INFLUENCE OF AIR VELOCITY AND TEMPERATURE ON ULTRASONICALLY ASSISTED LOW TEMPERATURE DRYING OF EGGPLANT

J.V. Santacatalina, J.R. Soriano, J.A. Cárcel, and J.V. Garcia-Perez*

Grupo ASPA, Departamento de Tecnología de Alimentos, Universitat Politècnica de València, Camí de Vera s/n, E46022, València, Spain.

*Corresponding author. Tel.: +34 963879376; fax: +34 963879839. E-mail address: jogarpe4@tal.upv.es (J.V. Garcia-Perez).

Abstract

The aim of this work was to evaluate the feasibility of power ultrasound (US) application during the low temperature drying (LTD) of eggplant, analyzing the influence of the process variables linked to the air flow (velocity and temperature) on the drying kinetics and different quality aspects of the dehydrated product. For that purpose, eggplant (*Solanum melongena* var. Black Enorma) cubes (8.6 mm side) were dried at different air velocities (1, 2, 4 and 6 m/s) and temperatures (10, 0 and -10ºC) without (AIR) and with (AIR+US) US application. The rise in the air velocity and temperature led to an increase in the drying rate in AIR experiments. US application accelerated the drying process under every experimental condition tested, shortening the drying time by up to 87%. As for the quality parameters, no remarkable influence of the process variables (US application, air velocity and temperature) on the rehydration, reconstitution in olive oil or hardness of the rehydrated product was observed.

Keywords: Dehydration; temperature; air velocity; ultrasound; modeling; rehydration

1. Introduction

Eggplant is a relevant crop in North America, Asia and the Mediterranean area. Its limited shelf life, about 10 days after being harvested and stored at a temperature between 10 and 15ºC (Hu et al., 2010), is one of the main restrictions on the trade of eggplant as a fresh product. Several studies have dealt with the possibility of extending the shelf-life using several preservation techniques, such as freezing, cooling, boiling, salting and sugaring, curing, vacuum and modified atmosphere packaging, high pressure treatment and dehydration (Arvanitoyannis et al., 2005; Hu et al., 2010; Jha and Matsuoka, 2002; Wu et al., 2008; 2009; Zhang and Chen, 2006). Dehydration provides stable dried eggplant products (Akpinar and Bicer 2005) that are, for example, common ingredients in the preparation of dry long-life vegetable mixtures (Brasiello et al., 2013). In most of the cases, dried eggplant must be rehydrated before consumption, as in the case of the preparation of soups (Doymaz, 2011). Convective drying is one of the most commonly-used dehydration techniques within the food industry, but it provokes a series of changes in materials, such as oxidation, browning, shrinkage, softening and loss of nutritional-functional properties (Russo et al., 2013; Vega-Gálvez et al., 2012). These changes largely depend on the drying conditions, with those parameters linked to the air flow, such as air velocity and temperature, being of particular relevance.

Nowadays, there is an increasing demand in the food market for high quality products that preserve the nutritional and sensorial properties of the fresh product. In this sense, low-temperature convective drying can represent an interesting alternative to both conventional hot air drying and freeze-drying and a low-cost means of obtaining high-quality dried products (Santacatalina et al., 2014). Low-temperature drying (LTD) is conducted at temperatures below standard room conditions (<20ºC), which includes figures above and below the products' freezing point. The low level of thermal energy available in LTD applications leads to very low drying rates. Therefore, there is a particular interest in the intensification of the LTD process, making its application in the food industry feasible.

