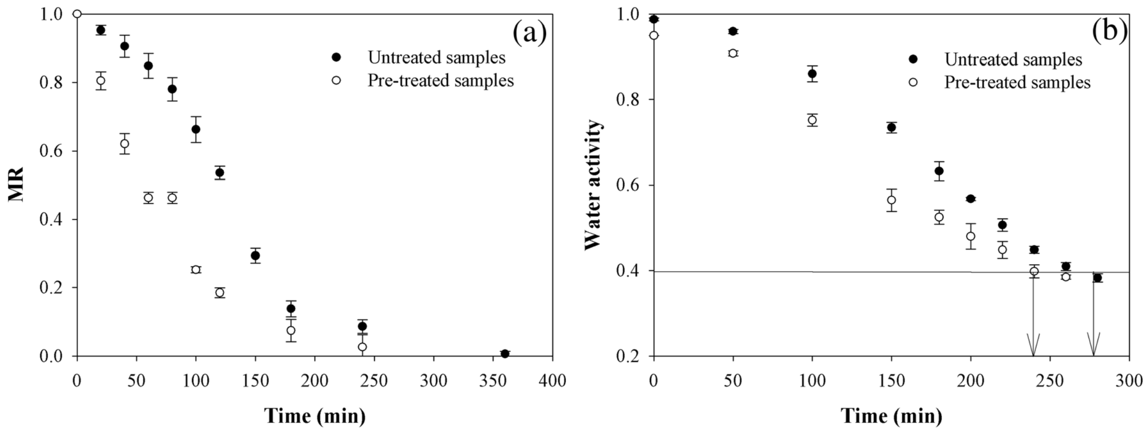

FIGURE 3 Untreated and pretreated apple slices treated by conventional dehydration. (a) Moisture ratio change based on time (MR); (b) Water activity change along drying time

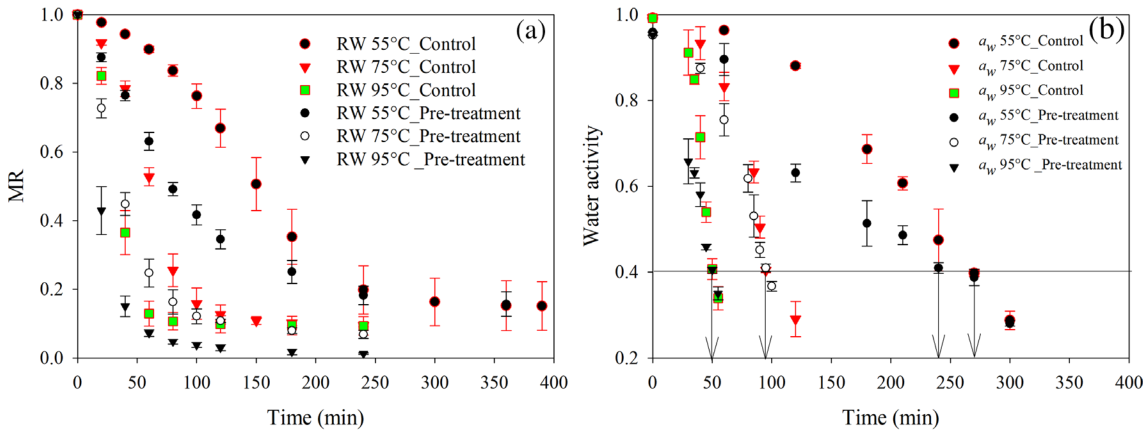

FIGURE 4 Untreated and pretreated apple slices treated with the Refractance Window (RW). (a) Moisture ratio change based on time; (b) water activity change along drying time

respectively. The use of RW at the three temperatures for pretreated samples revealed that the pretreatment affected the shape of the drying curve but did not affect the drying time required to achieve an A_w = 0.4, given that the same times were obtained for using RW with untreated samples. These differences in water activity curves could be attributed to the presence of a sugar concentration profile in the apple tissue, where the sugar concentration is higher at the surface than the inner portion, which favors the water release to the apple surface, facilitating the dehydration process. Conversely, in the case of untreated samples, the water movement from the inner portion of the sample to the surface is slower, but the process took the same processing time, as in the case of the treated samples, because the final amount of water present in the fruit is the same in both samples.

