Influence of applied time and power of ultrasonic pretreatment on convective drying of potato slices

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Abstract Ultrasound is a novel technology that can be applied as a pretreatment for the convective drying in order to reduce its undeniable shortcomings. The objectives of the present study are to ascertain the influence of sonication time (10, 20, and 30 min) and sonication power (100 and 300 W) on the performance of drying potato slices with regard to the drying kinetics and energy efficiency as well as the final product quality. The results showed that the application of ultrasound pretreatments significantly increased the drying rate of potato slices during the initial period of the drying process. Furthermore, ANOVA showed that the decrease in the sonication time and power gave rise to a significant reduction in drying time, specific energy consumption (SEC), and shear strength. In addition, compared to the control (pure convective drying), ultrasound pretreatments reduced the drying time, SEC, and the shear strength of dried potato slices.

Keywords Ultrasonic pretreatment · Convective drying · Drying kinetics · Energy efficiency · Quality attributes

Introduction

Foods tend to deteriorate microbiologically and chemically during storage because of their high water activity. Therefore, numerous preservation methods have been developed to extend their shelf life since ancient times (Başlar et al., 2014). Among these methods, drying is one of the earliest food preservation methods practiced by human (Taghian Dinani and Havet, 2015). The main purpose of drying is to prolong the shelf life of the foodstuff under ambient temperatures by its reducing water activity, controlling microbiological stability, and decreasing chemical reactions (Rodríguez et al., 2014). In addition, it is favorable to decrease the packaging, storage, and transportation costs by considerably reducing the volume and weight of the product (Taghian Dinani and Havet, 2015).

Owing to its simplicity and easiness of control, convective drying is the most widespread drying technique for foodstuff over many decades (Sledz et al., 2017). In this connection, the most commonly-addressed drying technique, convective drying, is the most energy-intensive industrial operation (Gamboa-Santos et al., 2014) because its drying rate is quite low (Bantle and Eikevik, 2014). It is estimated that the thermal drying processes account for up to 25% of industrial energy consumption in developed countries (Gamboa-Santos et al., 2014). In addition, it adversely affects the quality factors of the final product such as its color, texture, and rehydration ability (Başlar et al., 2014). The mentioned limitations of convective drying method could be partially overcome by coupling additional energy sources such as ultrasound (Gamboa-Santos et al., 2014) as a pretreatment prior to drying different foodstuffs.

Ultrasound is a mechanical and cyclic sound wave with the frequency range of 20 kHz to 1 MHz, which is above

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the threshold of the human ear. The frequency range of 20–40 kHz is generally applied in ultrasonic-assisted convective drying (Bantle and Eikevik, 2014). Because ultrasonic waves are easily transmitted through liquids (Taylor et al., 2014), ultrasonic pretreatment includes the immersion of sample in water or in hypertonic aqueous solutions to which ultrasound is applied (He et al., 2016). The application of ultrasound in a liquid medium as a pretreatment can lead to the creation of thousands of gaseous cavitation bubbles. Imploding bubbles causes surface tension, viscosity variation, local heating, pressure changes, elongation and flattening of the cells (Sledz et al., 2017), and alterations to porous solid material (de la Fuente-Blanco et al., 2006). In fact, ultrasound waves induce a rapid series of compression and rarefactions in elastic materials (a phenomenon called the “sponge effect”) leading to more water release (Garcia-Perez et al., 2013) due to the formation of microscopic channels in the cells and leakage of intracellular liquid into extracellular surroundings (Nowacka et al., 2012). These mechanical processes and changes may affect the diffusion boundary layer (Fernandes et al., 2008) and enhance the moisture removal caused by phenomena of diffusion, capillary flow in small pores, and pressure gradients (Schössler et al., 2012).

In this study, potato, as a functional food ingredient and the fourth main vegetable crop for human nutrition in the world, was chosen for drying through applying ultrasound pretreatment. It is of note that 12% of this crop is dehydrated (Aghbashlo et al., 2009). To the best of our knowledge, there have been no previous studies regarding the influences and interactions of sonication time and power parameters on the convective drying of potato slices. Therefore, the general objective of this study is to investigate the effect of three levels of sonication time (10, 20, and 30 min) and two levels of power (100 and 300 W) on drying kinetics, drying time, specific energy consumption (SEC), porosity, shear strength, and water absorbing capacity (WAC) of the dried potato slices. To obtain this goal, ultrasound was used as a pretreatment prior to convective drying of potato slices.

