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ORIGINAL ARTICLE

Ultrasound pre-treatment prior to unripe banana air-drying: effect of the ultrasonic volumetric power on the kinetic parameters

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Abstract Aiming to decrease the water content during the air-drying process of unripe banana slices, ultrasound (US) pre-treatments (25 °C) for 20 and 25 min at 9.38 and 25.63 W/L ultrasonic volumetric power were evaluated. Air-drying was performed at 50 and 60 °C for 360 min. Unripe banana slices pretreated at 25.63 W/L did not improve water migration, under either air-drying temperature, while slices pretreated at 9.38 W/L resulted in an increase in water effective diffusivity of 4.8 and 13.7% at 20 min US + air-drying at 50 °C and 25 min US + air-drying at 60 °C, respectively. The drying time saving of 7% and 9%, respectively, was achieved, showing that these treatments were alternative for processing unripe banana slices. Thus, ultrasound and air-drying operational parameters required accurately defined to achieve desirable results. Experimental data were adjusted to four models and the Midilli model resulted in the best experimental data fit, with $r^2 > 0.9988$, RMSE < 0.0873 and $\chi^2 < 0.00996$.

Keywords Kinetics · Water effective diffusivity · Activation energy · Drying curves

List of symbols

a	Constant of Logarithmic and Midilli's models (–)
b	Constant of Midilli's model (1/min)
c	Constant of Logarithmic model (–)
C_p	Specific heat (J/g K)
D_{eff}	Water effective diffusivity (m^2/s)
D_0	Arrhenius factor (m^2/s)
E_a	Activation energy (kJ/mol)
k	First order constant of semi-empirical drying models (1/min)
L	Sample half-thickness (m)
m	Mass (g)
MR	Moisture ratio (–)
n	Constant of Page and Midilli's model (–)
P_{US}	Ultrasonic volumetric power (W/L)
R	Universal constant of gases (8.1314 J/mol K)
t	Time (min)
T	Temperature (°C)
V	Volume (L)
x	Moisture content on wet basis (g H_2O/g)
X	Moisture content on dry basis (g H_2O/g)
WG	Water gain (g/100 g)

Subscripts

0	Initial
e	Equilibrium
US	Ultrasound

Introduction

Air-drying is the oldest industrial method used to process food. Its main advantage is that it provides dehydrated products with a relatively long shelf life (Park et al. 2007). However, one of the problems of using this technology alone is that the final product, due to the long processing time under medium or high temperatures, shows reduced color, aroma, texture and nutritional characteristics (Kim and Toledo 1987). In addition, it is one of the most energy-consuming processes (Yao et al. 2009). Recent

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investigations have focused on developing new food processing technologies to save energy and to minimize changes in food physical and chemical properties (Witrowa-Rajchert et al. 2014). These innovative processes are environmentally friendly, due to low energy consumption requirements and reduced water use, thus overcoming some limitations of current food processing technologies (Knorr et al. 2011). Ultrasound (US) is an example of a new technology, which can be scaled up to the industrial level. High-intensity US considers the use of frequencies ranging from 20 kHz to 1 MHz and power intensity > than 1 W/cm^2 (Cárcel et al. 2014). These applications, used as a pre-treatment prior to air-drying, may represent an attractive alternative so as to intensify dehydration and dewatering in gas–solid and liquid–solid systems, affecting both internal and external resistances to mass transfer (Mulet et al. 2003). The effect of US pre-treatment is mainly observable during air-drying, leading to an increase of water effective diffusivity and a decrease of drying times (Rodrigues and Fernandes 2008). However, the effects produced by US pre-treatment depend on the ultrasonic wave characteristics and the amount of transmitted energy, both directly affecting mass transport (Cárcel et al. 2014). The US positive effects on the air-drying of different fruits and vegetables were reported in previous studies (Azoubel et al. 2010; Fernandes and Rodrigues 2007; Santacatalina et al. 2016, among others). However, the volumetric power effect of US during the pre-treatment and its relationship with the mass transport of unripe banana slices has not yet been reported. In this context, the aim of the present study was to investigate the effects of US pre-treatment of two ultrasonic volumetric powers on the air-drying kinetic parameters of unripe banana slices.