Finally, the drying time for hot-air drying and RW was dependent upon the application of pretreatment. As shown in Table 2, untreated samples dehydrated with hot-air at 55°C achieved an A_w = 0.4 in 280 min, whereas untreated samples dehydrated with RW at 55°C achieved an A_w = 0.4 in 270 min, which is a reduction of only 10 min. In the case of pretreated samples, the time required for conventional drying and RW was similar, approximately 240 min. The differences in the processing time attained for hot-air drying and RW obtained for apple slices in this work are not in concordance with other results reported in the literature, where a clear advantage in terms of processing time was obtained by RW in fruits such as kiwi and mango. For example, Robbers (1997) showed that during drying of kiwi slices (13 mm thickness), the time for RW were threefold lower when compared with a convection oven. Similarly, Ochoa-Martínez et al. (2012) reported that 60 and 240 min of drying in the RW and tray dryer, respectively, were required to achieve a moisture content of 5% for mango slices (2 mm thickness).

Based on Fick's second law, D_{eff} was calculated for hot-air drying and RW. The results are presented in Table 2. For hot-air drying, D_{eff} values were 1.41×10^{-11} m^2/s for untreated samples and 2.24×10^{-11} m^2/s for pretreated samples. The observed D_{eff} was significantly increased for pretreated samples. Ramírez et al. (2017) obtained similar D_{eff} values for air drying, ranging from 5.59×10^{-12} to 25.52×10^{-12} m^2/s. On the other hand, Nieto, Salvatori, Castro, and Alzamora (1998) reported D_{eff} values from 6.1×10^{-10} m^2/s at an A_w = 0.84 to 1.05×10^{-9} m^2/s at an A_w = 0.97 per glucose impregnation of apple in a vacuum or at atmospheric pressure, respectively.

TABLE 1 Mean values (with standard deviations) of soluble solids, firmness, and color parameters in fresh and dried apples

Process	Treatment	Temperature (°C)	Soluble solids (g/100 g of sample)	Hardness (N)	L^*	a^*	b^*	ΔE	BI
Fresh sample			10.70 ± 1.10^{a}	421.70 ± 7.90^{a}	72.28 ± 2.93^{a}	-9.10 ± 2.93^{a}	18.08 ± 0.80^{a}	0.00 ± 0.00	17.91 ± 1.72^{a}
Hot-air drying	Untreated	55	65.92 ± 6.63^{b}	143.33 ± 5.06^{b}	80.64 ± 1.25^{b}	-7.85 ± 0.34^{a}	20.29 ± 0.83^{b}	8.78 ± 1.18^{a}	19.96 ± 0.30^{a}
	Pretreated	55	80.13 ± 4.86^{c}	139.42 ± 3.95^{b}	79.88 ± 2.00^{b}	-7.69 ± 0.88^{a}	22.31 ± 2.44^{b}	9.61 ± 1.01^{a}	24.29 ± 0.70^{b}
RW	Untreated	55	73.09 ± 1.66^{d}	113.48 ± 5.42^{c}	82.12 ± 0.97^{b}	-8.21 ± 0.64^{a}	24.92 ± 2.37^{c}	12.21 ± 1.35^{b}	$26.48 \pm 2.87^{c,b}$
		75	71.31 ± 3.73^{d}	87.24 ± 8.86^{d}	80.95 ± 1.19^{b}	-8.62 ± 0.64^{a}	24.33 ± 1.50^{c}	$10.83 \pm 0.94^{a,b}$	26.04 ± 1.35^{c}
		95	$69.10 \pm 4.37^{b,d}$	77.71 ± 4.93^{e}	80.64 ± 2.33^{b}	-8.54 ± 0.66^{a}	23.91 ± 1.00^{c}	$10.35 \pm 1.92^{a,b}$	26.14 ± 2.49^{c}
RW	Pretreated	55	80.13 ± 4.86^{c}	146.03 ± 9.96^{b}	79.88 ± 2.00^{b}	-7.86 ± 1.08^{a}	22.31 ± 2.65^{b}	9.32 ± 1.31^{a}	23.87 ± 2.49^{b}
		75	80.75 ± 3.27^{c}	106.28 ± 8.22^{f}	78.91 ± 1.83^{b}	-7.78 ± 1.12^{a}	25.63 ± 0.88^{d}	$10.73 \pm 1.45^{a,b}$	29.18 ± 1.56^{d}
		95	82.98 ± 4.06^{c}	$103.15 \pm 7.42^{d,f}$	78.53 ± 1.88^{b}	-6.83 ± 1.77^{a}	24.64 ± 0.92^{c}	9.09 ± 1.62^{a}	29.71 ± 1.21^{d}

Note: Different letters in the same column indicate significant differences between means ($p < .05$).