Materials and methods

Sample preparation

Fresh potatoes (*Solanum tuberosum*) with uniform size and color and free from defects were bought from a local supermarket in Isfahan, Iran. To perform the whole experiments, potatoes were washed with running water so that their external impurities would be removed. The potatoes were manually peeled and sliced to the thickness of 6-mm using a food slicer (model Delmonti DL 610,

Italy). To avoid undesirable enzymatic reactions and to improve the structural properties, potato slices were blanched for 11 min in boiling water. After blanching, the hot-water-treated slices were immediately cooled to the room temperature by cold tap water. Then, they were blotted with a filter towel and were subjected to sonication.

Sonication pretreatment

All experiments with sonication pretreatment were performed in the ultrasonic equipment (TOPSONICS, Ultrasonic Technology Development Company, Tehran, Iran), shown in Fig. 1A. The ultrasonic device consists mainly of a piezoelectric composite transducer working at a frequency of 20 kHz with a power capacity of 400 W generated by a power generator system. For each ultrasonic treatment, 200 g of blanched potato slices were placed in a 1000 mL Erlenmeyer flask containing 800 mL of distilled water at the ambient temperature of 25 °C and the ratio of water to potato slices was maintained at 4:1 (weight basis) as recommended by Fernandes and Rodrigues (2007). The filled Erlenmeyer flask was placed in the cabinet of the ultrasonic system, and the ultrasonic probe was submerged in water with a depth of 1–2 cm. The ultrasonic mode was 5 s on and 5 s off, and samples were exposed to ultrasonic waves for 10, 20, and 30 min with two ultrasonic power levels of 100 and 300 W. Having completed the set time, the ultrasound equipment was turned off, followed by collecting the potato slices and blotting them with filter paper. Then, 22 potato slices with an average slice diameter of 6 cm were spread on two perforated metallic plates (20 × 20 cm²) of convective dryer shown in Fig. 1B in a single layer, and were subjected to the convective drying process.

Convective drying

Drying experiments of potato slices were carried out both with and without the application of ultrasound pretreatment (control treatment). In both cases, convective drying was carried out at the constant temperature of 70 °C and at the air velocity of 2.0 m/s in a laboratory scale convective dryer (Isfahan, Iran) shown in Fig. 1B. Before each treatment, the dryer was turned on to reach the desired temperature set point. Then, two perforated metallic plates containing potato slices were placed inside the drying chamber. During the drying process, the weight reduction of the slices was determined continuously with 15 min intervals using a digital balance (Kern, Germany with the accuracy of 0.01 g). In addition, an anemometer (TES 1341, Electrical Electronic Corp. Taipei, Taiwan) was used to measure the air velocity, the air humidity, and the dry bulb temperature. The drying process was performed until

Fig. 1 (A) Schematic illustration of ultrasonic system (1: ultrasonic transducer, 2: ultrasonic horn and tip, and 3: Erlenmeyer flask containing potato slices and distilled water) and (B) a schematic

illustration of convective dryer (4: power supply and control panel, 5: anemometer, 6: balance, 7: two perforated metallic plates and potato slices, 8: electric heater, and 9: fan)

the potato slices reached a constant weight. In addition, the quality attributes were measured at the end of each drying experiment. All the drying processes were carried out in triplicate.

Procedures

Determination of moisture content

The moisture content of potato slices was gravimetrically calculated before and after each drying experiment through the hot air oven (ALFA INC 55) at the temperature of 70 °C until a constant weight was obtained. The moisture content (MC) based on a dry basis (kg water/kg dry matter) was calculated from Eq. (1) (Taghian Dinani et al., 2014a):

$$MC = \frac{W_0 - W_d}{W_d} \quad (1)$$

where W_0 is the initial weight of the sample (kg) and W_d is the weight of the dried sample (kg).

The moisture ratio and drying rate

The dimensionless moisture ratio (MR) of potato slices was calculated from Eq. (2) (Taghian Dinani et al., 2014a):

$$MR = \frac{MC_t}{MC_0} \quad (2)$$

where MC_t is the moisture content of potato slices at any time of drying and MC_0 stands for the initial moisture content of potato slices. Furthermore, the drying rate (DR) was defined as the moisture content (dry basis) change per

unit time (kg water/(kg dry matter min)) using Eq. (3) (Taghian Dinani et al., 2014b):

$$DR = - \frac{MC_t - MC_{t+\Delta t}}{\Delta t} \quad (3)$$

where MC_t and $MC_{t+\Delta t}$ are moisture contents based on a dry basis (kg water/kg dry matter) at t and $t + \Delta t$, respectively, and Δt is the time difference (min). Drying rate (DR) curves versus moisture ratio parameter were plotted based on the measurements of weight losses of the potato slices during the drying process and their initial moisture content (Nowacka et al., 2012).