Materials and methods

Raw material

Unripe bananas (*Musa cavendishii*) of the Nanicão variety from the Vale do Ribeira region (São Paulo, Brazil) were purchased from a local market. The fruits were characterized regarding soluble solids and firmness and processed immediately upon arrival at the laboratory. For this cultivar, to confirm the first stage of maturation, the mean values of soluble solids should be close to (3.5 ± 0.8) °Brix and firmness (25.8 ± 2.4) N (Tribess et al. 2009).

Soluble solids were determined by a refractometer and corrected for acidity and temperature values (Zenebon and Pascuet 2008). A TA-XT2i*plus* texture analyzer was used to evaluate firmness with a 6 mm diameter flat probe, at penetration velocity of 1 mm/s until 20 mm in depth. The initial moisture content was determined by the gravimetric method at 70 °C under vacuum pressure (≤ 20 kPa) until constant weight (Zenebon and Pascuet 2008). Soluble solids, firmness, and initial moisture content tests were performed before processing, in triplicate.

Ultrasonic volumetric power

Acoustic energy differs from electrical consumption, and its direct measurement is difficult; however, some methods based on the measurement of physical or chemical changes produced by US can accomplish this. In the case of liquid applications, the calorimetric method leads to remarkable results (Cárcel et al. 2014). Ultrasonic volumetric power was calculated by Eq. (1), considering the heating power as a consequence of the energy delivered by the US waves:

$$P_{US} = \left(mC_P \frac{dT}{dt} \right) \frac{1}{V} \tag{1}$$

wherein C_p is the specific heat (J/g K); m is the mass (g); V is the volume (L) and T is the temperature (°C).

The experiments were conducted in two ultrasonic baths, both without mechanical agitation, being the first one (UNIQUE, model USC-1850, Brazil) with the nominal characteristics of 154 W and 25 kHz, and the second (FISHER SCIENTIFIC, model FS 110, USA), 135 W and 42 kHz. The ultrasonic baths were insulated to minimize heat transfer to the surroundings. In order to avoid the return of the ultrasonic waves to the transducer and to guarantee perfect absorption in water, the baths were tilted 30° and the walls and the bottom were covered with aluminum paper (Kikuchi and Uchida 2011; Vinatoru 2015). The baths were filled with 2 L of distilled water at 26 °C and turned on for 5 min (300 s) while the water temperature was monitored with a thermocouple. Ultrasonic volumetric power was determined in quintuplicate.

Ultrasound pre-treatment

The bananas were peeled, cut into 5-mm thick slices and immersed in the ultrasonic baths for (20 or 25) min. The water fruit ratio was maintained at 4:1 (weight basis) at 25 °C and the experiments were carried out in duplicate. After US pre-treatment, samples were drained to remove the water excess. Moisture content was determined in triplicate by the gravimetric method at 70 °C under vacuum pressure (≤ 20 kPa) until constant weight (Zenebon and Pascuet 2008). Initial and after pre-treatment weight and moisture content were used to calculate the Water Gain (*WG*) according to Eq. (2):

$$WG = \left(\frac{m_{us}x_{us} - \mathrm{m_0 x_0}}{m_0} \right) \times 100 \tag{2}$$

wherein *WG* is the water gain (g H_2O/g); *m* is the mass (g); *x* is the moisture content based on wet basis (g H_2O/g); and the subscripts *US* and 0 correspond to after and before (initial) pre-treatment, respectively.

Air-drying process

The air-drying process (AD) was performed in duplicate in a convective oven (NOVA ÉTICA, model 410/4, Brazil) at (50 and 60) °C and 1 m/s of air velocity for 360 min. A diagram describing the experiments performed is displayed in Fig. 1.

Moisture ratio (*MR*) was calculated from experimental drying curves according to Eq. (3).

$$MR = \frac{X - X_e}{X_{us} - X_e} \quad (3)$$

wherein *X* is the moisture content based on dry basis (g H_2O/g) and the subscripts *e* and *US* correspond to equilibrium and after US pre-treatment, respectively. For X_e, values previously reported for unripe banana slices at (50 and 60) °C were considered (Zabalaga et al. 2016). Water effective diffusivity (D_{eff}) for the falling-rate period was calculated according to Fick's 2nd law of diffusion. Considering banana slices as a plane sheet, with *L* the sample half-thickness (m), the following boundary conditions were applied:

- Uniform initial moisture content: $X(z,0) = X_{us}$
- Symmetry of moisture: $\frac{\partial y}{\partial x}\Big|_{z=0} = 0$
- Equilibrium moisture on surface: $X(L,t) = X_e$

The solution for the water effective diffusivity at the falling-rate period is Eq. (4) (Crank 1975).

$$\frac{X - X_e}{X_{us} - X_e} = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\cdot\exp\left[-(2i+1)^2\cdot\pi^2\cdot\frac{D_{eff}}{4L^2}\cdot t\right] \quad (4)$$

This equation assumes negligible product shrinkage, although this is an important phenomenon occurring during drying of high-porosity products (Schössler et al. 2012a). Nevertheless, Koua et al. (2009); Park et al. (2001) among others, have previously applied Eq. (4) with adequate results.