Regarding RW samples, D_{eff} values for both untreated and pretreated samples were affected by the drying temperature. Specifically, the D_{eff} value increased as the temperature increased ($p < .05$). The D_{eff} for untreated samples varied from 1.12×10^{-11} to 5.24×10^{-11} m^2/s for 55 and 95°C, respectively. No significant differences between untreated and pretreated samples ($p > .05$) were observed in the present study. This dependence of D_{eff} on temperature was analyzed using the Arrhenius model for both untreated and pretreated samples, with the resulting R^2 values being 0.988 and 0.998, respectively. E_a and D_0 values were 38.83 ± 4.95 kJ/mol and $1.79 \pm 0.18 \times 10^{-4}$ m^2/s, respectively, for untreated samples and 42.89 ± 5.41 kJ/mol and $6.15 \pm 0.25 \times 10^{-4}$ m^2/s, respectively, for pretreated samples. No significant differences in E_a were noted for untreated and pretreated samples using RW ($p > .05$).

Previous research has indicated that the anomalous diffusion model provides a better phenomenological description and fitting of drying data when compared with Fick's second law model, even when maintaining the Arrhenius behavior of D_{eff} with temperature (Ramírez et al., 2017; Simpson et al., 2015). When drying analysis was performed using the anomalous diffusion model based on fractional time calculations, the α value was 3.20 for untreated samples and 1.29 for pretreated samples subjected to hot-air drying. This finding implies that pretreatment tends to favor Fickean behavior during the drying process, which has previously been reported by Simpson et al. (2015). The same analysis was performed for RW drying data, revealing α values of 2.76 for untreated samples and 1.33 for pretreated samples. A similar trend was observed for conventional hot-air drying, implying that the OD process, coupled with a MEF, modified the structure, favoring the path that facilitates water movement during drying (Simpson et al., 2015).

Effective diffusion values calculated with the anomalous model revealed an Arrhenius dependence on the temperature for untreated and pretreated samples. For example, for untreated samples, the E_a was 145.47 ± 604 kJ/mol, and the D_0 was $8.32 \pm 0.35 \times 10^{-10}$ m^2/s, with an R^2 of 0.998. In contrast, for pretreated samples, the E_a was 66.35 ± 6.96 kJ/mol, and the D_0 was $4.55 \pm 0.47 \times 10^{-1}$ m^2/s, with a R^2 of 0.989. Interestingly, the E_a obtained for untreated samples was significantly increased when compared with the E_a for pretreated samples, which is consistent with the fact that the electric field produced more paths, facilitated water migration, and required less energy to remove the water for pretreated samples (Ramírez et al., 2017).

3.3 | Effect of drying processes on the quality attributes of dehydrated apple

To compare the modifications of the quality parameters after OD, color, texture, and soluble solid content were determined (Table 1). Comparing all treatments, the solid gain was higher when the apple slices were pretreated, attaining almost 80 g of soluble solids/100 g of sample, independent of the dehydration method applied. The increase could be explained by electroporation effects promoting changes in the structure of the treated apples (Moreno et al., 2011, 2013). In the case of untreated samples, soluble solids ranged between 66 g/100 g of sample for hot-air drying and 73 g/100 g for RW at 55°C.

TABLE 2 Drying time and effective diffusion coefficient calculated using Fick's second law and anomalous diffusion model for the different drying treatments

				Fick's model			Anomalous diffusion model			
Drying process	Treatment	Temperature (°C)	Drying time (min)[a]	D_{eff} (10^{-10} m/s^2)	R^2	SSE	D_{eff} (10^{-14} m/s$^{\alpha}$)	R^2	SSE	α
Hot-air drying	Untreated	55	280	1.41 ± 0.12	0.9262	0.086	0.17 ± 0.001	0.9428	0.004	3.20 ± 0.12
	Pretreated		240	2.24 ± 0.14	0.9976	0.013	5,880 ± 647	0.9989	0.003	1.29 ± 0.15
RW	Untreated	55	270	1.12 ± 0.18	0.9038	0.049	0.87 ± 0.035	0.9877	0.005	2.76 ± 0.15
		75	95	2.93 ± 0.31	0.8870	0.115	15.4 ± 8.59	0.9811	0.015	
		95	50	5.24 ± 0.59	0.7540	0.021	289 ± 12	0.9927	0.023	
RW	Pretreated	55	240	0.89 ± 0.07	0.9774	0.008	1,330 ± 647	0.9891	0.006	1.33 ± 0.12
		75	95	2.32 ± 0.12	0.9565	0.027	4,250 ± 446	0.9878	0.013	
		95	50	4.91 ± 0.66	0.9766	0.009	18,900 ± 7,410	0.9927	0.005	

Abbreviations: RW, Refractance Window; SSE, sum of square error.
[a]Drying time required to attain an A_w = 0.4.