Specific energy consumption (SEC)

In this paper, SEC (kWh/kg) for all the drying treatments was calculated using Eq. (4)

$$SEC = \frac{P \cdot t}{W_i - W_f} + \frac{A \cdot v \cdot \rho_a \cdot C_a \cdot \Delta T \cdot t}{W_i - W_f} \quad (4)$$

In the left side of the Eq. (4), P is the applied electrical power (kW) and t is time (h) of the ultrasonic pretreatment. In the right side, A is the area of the sample container in convective drier (m^2), v is the velocity of air (m/s), ρ_a is the air density (kg/m^3), C_a is the specific heat of air ($kJ/kg \text{ } ^\circ C$), t is time (h) of convective drying process, and ΔT is the temperature difference ($^\circ C$). Finally, W_i and W_f are the weights of the potato slices before and after drying (kg), respectively. Therefore, " $W_i - W_f$ " is the evaporated water weight (kg) of the potato slices. In fact, SEC was calculated by adding the specific energy consumption of the convective dryer (the right term of Eq. 4) (Taghian Dinani and Havet, 2015) to the specific energy consumption of the

ultrasound system (the left term of Eq. 4) (Abramov et al., 2009).

Porosity

The accurate weight (W) and the apparent volume (V_a) of the dried potato slices were measured. The apparent volume was calculated by the displacement method, in which a volumetric pycnometer, an analytical balance, and distilled water as the reference liquid were used. This method allows calculating the apparent density by equation $\rho_a = W/V_a$ (Taghian Dinani and Havet, 2015). Moreover, the calculation of solid density was performed by applying Eq. (5):

$$\rho_s = \frac{1 + MC}{\frac{1}{1480} + \frac{MC}{1020}} \quad (5)$$

where ρ_s is the solid density and MC is the moisture content (kg water/kg dry matter) of the dried potato slices (Srikiatden and Roberts, 2008). Porosity, which represents the ratio between the air volume in the sample and its total volume (Ozuna et al., 2014b), was calculated using Eq. (6):

$$P = \frac{\rho_s - \rho_a}{\rho_s} \quad (6)$$

where P is the porosity (%) and ρ_a and ρ_s are the apparent and solid densities (kg/m^3), respectively (Taghian Dinani and Havet, 2015). The average value of the porosity for the three repetitions was calculated for each of the drying treatments.

Shear strength

The texture of the dried potato slices was measured by shear strength test using an Instron universal testing machine (Model DBBP, Bongshin, China) with a 6-mm flat cylindrical probe at the room temperature of 25 °C. The probe was moving at a speed of 100 mm/min and the shear strength was calculated by making one puncture in each slice according to Eq. (7) (Taghian Dinani and Havet, 2015):

$$SS = \frac{F}{\pi DL} \quad (7)$$

where SS is the shear strength (N/m^2), F is the maximum resistance force (N), D is the diameter of the probe (m), and L is the slice thickness (m). The mean value of the shear strength of at least five measurements was used for each treatment.

Water absorbing capacity (WAC)

For WAC, the dried potato slices were weighed and immersed in beakers containing 500 mL distilled water. The beakers were placed in a water bath (Shimifan, Tehran, Iran) and rehydration was carried out at 50 °C for 1 h. Then, the samples were separated from water, blotted with a tissue paper, and weighed. Finally, they were dried in the oven to determine the dry matter content (%). WAC was calculated from Eq. (8) (Taghian Dinani et al., 2015):

$$WAC = \frac{W_r(100 - S_r) - W_d(100 - S_d)}{W_0(100 - S_0) - W_d(100 - S_d)} \quad (8)$$

where W is the sample weight (g), S is the dry matter content (%), and the subscripts d, 0, and r refer to dried, before drying, and rehydrated modes, respectively. WAC is in the range of 0–1. The more the water absorption capacity is lost during drying, the smaller the WAC index will be (Lewicki, 1998). Three repetitions were performed for each treatment, and the mean values were calculated.