The activation energy was calculated from the Arrhenius equation, represented in Eq. (5):

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{RT} \quad (5)$$

wherein D_{eff} is the water effective diffusivity (m^2/s); D_0 is the Arrhenius factor (m^2/s); E_a is the activation energy (J/mol); *R* is the universal constant of gases (8.1314 J/mol K) and *T* is the temperature (K).

Unripe banana slices final moisture content (after 360 min of air-drying) was determined by the gravimetric method at 70 °C under vacuum pressure ($\leq$ 20 kPa) until constant weight (Zenebon and Pascuet 2008).

Mathematical modeling of experimental drying curves

Data from drying experiments were fitted to four models containing one, two, three and four terms, typically used for modeling drying curves. These models were: Newton (O'Callaghan et al. 1971), Page (Zhang and Litchfield 1991), Logarithmic (Yaldiz et al. 2001) and Midilli (Midilli et al. 2002) presented in Eqs. (6) to (9), respectively. The coefficient of correlation (r^2), the root mean square error (RMSE) and the reduced Chi square (χ^2) were used to determine the quality of the fit.

$$MR = \exp(-kt) \quad (6)$$

$$MR = \exp(-kt^n) \quad (7)$$

$$MR = a\exp(-kt) + c \quad (8)$$

$$MR = a\exp(-kt^n) + bt \quad (9)$$

wherein *a* is the constant of the Logarithmic and Midilli models (–); *b* is the constant of the Midilli model (1/min); *c* is the constant of the Logarithmic model (–); *n* is the constant of the Page and Midilli models (–) and *k* is first order constant of semi-empirical drying models (1/min).

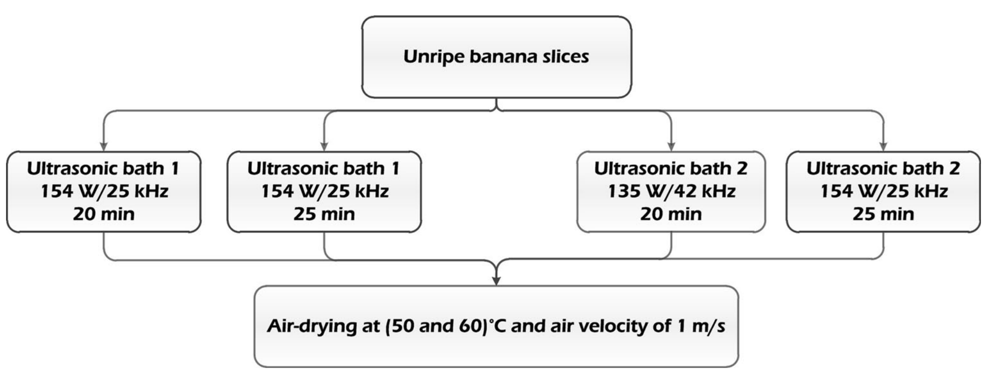

Fig. 1 Flow diagram of unripe banana slices drying experiments performed in a convective oven

Results and discussion

Unripe bananas presented (2.0 ± 0.7) °Brix, firmness values of (32.8 ± 4.1) N and initial moisture content of (2.69 ± 0.26) g H_2O/g on dry basis (d.b.) confirming that the fruit was in the first stage of maturation.

Ultrasonic volumetric power (P_{US})

The calculated ultrasonic volumetric power of the baths was (9.38 ± 0.60) W/L and (25.63 ± 1.24) W/L for the baths of 154 W/25 kHz and 135 W/42 kHz, respectively. The values correspond to the average of five determinations. Although each ultrasonic system has its own characteristics, similar ultrasonic volumetric power values have been reported in the literature in analogous conditions. Kek et al. (2013) obtained a P_{US} value close to 9 W/L with a bath operating at 25 kHz and 100 W, whereas Patero and Augusto (2015) and Yildirim et al. (2011) determined P_{US} of 26 and 25 W/L with baths operating at 40 kHz and 135 W, and 40 kHz and 100 W, respectively.