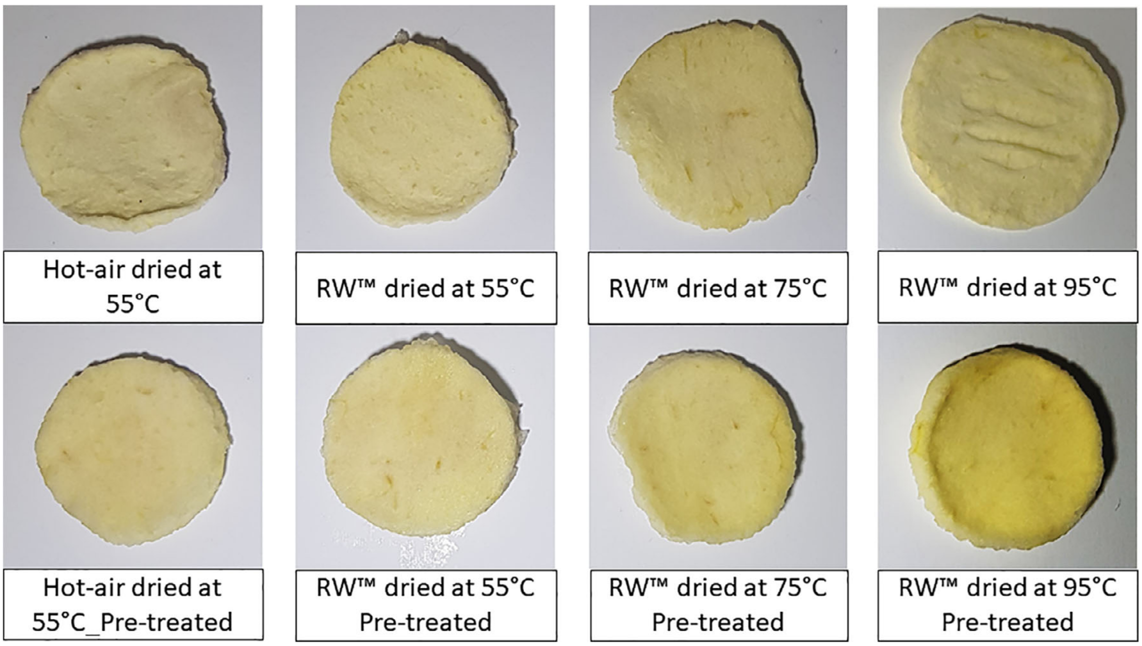

FIGURE 5 Untreated and pretreated apple slices dehydrated with hot-air at 55°C and Refractance Window (RW) at 55, 75, and 95°C

In general, the drying process caused a decrease in apple firmness, independent from the technique used (Table 1). These results confirmed that drying methods influence the mechanical properties of dried apples (Djekic et al., 2018). In specific, the results showed that for hot-air drying, the firmness values were similar, with a firmness of around 140 N. For untreated samples dehydrated under RW, the firmness values presented a maximal value of 113 N at 55°C and were decreased as the temperature increased until 95°C, with a firmness of 77 N. In the case of pretreated samples and RW dehydration, the tendency was similar to that presented by untreated samples, with a higher firmness at 55°C, and a decrease as the temperature increased, attaining values of 103 N. Interestingly, the firmness values were higher in the case of pretreated samples.

A reduction in hardness of 1.4-fold was observed at 95°C compared to process at 55°C during RW drying, without effect of pretreatment. The effect of temperature on firmness could be explained because at higher temperatures, the fruit texture becomes less plasticized, and converts into crispy sheets, and therefore, exhibits less hardness (Jafari, Azisi, Mirzaei, & Dehnad, 2016). On other hands, fresh apple slices (421.70 ± 7.90 N) showed a drying-time reduction for RW of only 10 min compared to the threefold lower reported for softest kiwi slices (58 N) (Robbers, 1997). The above suggests that the physicochemical characteristic of fruit—such as turgor pressure or pectin composition—could affect the time of drying process.