Browning index (BI)

The color of potato slices was expressed in units of L (blackness/whiteness), a [redness (+)/greenness (–)], and b [yellowness (+)/blueness (–)] (Ozuna et al., 2014a) using a chromameter (TES 135 A, Taipei, Taiwan). To describe the color change during drying, the browning index between the undried (BI_i) and dried (BI_d) potato slices were calculated from Eq. (9) (Taghian Dinani and Havet, 2015):

$$BI = \frac{100}{0.17} \left(\frac{a + 1.75L}{5.645L + a - 3.012b} - 0.31 \right) \quad (9)$$

In this study, the browning index difference (ΔBI or $BI_i - BI_d$) of potato slices is reported.

Statistical analysis

A Factorial Experiment in a Randomized Complete Block Design (RCBD) with two independent variables of sonication time (at three levels of 10, 20, and 30 min) and sonication power (at two levels of 100 and 300 W) was used to evaluate the effects of sonication time, power, and their interactions on the dependent variables of the drying time, SEC, porosity, shear strength, and WAC parameters. Additionally, Complete Randomized Design (CRD) was used to compare the control treatment (convective treatment without ultrasonic pretreatment) with six convective drying treatments having different ultrasound pretreatments (100 W–10 min, 100 W–20 min, 100 W–30 min, 300 W–10 min, 300 W–20 min, and 300 W–30 min). An analysis of variance (ANOVA) was performed using the General

Linear Model procedure (GLM) of the SPSS software, version 20 (IBM Corporation, New York, USA). For both statistical methods, individual group differences were identified using the Duncan's New Multiple Range Test at 95% confidence level ($p \leq 0.05$). Finally, the results were presented as the mean $\pm$ standard deviation (SD).

Results and discussion

Drying rate

The experimental drying rate data for potato slices in a convective drying system with and without (control) the ultrasound pretreatment [at three levels of sonication time (10, 20, and 30 min) and two levels of sonication power (100 W and 300 W)] were graphically analyzed in term of the reduction in moisture ratio (Fig. 2A). As shown in Fig. 2A, all the plots experience the falling rate period from the starting time of the drying process to a period of time afterward (Taghian Dinani et al., 2014b). Additionally, in the very beginning of the process (approximately the first 50 min), the drying rates of the ultrasound pretreated potato slices for all sonication times and powers were faster than those of the control treatment. Therefore, ultrasound pretreatment applied to potato slices resulted in an intensification of water evaporation. This result is in agreement with the findings of Jambrak et al. (2007) who reported that after using ultrasound treatment, the drying rates of mushrooms, Brussels sprouts, and cauliflower increased compared to the drying rates of the untreated samples.

Figure 2 also displays that the efficiency of drying processes with ultrasound pretreatment decreased toward the end of the process. Furthermore, like most drying techniques, ultrasound displayed its highest potential to enhance the drying rate at the beginning of the drying process, when the drying rate was already high, and the drying process was controlled by diffusion or internal mass transport mechanisms (Nowacka et al., 2012). In other words, the potato slices had a considerable moisture content at the beginning of the process, and thus the moisture diffusion rate was the highest at the beginning of the drying process. Nevertheless, as the drying process continues, the moisture content of the potato slices decreases, moisture diffusion from inside the potato slices to their surfaces and to the air decreases (Sabarez et al., 2012) and, therefore, drying rate declines. Similarly, Bantle and Eikevik (2014) reported that the drying rate for ultrasonic drying was mostly improved during the initial period of the drying process while its effect was insignificant toward the end of the process.

Drying time

Reducing the drying time is of great necessity for foods having thermolabile substances (Chen et al., 2016). Figure 2B compares the mean values of the drying time of the dried potato slices obtained by CRD statistical analysis method. The figure shows that the treatments had an obvious impact on the drying time of the dried potato slices ($p \leq 0.05$). As shown in Fig. 2B, the potato slices dried by 100 W–10 min and those dried by control treatments showed the lowest and the highest drying time, respectively. Moreover, the time values for the mentioned drying treatments were significantly different from those for all of the other treatments. Generally, it could be observed that the convective drying assisted by all ultrasonic pretreatments was faster than the control treatment. For such a drying process, the reduction of the drying time can be observed at least by 19.58% for 300 W–30 min (193.00 ± 3.00 min) and at most by 38.47% for 100 W–10 min (147.67 ± 2.52 min) compared to that for the control treatment (240.0 ± 0.00 min). The ultrasound pretreatment improved the drying rate due to the creation of microchannels in the sample. At such condition, the mass transfer rate and moisture diffusion from sample inside to its surface increased during convective drying and, consequently, it dries faster in comparison to control treatment (without ultrasonic pretreatment). These findings are in agreement with the results reported by other researchers. For instance, it was reported that sonication application led to a shortening of the drying time from 11 to 56% for parsley leaves (Śledź et al., 2014), from 18.2 to 20.0% for basil (Śledź et al., 2017), 31 to 40% for apple cubes (Nowacka et al., 2012), and by 32% for cassava cubes (Ozuna et al., 2014b).