Power ultrasound (US) application constitutes an interesting non-thermal intensification for LTD (Cárcel et al., 2011). The mechanical energy introduced into the drying medium by US could help to reduce both the external and the internal mass transfer resistance (Riera et al. 2011). US has recently been applied in the LTD of different products, such as fish, fruits and vegetables, leading to shorter drying times. Thus, Ozuna et al. (2014a) reported a shortening of the drying time by between 35 and 54% when US was applied during the drying of salted cod (from -10 to 20ºC). Santacatalina et al. (2014) and Garcia-Perez et al. (2012) obtained similar drying time reductions by applying US (50 W) during apple drying at -10ºC (77%) and -14ºC (70%), respectively. Using a contact ultrasonic system for the freeze-drying of red bell pepper cubes, Schössler et al. (2012) found a drying time 11.5% shorter than in conventional experiments. Meanwhile, Bantle and Eikevik (2011) succeeded in reducing the drying time by around 10% when drying green peas at -3ºC using a commercial air-borne ultrasonic radiator. The variable ultrasonic performance of LTD applications found in the literature could be linked to the efficiency of the ultrasonic system used. The ultrasonic effects also depend on the magnitude of the process variables used, such as air velocity, temperature or ultrasonic power applied (Garcia-Perez et al., 2006). In this sense, during the atmospheric freeze drying of apple, Santacatalina et al. (2015) reported that the effect of US application on drying time was more marked than other factors, such as air temperature or velocity. As far as we are concerned, the influence of these aspects on the LTD of a high porosity product like eggplant have not been reported. This is especially relevant if it is borne in mind that the performance of US application is also product-dependent (Ozuna et al., 2014b). Therefore, the aim of this work was to evaluate the influence of the air velocity and temperature during the low-temperature drying of eggplant assisted by power ultrasound, analyzing the impact of these variables on both the drying kinetics and quality parameters of the dried product.

2. Materials and methods

2.1. Raw material

Eggplants (*Solanum melongena* var. Black Enorma) were purchased from a local market (Valencia, Spain). The pieces were selected to obtain a homogeneous batch in terms of ripeness, size and color, and held at 4±1ºC until processing. Cubic samples (8.6 mm side) were obtained from the flesh using a household tool. Samples to be dried at 10ºC and 0ºC were immediately processed, while those to be dried at -10ºC were wrapped in plastic film and frozen by placing in a freezing room at -18±1ºC until processing (at least 24 h). The initial moisture content was measured by placing samples in a vacuum oven at 70ºC and 200 mmHg until constant weight according to the Association of Official Analytical Chemists standard method no. 934.06 (AOAC, 1997).

2.2. Drying experiments

Drying experiments were carried out in a convective drier with air recirculation, already described in the literature (Garcia-Perez et al., 2012). The system is provided with an air velocity and temperature control and an ultrasonically activated drying chamber excited by an ultrasonic transducer. Air-borne ultrasound is transmitted from the walls of the drying chamber to the air, finally reaching the samples. The system is able to generate an acoustic field (21.9 kHz) of 157 dB inside the chamber with an electric power input of 90 W at stagnant air conditions, which is reduced to 154 dB at an air velocity of 6 m/s (Riera et al., 2011). Based on the results of Ozuna et al. (2014b), the ultrasonic transmission coefficient in the interface air/eggplant should be of 0.011.

The drying experiments were carried out at different air velocities (1, 2, 4 and 6 m/s) and temperatures (10, 0 and -10ºC) without (AIR, 0 W) and with (AIR+US, 50 W) US application. The relative humidity of air was maintained below 15±5% for the entire drying time and the initial mass load density was 5.3 kg/m^3, which corresponds with 40 cubes of fresh eggplant. The drying kinetics were determined from the initial moisture content of the eggplant and by automatically weighing the samples at preset times (every 300 s). Every condition was tested in triplicate at least and the drying experiments were extended until the samples lost 90% of the initial weight. Thus, the total number of experiments carried out was 72 (3 Temperaturesx4 Air velocitiesx2 US applicationx3 Replicates).

2.3. Modeling of the drying kinetics

The modeling of the drying kinetics focused only on quantifying the effect of the drying conditions tested on overall mass transport. For that purpose, a diffusion model was used to describe the drying kinetics of eggplant cubes, considering the effective moisture diffusivity to be constant, the temperature uniform and the shrinkage negligible. Thus, the governing equation of diffusion (Equation 1) is written as follows:

$$\frac{\partial W_p(x,y,z,t)}{\partial t} = D_{ed}\left(\frac{\partial^2 W_p(x,y,z,t)}{\partial x^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial y^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial z^2}\right) \quad (1)$$

where W_p is the local moisture (kg water/kg dry matter, kg w/kg dm), t is the drying time (s), D_{ed} is the effective moisture diffusivity (m^2/s) and x, y and z represent the characteristic mass transport pathways in the cubic geometry (m).