Other aspect that was possible to observe was that for untreated RW dehydrated samples at 55°C, the firmness presented slight

Journal of Food Process Engineering

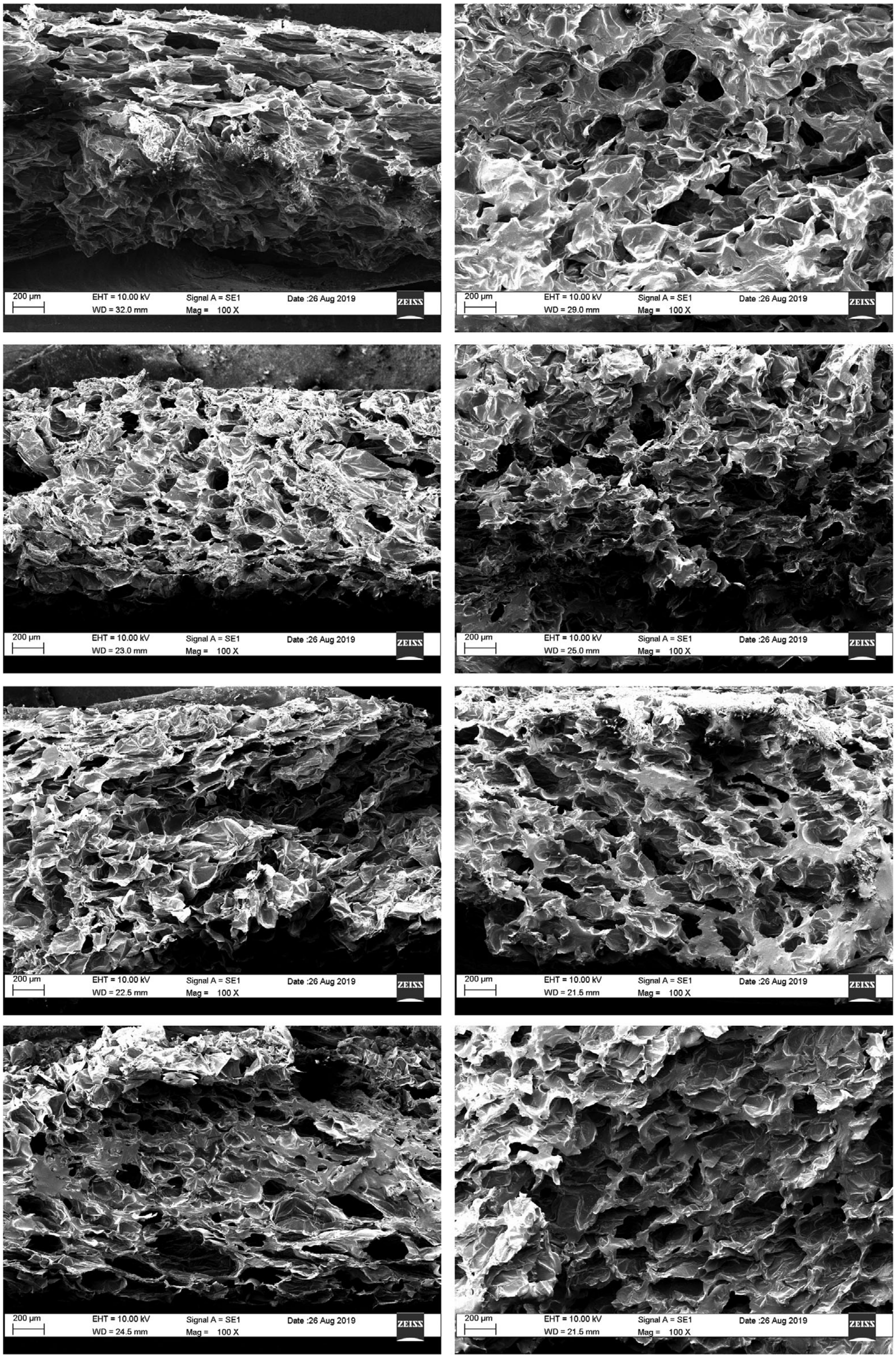

FIGURE 6 SEM images obtained for untreated and retreated apple slices dehydrated with hot-air at 55°C and RW at 55, 75, and 95°C

differences with respect to pretreated samples dehydrated under hot-air drying methods. This means that osmotic pretreatment can be neglected when RW is applied as the dehydration method, which suggests an important reduction in processing time, in this case, at least 80 min, and the time that was spent in OD treatment.

The differences of luminosity L^*, a^*, b^*, color difference (ΔE), and browning index (BI) obtained for the fresh and dehydrated samples can be observed in Table 1. The results showed that the L^* values were significantly different compared to fresh apples ($p < .05$), but no significant differences were found between the different treatments. In general, L^* values increased in comparison to the fresh sample, which means that samples were lighter for both types of drying. The a^* value for fresh apples was −9.10 ± 2.93. In general, for hot-air or RW dehydration, the red color (a values) decreased significantly when compared with fresh samples, without significant differences among treatments. On the other hand, a considerable increase in yellow color (b^* value) was observed for both the hot-air and RW drying, without significant differences among then. Δ*E* value for RW increased with the temperature and the application of OD (Table 1). Nevertheless, the results showed that it is possible to obtain dehydrated samples with RW without pretreatment using temperatures between 55 and 95°C with similar values of Δ*E* attained with hot-air drying and pretreatments.