One-way ANOVA results indicated that the sonication time ($p \leq 0.001$), power ($p \leq 0.001$), and the interaction of the sonication time and power ($p \leq 0.05$) significantly affected the drying time of potato slices. The results confirm that the ultrasonic pretreatment at the low levels of sonication time and power had a major effect on reducing the drying time: the higher the time and power of ultrasonic pretreatment, the milder the effect (Tables 1 and 2, respectively). The convective drying time of the dried potato slices at 10 min ultrasonic duration was significantly less than that at 30 min ultrasonic time ($p \leq 0.001$), but there was no statistically significant difference ($p > 0.05$) in the mean values of the drying time of 10, and 20 min ultrasonic duration (Table 1). A 16.76% and 15.90% increase in the drying time of the potato slices pretreated at 30 min (183.50 ± 10.87 min) compared to the drying time of those pretreated at 10 and 20 min (157.16 ± 10.57 min and 158.33 ± 6.43 min, respectively) was calculated, respectively. Severe ultrasonic pretreatment at high

Fig. 2 (A) Variation of drying rate against moisture ratio of potato slices at different drying treatments and (B) effect of different drying treatments on specific energy consumption (SEC) and drying time of potato slices. Data are shown as the mean $\pm$ SD in (B). For each response in (B), means (shown with different lower case letters) are significantly different ($p \leq 0.05$)

Table 1 Effect of sonication time on measured responses of drying the potato slices

Sonication time (min)	Responses					
	Drying time (min)	SEC (kWh/kg)	Porosity (%)	Shear strength (N/m ²)	WAC	Δ BI
10	157.16 $\pm$ 10.57 ^b	52.19 $\pm$ 6.16 ^b	60.09 $\pm$ 4.30 ^a	31.48 $\pm$ 6.74 ^b	0.46 $\pm$ 0.09 ^a	52.68 $\pm$ 5.48 ^b
20	158.33 $\pm$ 6.43 ^b	53.49 $\pm$ 2.99 ^b	58.77 $\pm$ 1.71 ^{ab}	35.49 $\pm$ 6.03 ^{ab}	0.36 $\pm$ 0.03 ^b	71.04 $\pm$ 10.99 ^b
30	183.50 $\pm$ 10.87 ^a	61.73 $\pm$ 6.97 ^a	54.58 $\pm$ 3.92 ^b	38.85 $\pm$ 5.10 ^a	0.29 $\pm$ 0.04 ^b	119.43 $\pm$ 21.00 ^a

Data are shown as the mean $\pm$ standard deviation (SD). For each response in this table, means in each column not sharing the same lowercase letters are significantly different ($p \leq 0.05$)

Table 2 Effect of sonication power on measured responses of drying the potato slices

Sonication power (W)	Responses					
	Drying time (min)	SEC (kWh/kg)	Porosity (%)	Shear strength (N/m ²)	WAC	ABI
100	158.11 ± 12.4 ^b	51.41 ± 4.68 ^b	59.12 ± 3.02 ^a	30.63 ± 4.88 ^b	0.39 ± 0.11 ^a	82.52 ± 32.31 ^a
300	174.5 ± 13.99 ^a	60.19 ± 5.87 ^a	56.50 ± 4.74 ^a	39.92 ± 3.93 ^a	0.34 ± 0.05 ^a	79.59 ± 33.23 ^a

Data are shown as the mean ± standard deviation (SD). For each response in this table, means in each column not sharing the same lowercase letters are significantly different ($p \leq 0.05$)

sonication time and power can damage the tissue of the product. It was reported that longer sonication pretreatment time led to the greater destruction of structure and to more collapses of the sample (He et al., 2016). Similar results were obtained by Śledź et al. (2014) who reported that sonication of parsley leaves reduced the drying time by around 56% for 20 min. However, when treatment was prolonged to 30 min, the decrease in the drying time equaled only 11%. Thus, drying time for these cases decreased with a decrease in the ultrasonic pretreatment time. However, it is worth emphasizing that the effect of ultrasound treatment is not similar to various types of raw materials (Fernandes and Rodrigues, 2008a). For instance, the Sapota fruits exposed to 30 min of ultrasonic pretreatment dried faster than those pretreated for 10 min (Fernandes and Rodrigues, 2008b). However, drying of pineapples was faster after 20 min of ultrasound application than after 10 and 30 min of ultrasound application (Fernandes and Rodrigues, 2008a).