Ultrasound pre-treatment

The water gain of unripe banana slices is directly related to the immersion time as shown in Table 1. The unripe banana slices pretreated at 9.38 W/L of ultrasonic volumetric power presented higher *WG* values when compared to the slices pretreated at 25.63 W/L. According to the results herein, the lower frequency (25 kHz) and higher nominal power (154 W) favored *WG* in unripe banana slices, the same effect observed in guava slices pretreated for 60 min (Kek et al. 2013). Fernandes and Rodrigues (2007) pretreated ripe banana slices for 10, 20 and 30 min in an ultrasonic bath at 4870 W/m^2 and 25 kHz. According to the authors, slices pretreated for 20 min presented *WG* of 11.1 g H_2O/100 g, higher than those immersed for (10 and 30) min. Azoubel et al. (2010) observed a *WG* of 3.47 g H_2O/100 g for ripe bananas immersed for 20 min at 220 W and 25 kHz. The authors also observed an increase of water gain as a function of immersion time, corroborating the behavior observed herein.

Table 1 Water gain (*WG*) of unripe banana slices pretreated with ultrasound for (20 and 25) min at (9.38 and 25.63) W/L

US time (min)	*WG* (g H_2O/100 g)	
	9.38 (W/L)	25.63 (W/L)
0	0.00 ± 0.00	0.00 ± 0.00
20	6.40 ± 0.26	5.35 ± 0.48
25	7.54 ± 0.26	5.54 ± 0.44

Air-drying process

Water effective diffusivity (D_{eff}) values, calculated by applying Eq. (4), are presented in Table 2. The values obtained at 60 °C were higher when compared to those obtained at 50 °C for each pre-treatment condition, as expected. At 50 °C, ANOVA revealed statistical difference for slices pretreated for 20 and 25 min at 25.63 W/L in comparison to those untreated and pretreated at 9.38 W/L slices. At 60 °C, no statistical difference was observed for untreated and pretreated at 9.38 and 25.63 W/L slices. However, unripe banana slices pretreated for 20 min with US at 9.38 W/L and dried at 50 °C resulted in a 4.8% increase in water effective diffusivity compared to the untreated slices. Regarding the experiments performed at 60 °C, the increase of the water effective diffusivity in unripe banana slices pretreated for 25 min with US at 9.38 W/L was of 13.67% compared to the untreated slices. The increase in D_{eff} value due to US pre-treatment for ripe bananas was previously reported in the literature (Azoubel et al. 2010; Fernandes and Rodrigues 2007). However, US pre-treatment did not affect water effective diffusivity in pineapple, sapota and papaya (Rodrigues and Fernandes 2008); this indicates that the effect of US may be dependent on the structure of the fruit cell tissue. In the case of unripe banana slices, pretreatment with US at higher nominal power (154 W) and lower frequency (25 kHz) favored water diffusion, in comparison to pretreatment at lower nominal power (135 W) and higher frequency (40 kHz), the same effect observed in *WG* (Table 1). For the air-drying of apple pieces assisted with US, at the same frequency, the increase in the US power was observed to positively affect the D_{eff} (Santacatalina et al. 2016). Moreover, ultrasound pretreatment at (20 or 35) kHz of lotus (*Nelumbo nucifera Gaertn*) seeds remarkably accelerated the drying rate, thus increasing the value of D_{eff}. However, this positive influence was not observed for the ultrasonic pre-treatment at 80 kHz. The reason for this could be that D_{eff} decreased when the effect of cavitation is limited (Zhao et al. 2017). As the frequency of irradiation is increased, the rarefaction phase shortens, consequently resulting in a decrease of D_{eff} (Capelo et al. 2005).