In order to solve Equation 1, the initial moisture was assumed to be uniform and the symmetry was considered in directions x, y, z. The moisture transport was considered to be jointly controlled by diffusion and convection, the latter being included in the model by the boundary condition shown in Equation 2 for the x coordinate. Thus, the diffusion model permits the quantification of both the effective diffusivity and the external mass transfer coefficient (k, kg w/m^{2}s):

$$t > 0 \qquad x = L \qquad -D_{ed}\rho_{ds}\frac{\partial W_p(L,y,z,t)}{\partial x} = k(a_w(L,y,z,t) - \varphi_{air}) \qquad (2)$$

where ρ_{ds} is the dry solid density (kg dm/m^3) and φ_{air} is the relative humidity of the drying air. The water activity on the surface of the material (a_w (L,y,z,t)) was estimated from sorption isotherm data at 20ºC as reported in the literature (Moreira et al., 2010).

The fact of considering the samples as homogeneous and isotropic is only valid for drying experiments carried out at 0 and 10ºC. In drying experiments at -10ºC where samples were frozen before drying, it was possible to distinguish two main zones in the particle during drying: an inner frozen core and an outer dry layer. The vapor diffusion only occurs in this outer layer, which becomes thicker as the drying progresses. Then, in the experiments at -10ºC, the proposed diffusion model just becomes an empirical model. A more rigorous approach for modeling LTD at -10ºC was addressed by Santacatalina et al. (2015). However, the proposed diffusion model in this work allowed for the comparison and quantification of the effect of the studied variables on the drying kinetics, which was, as mentioned above, the main goal of the modeling.

The model was numerically solved by applying an implicit finite difference method (Garcia-Perez et al., 2012), for which a computational algorithm was written in MATLAB 7.13.0.564 (The MathWorks, Inc., USA). An optimization problem was defined for the purposes of fitting the model to the experimental data. The objective function was the sum of the squared differences between the experimental and the calculated average moisture contents. The kinetic parameters, D_{ed} and k, were jointly identified by minimizing the objective function using the SIMPLEX method available in the fminsearch function (MATLAB). The model was fitted to each drying run and the kinetic parameters averaged. The percentage of explained variance (VAR, Equation 3) and the mean relative error (MRE, Equation 4) were calculated in order to determine the goodness of the fit.

$$VAR(\%) = \left[1 - \frac{S_{xy}^2}{S_y^2}\right] \cdot 100 \qquad (3)$$

$$MRE(\%) = \frac{100}{N}\left[\sum_{i=1}^{N} \frac{|W_{ei} - W_{ci}|}{W_{ei}}\right] \qquad (4)$$

where S_{xy} and S_y are the standard deviation of the estimation and the sample, respectively, W_{ei} and W_{ci} are the experimental and calculated average moisture contents (kg w/kg dm) and N is the number of experimental data.

2.4. Rehydration experiments

The eggplant samples dried under the different conditions tested were rehydrated in distilled water at 30±1ºC using a thermostatic bath provided with an agitation system (Tectron 200, JP Selecta, Abrera, Spain). During rehydration, samples were taken out of the bath at preset times (0, 3, 10, 30, 60, 100, 200, 300, 400, 500 and 700 s), blotted with tissue paper to remove the surface water and weighed in order to estimate the rehydration kinetics. 10 cubes of dried eggplant (0.38±0.06 g) were used for each run and four replicates were performed for each drying condition tested.