The results in Table 2 indicate that the drying time of the potato slices pretreated at 300 W power was significantly ($p \leq 0.001$) more than that of the potato slices pretreated at 100 W. A 10.37% increase in the drying time of 300 W, compared to that of potato slices treated at 100 W, was calculated. However, the drying time of Brussels sprouts (Jambrak et al., 2007), apple (Santacatalina et al., 2016), and eggplant cylinders reduced dramatically with an increase in sonication power. It is noteworthy that these differences can be greatly attributed to the differences in power intensities and samples. For instance, power ultrasound was tested at 45 and 90 W for drying the eggplant cylinders (Bantle and Eikevik, 2014); these power levels are less than the minimum ultrasonic power level (100 W) in this study.

Specific energy consumption (SEC)

The energy consumption is the controlling cost factor in drying systems (Bantle and Eikevik, 2014). According to Fig. 2B, the mean values of SEC for drying of potato slices were significantly affected by treatments ($p \leq 0.001$). The

SEC necessary for achieving constant moisture content for drying the potato slices ranged from 46.77 ± 0.90 kWh/kg for 100 W–10 min treatment to 67.54 ± 3.04 kWh/kg for the control treatment. The SEC of the ultrasound-pretreated samples is greatly reduced compared to that of the control samples; however, the SEC value for control treatment was not significantly higher than that for 300 W–30 min treatment. In addition, the SEC value for 100 W–10 min treatment was not significantly lower than that for 100 W–20 min treatment. The SEC can be reduced at most by 30.75% for 100 W–10 min (46.77 ± 0.90 kWh/kg) in comparison to that for the control treatment. Sledz et al. (2016) reported that ultrasound applied for parsley, at 21 kHz and 300 W, contributed to a significant decrease in the energy costs maximally by 33.6% in comparison to the energy costs for untreated samples. This paper is in good agreement with our study regarding the maximum energy saving of the drying process by ultrasound application. It can be concluded that SEC data coincide with drying time changes for different treatments (Fig. 2B) and for different sonication time and power levels (Tables 1 and 2). As the drying time increases, the dryer is on for a longer time resulting in more electrical energy consumption by the convective system. The energy saving of the drying process caused by the drying time reduction was reported by Chen et al. (2016) as well.

Results show that the SEC values were significantly influenced by the power and sonication time ($p \leq 0.001$), whereas the interaction of the power and sonication time was not significant ($p > 0.05$). Decreasing the power and sonication time decreased the SEC because drying time [t in the right term of Eq. (4)] was decreased. The SEC of 10 min was significantly ($p \leq 0.001$) lower than that of 30 min (Table 1) and the SEC of 100 W was significantly ($p \leq 0.001$) lower than that of 300 W (Table 2). There were 15.45% and 13.35% reductions in the SEC of 10 and 20 min, respectively, compared to that of 30 min (Table 1). Furthermore, there was a 14.59% decrease in the SEC of 100 W in comparison to that of 300 W (Table 2). When ultrasonic pretreatment time (t) and power (P) of the left term of Eq. (4) decrease, the numerator of the left term

declines and thus the SEC reduces. Similarly, Garcia-Perez et al. (2013) reported that the experiments with ultrasound application were more energy-efficient for grape stalk drying at a lower power level (45 W) than at those at a higher power level (90 W). However, in another study, it was reported that the energy efficiency for orange peel was higher when the ultrasound process was applied at 90 W than when it was applied at 45 W (Garcia-Perez et al., 2012). Consequently, the most suitable ultrasonic power level is dependent on the product and it may differ with regard to energy issues (Garcia-Perez et al., 2013).