The drying rates corresponding to these experiments are presented in Fig. 2. As observed in Fig. 2a and b, slices pretreated for 20 and 25 min at 25.63 W/L and dried at 50 °C resulted in visible lower rates of water removal, and, consequently, lower D_{eff} values (Table 2). The drying rates at 60 °C were similar for unripe and untreated banana slices and those pre-treated for 20 and 25 min (Fig. 2c, d). Higher temperatures overlap the effect of US pre-treatment (Ricce et al. 2016). Furthermore, at lower temperatures, US provides mechanical energy that complements the thermal energy provided by the air temperature and,

Table 2 Water effective diffusivity (D_{eff}), activation energy (E_a), drying time (t) to remove 70 g/100 g of the initial moisture based on Midilli model of unripe banana slices untreated and pretreated with US at (9.38 and 25.63) W/L submitted to air-drying at (50 and 60) °C

US time (min)	P_{US} (W/L)	$D_{eff} \times 10^{-10}$ (m²/s)		E_a (kJ/mol)	t (min)		X_f (g/100 g)	
		50 °C	60 °C		50 °C	60 °C	50 °C	60 °C
0	0	1.25 ± 0.12[a]	1.39 ± 0.27[a]	8.94 ± 0.04[b]	270	268	0.024 ± 0.004[a]	0.019 ± 0.005[a]
20	9.38	1.32 ± 0.06[a]	1.40 ± 0.09[a]	5.79 ± 0.13[a]	250	251	0.032 ± 0.016[a]	0.036 ± 0.028[a]
	25.63	0.77 ± 0.04[b]	1.24 ± 0.00[a]	40.51 ± 0.14[e]	470	288	0.297 ± 0.027[b]	0.042 ± 0.002[a]
25	9.38	1.21 ± 0.07[a]	1.59 ± 0.40[a]	23.63 ± 0.15[c]	287	243	0.037 ± 0.008[a]	0.027 ± 0.014[a]
	25.63	0.85 ± 0.04[b]	1.23 ± 0.01[a]	32.76 ± 0.12[d]	408	295	0.283 ± 0.003[b]	0.046 ± 0.002[a]
Tukey HSD[a]		0.16	0.50	0.32			0.036	0.034

The same lower case letters in the same column are not significantly different ($p > 0.05$)