The BI value is one the most common indicators of browning in dried fruits (Quitão-Teixeira, Aguiló-Aguayo, Ramos, & Martín-Belloso, 2008) and is often associated with the nonenzymatic Maillard reaction (Baini & Langrish, 2009; Persic, Mikulic-Petkovsek, Slatnar, & Veberic, 2017). The BI values were significantly increased ($p < .05$) by the application of pretreatment and the temperature used compared with fresh sample. So, fresh samples presented a BI of 17.91, which increased until 26.14 for untreated samples dehydrated with RW, but for pretreated samples and dehydrated with RW the BI attained a maximal value of 29.71. Respect to the effect of temperature on BI was possible observe that using 55°C, no significant differences were observed between different treatments and dehydration methods (except in the case of hot-air dehydrated samples, where untreated presented lower values of BI); whereas at 75 and 95°C, significant differences were presented between the samples, showing an important browning when samples were pretreated and RW dehydrated. These results can also be observed in Figure 5, where it is possible to observe color differences between the samples, especially those samples that were pretreated osmotically, whose appearance was more brown than untreated samples. In case of pretreated samples, those dehydrated with RW at 75 and 95°C were notoriously more brown. Through this quantitative/qualitative analysis, it can be noted that Δ*E* was not enough to show the differences between the samples; however, BI was more representative of the visual analysis, being able to demonstrate numerically the brown appearance of the pretreated and RWdehydrated samples at 75 and 95°C.

3.4 | Microstructural analysis of dehydrated apple slices

Figure 6 depicts the micrographs obtained from the transversal section of dehydrated apple slices using hot-air drying (Figure 6a,b) and RW (Figure 6c–h) for different temperatures and treatments.

The images obtained for hot-air dehydrated apples showed the positive effect of pretreatment on the microstructure, which clearly presented a less collapsed structure than untreated sample. These structural behaviors can explain the differences in firmness values obtained. If untreated samples were more compact, then the firmness was higher than pretreated samples. However, interestingly, when RW was used, independent of the temperature, the micrographs showed a similar structuring of cells between untreated and treated apples (Figure 6c–h). In general, it can be observed an open structure with the presence of more pores, which increase as the drying temperature is higher. Clearly, this increase in the porosity produces a fragile structure, which was quantified and verified through firmness measurements.

Other aspect that worth mentioning is that it is not possible to observe notorious differences between untreated samples dehydrated with RW and pretreated samples dehydrated with hot-air dehydration at the microstructural level, which was also evidenced with the preliminary essays.

4 | CONCLUSIONS

RW is a drying technique that facilitates apple slices dehydration using elevated temperatures (95°C) with a short process time (50 min), while maintaining the final quality when compared with a conventional hot-air drying process (55°C, over 270 min). In addition, RW did not present differences in terms of time, microstructure, and color quality between untreated and pretreated samples. The results showed a reduction of 80 min when RW was used due the osmotic pretreatment can be neglected with similar dried fruit quality obtained by conventional hot-air drying process. The diffusion process can be modeled by Fick's second law obtaining D_{eff} values with Arrhenius behavior for temperature in both untreated and pretreated samples. However, regarding the anomalous model, the results exhibited improved data fitting; suggesting that the diffusion process in the context of pretreatment tends to be Fickean with time fractional exponents of approximately 1. In contrast, the values were approximately 2 for untreated samples, which suggested an anomalous diffusion behavior.

ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by CONICYT through FONDECYT project nos. 1181270 (Ricardo Simpson), 1191280 (Cristian Ramírez), and 1160761 (Jorge Moreno).

ORCID

Cristian Ramírez https://orcid.org/0000-0001-7339-4766

Ricardo Simpson https://orcid.org/0000-0002-6040-4387

REFERENCES

Abonyi, B. I., Feng, H., Tang, J., Edwards, C. G., Mattinson, D. S., & Fellman, J. K. (2002). Quality retention in strawberry and carrot purees dried with Refractance Window™ system. *Journal of Food Science*, *67*, 1051–1056.

Ahmed, I., Qazi, I. M., & Jamal, S. (2016). Developments in osmotic dehydration technique for the preservation of fruits and vegetables. *Innovative Food Science & Emerging Technologies*, *34*, 29e43.

AOAC. (2000). *Official methods of analysis* (16th ed.). Gaithersburg, Maryland USA: AOAC.