Porosity

Porosity is a crucial parameter in food processing because it determines the porous portion and the degree of compactness in the food (Ozuna et al., 2014b). The results of the CRD statistical analysis presented in Fig. 3A show that the porosity response of the dried potato slices was not significantly affected by the treatments and the porosity value for control treatment ($55.42 \pm 9.10\%$) was not significantly different from that for all of the drying treatments with various ultrasound pretreatments ($p > 0.05$). The results obtained based on the factorial statistical analysis technique show that the porosity values were significantly influenced by the sonication time ($p \leq 0.05$), whereas the effect of the sonication power and the interaction of sonication time and power on the porosity values were not statistically significant ($p > 0.05$). Table 1 demonstrates that the porosity of dried potato slices has an inverse relationship with sonication time. In other words, the porosity of dried potato slices pretreated at 10 min sonication ($60.09 \pm 4.30\%$) was significantly ($p \leq 0.05$) greater than those pretreated at 30 min sonication ($54.58 \pm 3.92\%$), but there was no significant difference between those pretreated at 10 and 20 min sonication. There was a 2.20% and 9.17% reduction in the porosity of dried potato slices pretreated at 20 and 30 min sonication, respectively, compared to those pretreated with 10 min sonication. The higher porosity of dried potato slices pretreated with ultrasound for 10 min can be related to their shorter drying time (Table 1) (Nowacka et al., 2012). It was reported that longer ultrasound pretreatment times led to the greater destruction of material structure and to more collapses (He et al., 2016). This result is in accordance with our study. In fact, fast drying obtained at a low sonication time (Table 1) or power (Table 2) resulted in a mechanical stabilization of the surface and in the production of more porosity in the samples (Taghian Dinani and Havet, 2015).

Table 2 shows that although there was an insignificant difference in the mean values of the porosity response of two levels of sonication power ($p > 0.05$), 100 W power level resulted in more porosity than 300 W did. Puig et al.

(2012) reported that the ultrasonic waves applied at the highest level of power (90 W) induced an excessive compaction of the internal tissue. This result is in accordance with those of us. The ultrasonic power at the higher levels led to more compressions of the samples, inducing less porosity. Therefore, it can be concluded that the application of too much sonication time and power could decrease the porosity of the dried samples.

Shear strength

The hardness of the dried potato slices was evaluated by computing their shear strength. It is obvious from the data in Fig. 3A that various drying specimens had an evident impact on the shear strength of the dried potato slices ($p \leq 0.001$). As shown in Fig. 3A, the shear strength of the potato slices dried by 100 W–10 min treatment was the lowest one ($337.31 \pm 23.62 \text{ kN/m}^2$), but that of the potatoes dried by control treatment was the highest ($1089.88 \pm 73.16 \text{ kN/m}^2$). The results indicate that the shear strength value for control treatment was significantly different from that for all other treatments, whereas the shear strength value for 100 W–10 min treatment was significantly lower than that for all drying specimens, except for the 100 W–20 min treatment (Fig. 3A). In fact, a more reduction in drying time (Fig. 2B) and a more porous structure of the potato slices pretreated at 100 W–10 min (Fig. 3A) explain their lower degree of hardness.

One-way ANOVA shows that the power ($p \leq 0.001$) and sonication time ($p \leq 0.01$) affected the shear strength of the potato slices significantly; whereas, the effect of the interaction among these factors on the shear strength values was not statistically significant ($p > 0.05$). The results confirm that the shear strength of dried potato slices increases as the sonication time and power increase (Tables 1 and 2, respectively). The results of Table 1 indicate that the shear strength of the dried potato slices pretreated at 30 min sonication time was significantly ($p \leq 0.01$) more than that of those pretreated at 10 min. A 23.41% increase in the shear strength of the potato slices pretreated at 30 min, in comparison to that of the potato slices pretreated at 10 min, was calculated. Generally, acoustic stress caused the reduction in the hardness of the samples, but high sonication time and power levels produced a greater degradation of the sample structure. This phenomenon could mask the ultrasonic effects on drying time reduction (Santacatalina et al., 2016). Table 2 shows that the shear strength of the dried potato slices pretreated at 100 W was significantly less than that of those pretreated at 300 W ($p \leq 0.001$). A 30.33% increase in the shear strength of the potato slices pretreated at 300 W was calculated compared to the shear strength of those pretreated at 100 W. This result is consistent with those obtained by

Fig. 3 Effect of different drying treatments (A) on shear strength and porosity of dried potato slices and (B) on WAC of dried potato slices. Data are shown as the mean $\pm$ SD. For each response, means (shown with different lower case letters) are significantly different ($p \leq 0.05$)

Ozuna et al. (2014b) and Taghian Dinani et al. (2015), who reported that the softer the products (less shear strength) have a more porous structure.