2.5. Modeling of the rehydration kinetics

The rehydration kinetics were also modeled following the diffusion theory. However, in this case, the external resistance was considered negligible due to the high turbulence maintained in the liquid medium during experiments. Therefore, it is assumed that the particle surface moisture content suddenly reached equilibrium, as reflected in Equation 5 for the x coordinate. The model's analytical solution, in terms of the average moisture content, is given in Equation 6.

$$W_p(L, y, z, t > 0) = W_e \quad (5)$$

$$W(t) = W_e + (W_0 - W_e)\left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-\frac{D_{er}(2n+1)^2 \pi^2 t}{4L^2}\right)\right]^3 \quad (6)$$

where W is the average moisture content (kg w/kg dm), L the half-length of the cube side (m) and subscripts 0 and e represent the initial and equilibrium states, respectively.

This model was fitted to the experimental rehydration kinetics in order to identify the effective moisture diffusivity (D_{er}) and the equilibrium moisture content (W_e). For that purpose, the objective function to be minimized was the sum of the squared differences between experimental and calculated average moisture contents. The optimization was conducted by applying the generalized reduced gradient method available in the Solver tool (Microsoft Excel 2014). In order to determine the goodness of the fit, the VAR (Equation 3) and the MRE (Equation 4) were calculated.

2.6. Hardness of the rehydrated samples

The textural properties of the fresh and rehydrated eggplant samples were measured using a TA-XT2 texturometer (SMS, Godalming, UK) provided with a load cell of 25 kg. Simple compression tests were carried out at constant temperature (16±1ºC) using a flat 75 mm diameter aluminum plunger (SMS P/75) and applying a compression ratio of 80%. Hardness was computed from the force/deformation profiles as the maximum force achieved. At least 40 cubes were analyzed for each set of samples.

2.7. Absorption capacity of olive oil

The absorption capacity (AC) of olive oil was evaluated in order to assess the interaction of dried eggplant with another liquid, which is frequently used for cooking in Mediterranean countries. Moreover, it is one of the most interesting parameters with which to determine the functional properties of dietary fiber (O'Shea et al., 2012) and could be used, for example, to estimate the needs of oil during a frying process. For that purpose, the eggplant samples dried under the different conditions tested were immersed in 300 mL of olive oil at 30±1ºC (stagnant conditions). The AC of olive oil was estimated as the weight increase (as a percentage with respect to the initial weight) after 60 s of immersion. 10 cubes (0.37±0.09 g) of dried eggplant were used for each run and four replicates were performed for each drying condition tested.

2.8. Statistical analysis

Multifactorial Analysis of Variance (MANOVA) ($p<0.05$) was carried out and LSD (Least Significant Difference) intervals were assessed using the statistical package, Statgraphics Centurion XVI (Statpoint Technologies Inc., Warrenton, VA, USA), in order to determine whether the operating conditions studied (air velocity, temperature and US application) significantly ($p<0.05$) influenced the D_e and k parameters identified in the drying kinetics and D_e and W_e in the rehydration kinetics. Likewise, the influence of drying conditions on the hardness of the rehydrated samples and the absorption capacity of olive oil were also compared. In every case, homogeneous groups (95% significance level) were established by considering the interaction of air velocity and US application for each drying temperature tested.

3. Results and discussion

3.1. Drying experiments

The vegetable tissue of eggplant is heterogeneous in structure (Ozuna et al., 2014b) which leads to a high degree of experimental variability in the drying kinetics (Figure 1). For this reason, in order to properly compare the influence of air velocity, temperature and US application on the drying kinetics, all the replicates performed under every drying condition tested were fitted to a polynomial function. Thereby, the polynomial equation obtained reflects the average behaviour for a particular drying condition (Figure 1) and permits comparison with trials conducted under other conditions (Figures 2 and 3).

As for AIR kinetics, it can be observed that the higher the air velocity, the faster the drying kinetic at every temperature tested (Figure 2). Thus, for example, the drying times (loss of 90% of the initial weight) for the AIR experiments carried out at 0ºC and 1 and 6 m/s were 425±74 and 313±33 minutes, respectively. The increase in air velocity reduced the external resistance to mass transfer due to the reduction in the thickness of the boundary layer (Garcia-Perez et al., 2007). No air velocity threshold, above which external resistance is negligible compared to internal, was found in the range of the air velocities studied. However, when US was applied during drying (AIR+US experiments), no clear trend in the air velocity effect was observed (Figure 2). This fact could be linked to the marked influence of US application on the drying kinetics, which could mask the air velocity effect (Garcia-Perez et al., 2007).