Baini, R., & Langrish, T. (2009). Assessment of colour development in dried bananas–measurements and implications for modelling. *Journal of Food Engineering*, *93*(2), 177–182.

Ciurzynska, A., & Lenart, A. (2010). Rehydration and sorption properties of osmotically pretreated freeze-dried strawberries. *Journal of Food Engineering*, *97*, 267–274.

Crank, J. (1975). *The mathematics of diffusion* (2nd ed., pp. 47–53). Oxford: Clarendon Press.

Derossi, A., Severini, C., Del Mastro, A., & De Pilli, T. (2015). Study and optimization of osmotic dehydration of cherry tomatoes in complex solution by response surface methodology and desirability approach. *LWT - Food Science and Technology*, *60*, 641–648.

Djekic, I., Tomic, N., Bourdoux, S., Spilimbergo, S., Smigic, N., Bdovicki, S., … Rajkovica, A. (2018). Comparison of three types of drying (supercritical CO_2, air and freeze) on the quality of dried apple – Quality index approach. *LWT - Food Science and Technology*, *94*, 64–72.

Franco, S., Jaques, A., Pinto, M., Fardella, M., Valencia, P., Nuñez, H., … Simpson, R. (2019). Dehydration of salmon (Atlantic salmon), beef, and apple (Granny Smith) using Refractance Window™: Effect on diffusion behavior, texture, and color changes. *Innovative Food Science and Emerging Technologies*, *52*, 8–19.

Gnanasekharan, V., Shewfelt, R. L., & Chinn, M. S. (1992). Detection of color changes in green vegetables. *Journal of Food Science*, *57*, 149–154.

Jafari, S. M., Azisi, D., Mirzaei, H., & Dehnad, D. (2016). Comparing quality characteristics of oven dried and refractance window dried kiwifruits. *Journal of Food Processing and Preservation*, *40*, 362–376.

Khin, M. M., Zhou, W., & Perera, C. (2006). A study of the mass transfer in osmotic dehydration of coated potato cubes. *Journal of Food Engineering*, *77*, 84–95.

Kudra, T., & Mujumdar, A. S. M. (2009). *Advanced drying technologies* (2nd ed.). Boca Raton, FL: CRC Press.

Lombard, G. E., Oliveira, J. C., Fito, P., & Andrés, A. (2008). Osmotic dehydration of pineapple as a pre-treatment for further drying. *Journal of Food Engineering*, *85*, 277–284.

Magoon, R.E. (1986). *US Patent No*. 4631837. Method and apparatus for drying fruit pulp and the like. Washington, DC: U.S. Patent and Trademark Office.

Moreno, J., Espinoza, C., Simpson, R., Nuñez, H., & Gianelli, M. P. (2016). Application of ohmic heating/vacuum impregnation treatments and air drying to develop an apple snack enriched in folic acid. *Innovative Food Science and Emerging Technologies*, *33*, 381–386.

Moreno, J., Simpson, R., Pizarro, N., Parada, K., Pinilla, N., & Almonacid, S. (2012). Effect of ohmic heating and vacuum impregnation on the quality and microbial stability of osmotically dehydrated strawberries (cv. Camarosa). *Journal of Food Engineering*, *110*, 310–316.

Moreno, J., Simpson, R., Pizarro, N., Pavez, C., Dorvil, F., Petzold, G., & Bugueño, G. (2013). Influence of ohmic heating/osmotic dehydration treatments on polyphenoloxidase inactivation, physical properties and microbial stability of apples (cv. Granny smith). *Innovative Food Science & Emerging Technologies*, *20*, 198–207.

Moreno, J., Simpson, R., Sayas, M., Segura, I., Aldana, O., & Almonacid, S. (2011). Influence of ohmic heating and vacuum impregnation on the osmotic dehydration kinetics and microstructure of pear (cv. Packham's Triumph). *Journal of Food Engineering*, *104*, 621–627.

Nieto, A., Salvatori, D., Castro, M. A., & Alzamora, S. M. (1998). Air drying behaviour of apples as affected by blanching and glucose impregnation. *Journal of Food Engineering*, *36*, 63–79.

Nindo, C. I., Feng, H., Shen, G. Q., Tang, J., & Kang, D. H. (2003). Energy utilization and microbial reduction in a new film drying system. *Journal of Food Processing and Preservation*, *27*, 117–136.

Nindo, C. I., Sun, T., Wang, S. W., Tang, J., & Powers, J. R. (2003). Evaluation of drying technologies for retention of physical quality and antioxidants in asparagus (*Asparagus officinalis*, L.). *Lebensmittel-Wissenschaft & Technologie*, *36*, 507–516.