[a]*HSD* honestly significant difference

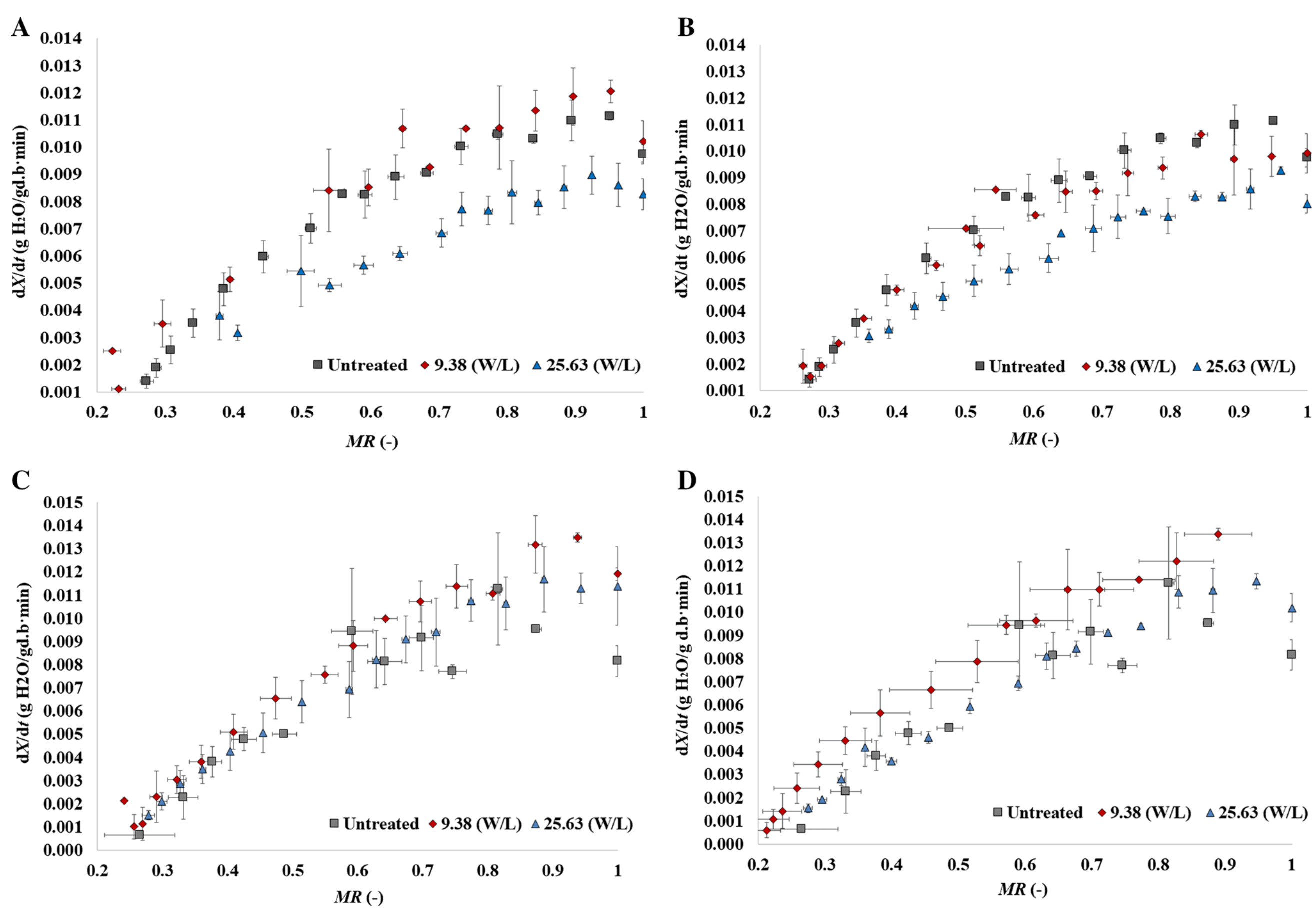

Fig. 2 Drying rates of unripe banana slices pre-treated with US at (9.38 and 25.63) W/L in comparison to those obtained for untreated slices: 20 min of US and air-drying at 50 °C (**a**); 25 min of US and air-drying at 50 °C (**b**); 20 min of US and air-drying at 60 °C (**c**); 25 min of US and air-drying at 60 °C (**d**)

jointly, these would contribute to the water transport. At higher temperatures, the thermal energy masks the effect linked to the mechanical energy provided by US. Therefore, the application of US to intensify the drying processes was more efficient at low temperature (Cárcel et al. 2014). Thus, US bath operational (i.e. P_{US}, frequency) and air-drying parameters (i.e. T, air velocity, relative humidity) must be accurately defined to achieve the desirable results.

Table 3 Constants and statistical parameters for the Midilli model obtained from adjusting the experimental data of unripe banana slices untreated and pretreated with US at (9.38 and 25.63) W/L submitted to air-drying at (50 and 60) °C

US time (min)	P_{US} (W/L)	T (°C)	k (1/min)	n (–)	a (–)	b (1/min)	r^2	RMSE	χ^2
0		50	0.0020 ± 0.0002[a]	1.21 ± 0.1[a]	0.9952 ± 0.0017[a]	0.0005 ± 0.0001[a]	0.9996	0.0105	0.00014
20	9.38		0.0016 ± 0.0009[a]	1.26 ± 0.13[a]	0.9911 ± 0.0103[a]	0.0003 ± 0.0000[a]	0.9990	0.0108	0.00014
	25.63		0.0024 ± 0.0004[a]	1.05 ± 0.06[a]	1.0011 ± 0.0032[a]	0.0001 ± 0.0002[a]	0.9998	0.0056	0.000004
25	9.38		0.0020 ± 0.0001[a]	1.19 ± 0.01[a]	0.9947 ± 0.0011[a]	0.0004 ± 0.0000[a]	0.9998	0.0044	0.00003
	25.63		0.0023 ± 0.0004[a]	1.09 ± 0.02[a]	1.0000 ± 0.0004[a]	0.0002 ± 0.0001[a]	0.9999	0.0873	0.00996
0		60	0.0047 ± 0.0023[a]	1.07 ± 0.11[a]	1.0050 ± 0.0121[a]	0.0004 ± 0.0002[a]	0.9989	0.0080	0.00009
20	9.38		0.0031 ± 0.0001[a]	1.13 ± 0.01[a]	0.9986 ± 0.0015[a]	0.0004 ± 0.0001[a]	0.9990	0.0077	0.00008
	25.63		0.0034 ± 0.0005[a]	1.09 ± 0.02[a]	1.0002 ± 0.0028[a]	0.0004 ± 0.0001[a]	0.9999	0.0067	0.00006
25	9.38		0.0072 ± 0.0061[a]	1.00 ± 0.16[a]	0.9896 ± 0.0083[a]	0.0003 ± 0.0002[a]	0.9988	0.0085	0.00010
	25.63		0.0033 ± 0.0000[a]	1.08 ± 0.00[a]	1.0014 ± 0.0002[a]	0.0004 ± 0.0001[a]	0.9999	0.0028	0.00001
Tukey HSD[a]			0.0083	0.31	0.0223	0.0005			