As regards the effect of temperature on the drying kinetics, the increase in the drying temperature in AIR experiments implied a shorter drying time at every air velocity used (Figure 3). The drying time was reduced by 73% (on average) when the drying temperature was increased from -10 to 10ºC. It should be noted that at 0 and 10ºC the water was removed from the solid matrix by evaporation, while at -10ºC, water removal occurred by sublimation, a process known as atmospheric freeze drying (Claussen et al., 2007). The temperature influence was less marked in AIR+US (Figure 3) than in AIR experiments. For example, in US experiments carried out at 4 m/s, the drying time was reduced by 47% when the drying temperature was increased from -10 to 10ºC. The kinetic effect of air temperature has been widely reported in the hot air drying of eggplant (Brasiello et al., 2013; Doymaz, 2011; Ertekin and Yaldiz, 2004; Russo et al., 2013) but, as far as we know, it has not been reported in the LTD of eggplant. The influence of temperature has been computed in the LTD of other products, such as apple (Santacatalina et al. 2014 and 2015) and salted cod (Ozuna et al., 2014a). Bantle and Eikevik (2011) also studied the influence of temperature on the drying of peas from -6ºC to 20ºC.

Under every drying condition tested, the application of power ultrasound increased the drying rate. The major difference in the drying time between AIR and AIR+US experiments (87%) was found in experiments at -10ºC and 4 m/s. The temperature influenced the magnitude of the ultrasound effects. Thus, the reduction in the drying time linked to US application was less significant at 10ºC than at -10ºC (Figure 4). However, the air velocity was found to exert no clear influence on US effects, so, the ultrasonic performance was similar at every air velocity tested. The kinetic intensification achieved in this study was greater than that reported by Santacatalina et al. (2014) and Garcia-Perez et al. (2012) using the same ultrasonically assisted drier during apple drying at -10ºC (77%) and -14ºC (70%), respectively. This could be explained by the greater porosity of eggplant, which favors the mechanical effects produced by US application (Puig et al., 2012).

3.2. Modeling of the drying kinetics

The diffusion model considered showed a good fit to the experimental data, with percentages of explained variance (VAR) of over 99% and mean relative errors (MRE) of under 9% in every case (Table 1). Moreover, this model allowed the identification of the effective moisture diffusivity (D_{ed}) and the external mass transfer coefficient (k), the drying parameters inversely linked to the internal and external resistances to water transfer, respectively. These parameters were analyzed in order to compute the influence of the drying conditions (air velocity, temperature and US application) on the drying rate.

The D_{ed} identified for AIR experiments (Table 1) ranged between 1.2x10^{-10} m^2/s (-10ºC; 2 m/s) and 5.7x10^{-10} m^2/s (10ºC; 4 m/s). These values are higher than those reported by Santacatalina et al. (2014) when performing the LTD of apple, probably due to the greater porosity of eggplant (Ozuna et al., 2014b) that makes it easier for the water to flow out of the solid matrix. Despite the fact that the increase in air velocity shortened the drying process of eggplant, the MANOVA reflected that this influence was non-significant ($p<0.05$) as regards the D_{ed} parameter (Table 1), which points to the fact that internal water transfer is not dependent on the air flow rate. However, the air temperature significantly ($p<0.05$) influenced the $D_{ed;}$ therefore, the higher the temperature, the higher the identified D_{ed} value (Table 1). These effects that the drying conditions had on D_{ed} were consistent with those reported by Santacatalina et al. (2015), who previously reported a significant effect of the air temperature in experiments carried out at for experiments carried out at -10, -5, 0, 5 and 10ºC).