Nindo, C. I., & Tang, J. (2007). Refractance window dehydration technology: A novel contact drying method. *Drying Technology*, *25*, 37–48.

Nindo, C. I., Tang, J., Powers, J. R., & Bolland, K. (2004). Energy consumption during Refractance Window™ evaporation of selected berry juices. *International Journal of Energy Research*, *28*, 1089–1100.

Nowak, D., & Lewicki, P. P. (2004). Infrared drying of apple slices. *Innovative Food Science & Emerging Technologies*, *5*, 353–360.

Ochoa-Martínez, C. I., Quintero, P. T., Ayala, A. A., & Ortiz, M. J. (2012). Drying characteristics of mango slices using the Refractance Window™ technique. *Journal of Food Engineering*, *109*, 69–75.

Ortiz-Jerez, M. J., Gulati, T., Datta, A. K., & Ochoa-Martinez, C. (2015). Quantitative understanding of Refractance window™ drying. *Food and Bioproducts Processing*, *95*, 237–253.

Ozdemir, M., Ozen, B. F., Dock, L. L., & Floros, J. D. (2008). Optimization of osmotic dehydration of diced green peppers by response surface methodology. *LWT - Food Science and Technology*, *41*, 2044–2050.

Persic, M., Mikulic-Petkovsek, M., Slatnar, A., & Veberic, R. (2017). Chemical composition of apple fruit, juice and pomace and the correlation between phenolic content, enzymatic activity and browning. *LWT - Food Science and Technology*, *82*, 23–31.

Prosapio, V., & Norton, I. (2017). Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance. *LWT - Food Science and Technology*, *80*, 401–408.

Quitão-Teixeira, L. J., Aguiló-Aguayo, I., Ramos, A. M., & Martín-Belloso, O. (2008). Inactivation of oxidative enzymes by high-intensity pulsed electric field for retention of color in carrot juice. *Food and Bioprocess Technology*, *1*, 364–373.

Raghavi, L. M., Moses, J. A., & Anandharamakrishnan, C. (2018). Refractance window drying of food: A review. *Journal of Food Engineering*, *222*, 267–275.

Rahman, M. S. (2008). *Osmotic dehydration of foods*. In M. S. Rahman (Ed.), *Handbook of food preservation* (pp. 403–432). Boca Raton: CRC Press.

Ramírez, C., Astorga, V., Núñez, H., Jaques, A., & Simpson, R. (2017). Anomalous diffusion based on fractional calculus approach applied to drying analysis of apple slices: The effects of relative humidity and temperature. *Journal of Food Process Engineering*, *40*, e12549.

Ramírez, C., Troncoso, E., Muñoz, J., & Aguilera, J. M. (2011). Microstructure analysis on pre-treated apple slices and its effect on water release during air drying. *Journal of Food Engineering*, *106*, 253–261.

Robbers, M. S. (1997). Osmotic convective dehydrofreezing process for drying kiwifruit. *Journal of Food Science*, *62*, 1039–1047.

Sacilik, K., & Elicin, A. K. (2006). The thin layer drying characteristics of organic apple slices. *Journal of Food Engineering*, *73*, 281–289.

Simpson, R., Jaques, A., Nuñez, H., Ramírez, C., & Almonacid, S. (2013). Fractional calculus as a mathematical tool to improve the modeling of mass transfer phenomena in food processing. *Food Engineering Reviews*, *5*, 45–55.

Simpson, R., Ramírez, C., Birchmeier, V., Almonacid, S., Moreno, J., Nuñez, H., & Jaques, A. (2015). Diffusion mechanism during the osmotic dehydration of Granny Smith apples subjected to a moderate electric field. *Journal of Food Engineering*, *166*, 204–211.

Talens, P., Escriche, I., & Chiralt, A. (2006). Influence of process conditions on mechanical properties of osmotically dehydrated mango. *Journal of Food Engineering*, *74*, 240–246.

Vega-Mercado, H., Góngora-Nieto, M., & Barbosa-Cánovas, G. (2001). Advances in dehydration of foods. *Journal of Food Engineering*, *49*, 271–289.

Vorobiev, E., & Lebovka, N. (2012). Pulsed electric field assisted extraction. In E. V. Lebovka & F. Chemat (Eds.), *Enhancing extraction processes in the food industry* (pp. 25–83). Boca Raton, FL: CRC Press, Taylor & Francis Group.

How to cite this article: Hernández Y, Ramírez C, Moreno J, et al. Effect of Refractance Window on dehydration of osmotically pretreated apple slices: Color and texture evaluation. *J Food Process Eng*. 2019;e13304. https://doi.org/10.1111/jfpe.13304