Water absorbing capacity (WAC)

Dried products can be directly consumed or rehydrated before use. Because drying causes the permanent changes in the structure of the dried samples, the capacity of the water absorption declines considerably (Nowacka et al., 2012). The results obtained by CRD statistical analysis

method (Fig. 3B) show that WAC of dried potato slices was significantly affected by treatments ($p \leq 0.001$). This figure shows that the WAC for the dried potato slices ranged from 0.29 ± 0.02 for 300 W–30 min to 0.51 ± 0.10 for 100 W–10 min treatments. The results indicate that the WAC value for 300 W–30 min treatment was not significantly different from those for 100 W–20 min, 100 W–30 min, and 300 W–20 min, and the WAC value for 100 W–10 min was significantly different from those for all of the other treatments, except for the control treatment.

Fig. 4 Effect of different drying treatments on Δ BI of dried potato slices. Data are shown as the mean $\pm$ SD. Means (shown with different lower case letters) are significantly different ($p \leq 0.05$)

The results obtained by the factorial statistical analysis method show that the WAC values were significantly influenced by the sonication time ($p \leq 0.001$). However, the effect of the sonication power and the interaction of sonication time and power on the WAC values were not statistically significant ($p > 0.05$). An increase in the sonication time resulted in the declined WAC of the dried potato slices. WAC of the dried potato slices pretreated at 10 min sonication was significantly ($p \leq 0.001$) more than WAC of those pretreated at 20 and 30 min sonication, but there was no significant difference ($p > 0.05$) between WAC values of dried potato slices pretreated at 20 and 30 min sonication times. In comparison to WAC of the dried potato slices pretreated at 10 min sonication time (0.46 ± 0.09), a 21.74% and 36.96% decrease was calculated in WAC of dried potato slices pretreated at 20 min (0.36 ± 0.03) and 30 min (0.29 ± 0.04) sonication times, respectively. Their less ability to rehydrate can be attributed to the harder texture of the dried potato slices pretreated for 20 and 30 min by sonication compared to those pretreated for 10 min (Table 1). It was reported that more water is absorbed by the highly porous structure (Taghian Dinani and Havet, 2015). In addition, the fact that ultrasound application leads to a shorter drying time can reduce the protein denaturation, contributing to a greater rehydration capacity (Ozuna et al., 2014a). This observation can be applied to interpret the obtained results. On the contrary, Nowacka et al. (2012) reported that the rehydration ability of the samples subjected to ultrasonic treatment for 10 and 20 min was lower than the rehydration ability of those subjected to ultrasound for 30 min. As explained before, these dissimilarities can be explained by the differences in various experimental parameters.

Browning index difference (Δ BI)

The color of the dried foodstuff influences the acceptability of the consumer and the value of the product in the market (Taghian Dinani and Havet, 2015). The results obtained by the CRD statistical analysis method in Fig. 4 show that there was a significant difference between the values of Δ BI ($p \leq 0.001$) for different drying treatments. This figure demonstrates that the Δ BI data of potato slices ranged from 48.57 ± 2.34 for the 100 W–10 min treatment to 121.15 ± 9.59 for the 100 W–30 min treatment. The Δ BI value for the 100 W–30 min was not significantly higher than that for the 300 W–30 min treatment. Moreover, the Δ BI value for the 100 W–10 min treatment was not significantly lower than that for 300 W–10 min, 300 W–30 min, and control treatments. In other words, power ultrasound pretreatment only at suitable sonication time and power levels can preserve attractive natural color and prevent severe browning of samples during convective drying.

The results obtained by the factorial statistical analysis method show that Δ BI values were significantly influenced by sonication time ($p \leq 0.001$) and the interaction of the sonication time and power ($p \leq 0.05$), while Δ BI was not significantly affected by sonication power ($p > 0.05$). According to Table 1, when sonication time increased from 10 min to 30 min, a more Δ BI of the potato slices was achieved, but no significant difference was found between the Δ BI values of the potato slices pretreated by 10 and 20 min sonication times. Table 2 shows that when power increased from 100 W to 300 W, there was no significant difference in the Δ BI values of potato slices. The results of color changes are in agreement with those reported for drying of seaweed (Kadam et al., 2015) and apple (Deng

and Zhao, 2008). Destruction of pigments, oxidation, enzymatic, and non-enzymatic browning lead to color variations (Chen et al., 2016). Ultrasound can result in degassing effects, physical and membrane damage of the cells, and a greater $\Delta B I$.

Generally, the application of ultrasonic pretreatment at suitable levels of sonication time and power is an outstanding additional power source prior to convective drying. This application positively affects the drying kinetics, energy efficiency, and the quality characteristics of the dried product and may potentially result in its industrial use. However, further investigation is required before its adoption on a large scale in industrial operations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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