The same lower case letters in the same column are not significantly different ($p > 0.05$)

[a] *HSD* honestly significant difference

Activation energy

The activation energy (E_a) involved in air-drying unripe banana slices submitted to US pre-treatments at different volumetric power estimated from Eq. (5) are also presented in Table 2. Thermodynamically, E_a is the relative ease with which water molecules go through the energy hurdle when migrating within the product. Lower E_a values indicate higher moisture diffusivity during the drying process (Sharma and Prasad 2004). As displayed in Table 2, unripe banana slices pretreated for 20 min at 9.38 W/L require less energy to promote water removal. Decreases in internal diffusion resistance, leading to decreases in activation energy and increases in water effective diffusivity have also been observed during air-drying of *Bartlett* pears (Park et al. 2001). Unripe banana slices pretreated for 20 min at 25.63 W/L resulted in the lowest values of water effective diffusivity (Table 2) as discussed previously, thus, in the highest values of activation energy. Moreover, slices pretreated for 25 min at 9.38 and 25.63 W/L resulted with higher values of E_a, in comparison to the untreated ones. An explanation for this could be the *WG*, since, due to the higher water intake (Table 1), a higher amount of energy is required to remove this initial moisture content.

Time saving

Based on the Midilli model, for example, the drying time to remove 70 g/100 g of the initial moisture was calculated for slices pretreated with US in relation to the untreated ones. Results are presented in Table 2. For the air-drying process at 50 °C, the application of US pre-treatment at 9.38 W/L for 20 and 25 min decreased the drying time by 7 and 6%, respectively. At 60 °C, the drying time decrease reached (6 and 9)% for unripe banana slices also pretreated at 9.38 W/L for 20 and 25 min, respectively. As discussed previously, unripe banana slices pretreated for 20 and 25 min at 9.38 W/L and dried at 50 and 60 °C, respectively, resulted in an increase of D_{eff} value, in comparison to the untreated ones, consequently resulting in time saving, indicating that this would be an interesting option to process unripe banana slices. Nevertheless, slices pretreated for 20 and 25 min at 25.63 W/L and dried under both temperatures did not reduce the drying time.

Final moisture content (X_f)

Banana slices pretreated for (20 and 25) min at 25.63 W/L and dried at 50 °C resulted in higher final moisture content as shown in Table 2. ANOVA revealed statistically significant difference for those slices in comparison with untreated and pretreated at 9.38 W/L slices, and dried at the same temperature. However, for air-drying at 60 °C, no statistical difference was observed for untreated and pretreated at (9.38 and 25.63) W/L banana slices.

Mathematical modeling of experimental drying curves

All the experimental data were adjusted to the Newton, Page, Logarithmic and Midilli models, described in Eqs. (6) to (9). The best mathematical model was chosen based on maximized r^2 and minimized RMSE and χ^2. The four models presented a good r^2, with values > 0.9901 for experiments performed at 50 and 60 °C (data not shown). However, the lowest RMSE and χ^2 values were observed

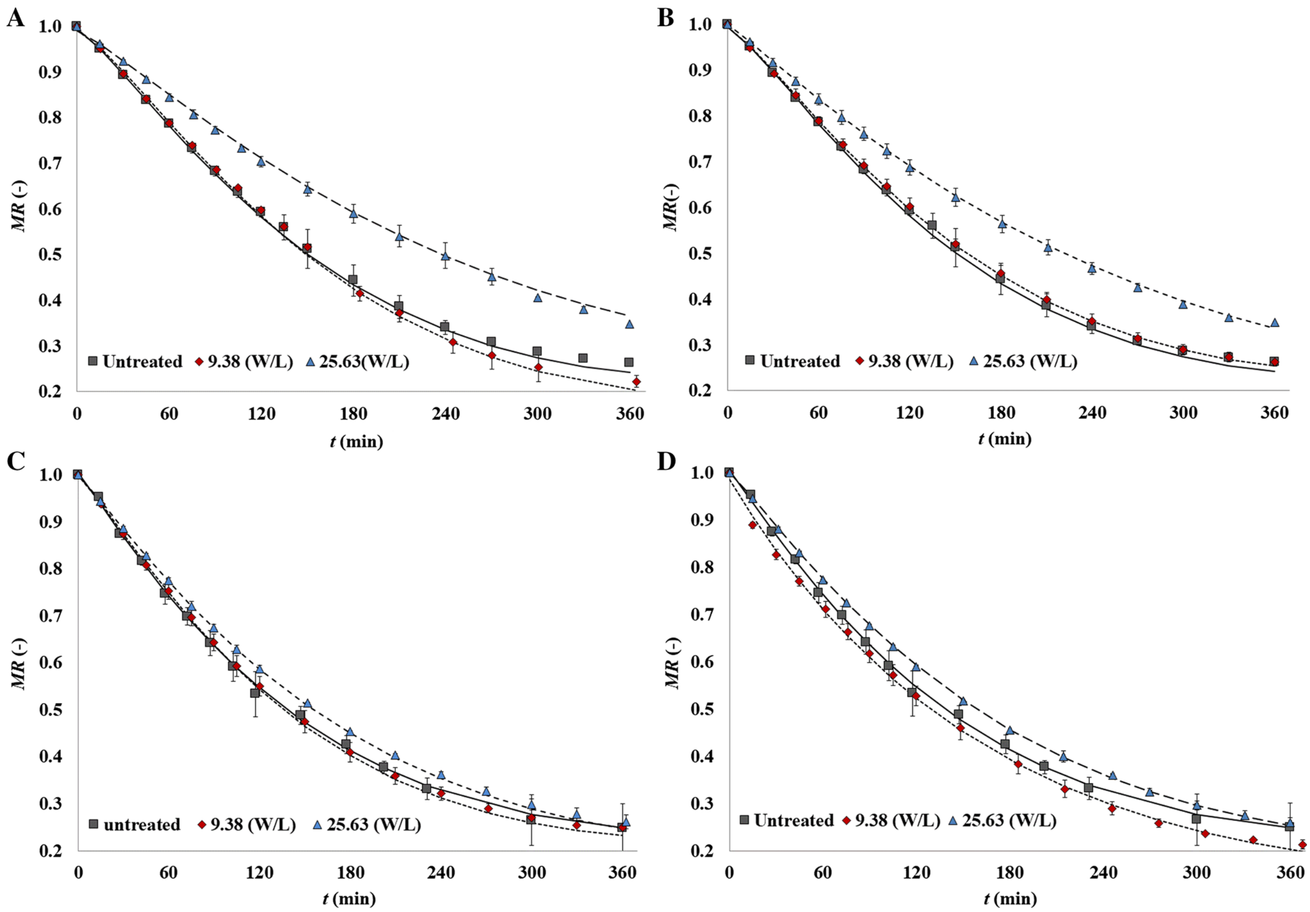

Fig. 3 Experimental and predicted from Midilli model drying curves of unripe banana slices pretreated with US at (9.38 and 25.63) W/L in comparison with those obtained for untreated banana slices: 20 min of US and air-drying at 50 °C (**a**); 25 min of US and air-drying at 50 °C (**b**); 20 min of US and air-drying at 60 °C (**c**); 25 min of US and air-drying at 60 °C (**d**)

for the model with the greatest number of terms. Thus, the best fit obtained between the experimental data and the predictive values was the Midilli model, resulting in r^2 value > 0.9988, RMSE < 0.0873 and $\chi^2 < 0.00996$ (Table 3). Good adjustment applying the Midilli model had also been observed previously for apple, red bell pepper (Schössler et al. 2012a) and potato (Schössler et al. 2012b). The experimental data and the predicted values according to the Midilli model for untreated unripe banana slices and pretreated with US at 9.38 and 25.63 W/L and dried at (50 and 60) °C are shown in Fig. 3.

Conclusion

Results indicated that unripe banana slices pretreated with US at 9.38 and 25.63 W/L gained water. Slices pretreated at 25.63 W/L for 20 and 25 min and dried at 50 and 60 °C, no increase in water effective diffusivity. However, increases in D_{eff} of 4.8 and 13.67% were observed for ultrasound application at 9.38 W/L for 20 min + air-drying at 50 °C and 25 min of US + air-drying at 60 °C, respectively. Thus, decrease in drying time were achieved by applying this technology. Moreover, slices pretreated for 25 min led to higher activation energy, probably due to the higher water intake during the US pre-treatment. Therefore, as demonstrated herein, P_{US} was an important variable to be determined to achieve desirable results. Mathematical modeling of the drying curves indicated that the best model to fit the data was the Midilli model.

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