US application significantly ($p<0.05$) increased the D_e (Table 1), the average improvement ranging from 153 to 824% (Table 1). Previous studies have shown that the improvement in D_{ed} brought about by US application is linked to the mechanical effects provoked in the material (Garcia-Perez et al., 2009). Power ultrasound generates alternating expansions and contractions when travelling in a medium (Riera et al., 2011); this mechanical stress facilitates the water movement to the product surface. In addition, the thermal effect of air-borne ultrasonic application has also been documented (Garcia-Perez et al., 2013; Bantle and Hanssler, 2013), which would also contribute to the kinetic improvement linked to US application. Thus, Bantle and Hanssler (2013) reported an increase of approximately 5ºC in US drying of clipfish at 10, 20 and 30ºC. While, Garcia-Perez et al. (2013) found an increase of air temperature of up to 10ºC by US application in hot air drying of grape stalk. The temperature rise would contribute to increase the evaporation/sublimation rates and the inner water diffusion. Although, it should be mentioned that this thermal effect would be dependent on the product being dried and the US device used as well as the process variables involved (air temperature, velocity and ultrasonic power). Further studies should assess the importance of the thermal effect and its comparison with the mechanical stress.

As regards the external mass transfer coefficient, both air velocity and temperature were shown to have a significant ($p<0.05$) influence in the AIR experiments; thus, the higher the air velocity and temperature, the higher the k parameter (Table 1). Santacatalina et al. (2014) and Garcia-Perez et al. (2012) obtained similar values of k to those reported in this study when carrying out LTD drying of carrot, eggplant and apple. In AIR+US experiments, the influence of air velocity and temperature was similar to that found in AIR experiments except for those carried out at 0ºC, where the effect of air velocity was negligible. The US application provoked a significant ($p<0.05$) increase in k (Table 1), which ranged between 79% (0ºC; 6 m/s) and 383% (0ºC; 1 m/s). This increase is linked to the decrease in the external resistance to water transfer due to the reduction of the boundary layer caused by the pressure variations, oscillating velocities and microstreaming that US generates on the solid-gas interfaces (Ozuna et al., 2014a). As for AIR+US experiments at 0ºC, it can be observed that the higher the air velocity, the lower the increase in k. This could be linked to the disruption of the ultrasonic field by the high air flow rates. Low air flow rates would not affect the ultrasonic field; thus, a greater amount of ultrasonic energy is available to increase the drying rate than at high air velocities (Garcia-Perez et al., 2006). Moreover, high air velocities reduced the external resistance because they increased the air turbulence and, therefore, the scope for improvement is narrower at these velocities.

It should be noted that US application led to a greater increase in D_{ed} than in k (Table 1) under every drying condition. This suggests that ultrasound effects had a greater influence on internal transport than on external. Therefore, ultrasound application reduced the relative importance of diffusion in mass transport and, as a consequence, increased the relative influence of convection in drying. The greatest differences between the degree to which D_{ed} and k improved were found at -10ºC because atmospheric freeze drying generates a very porous external layer that is more prone to the effects of ultrasound because more acoustic energy is absorbed into the particle (Ozuna et al., 2014b).

3.3. Rehydration

The rehydration ability of dried eggplant was assessed from the experimental determination of the rehydration kinetics. The fit of a diffusion model to experimental data permitted the identification of the effective moisture diffusivity (D_{er}) and the equilibrium moisture content (W_e), parameters which are directly linked to the water absorption rate and the rehydration capacity, respectively. Thus, the proposed diffusion model fitted the experimental rehydration kinetics appropriately, providing VAR of over 95% and MRE of under 10% (Table 2). The agreement between the experimental and calculated data can also be observed in Figure 5.

Compared with the drying process, rehydration was a faster operation regardless of the drying condition used (Figure 5). Thus, the dried eggplant was totally rehydrated in less than 700 s (approximately 12 min). This was confirmed by the high identified D_{er} values, which were over 10^{-8} m^2/s (Table 2). The air velocity used in AIR experiments had no significant ($p<0.05$) effect on the D_{er} identified in the subsequent rehydration. Thus, the increase in air velocity gave rise to the D_{er} identified at -10ºC, whereas, at 10ºC, the opposite behavior was found. On the contrary, the influence of the drying temperature on D_{er} was significant ($p<0.05$). In this sense, the D_{er} identified for the experiments carried out at -10ºC was higher than those obtained at 0 and at 10ºC (Table 2). These results could be explained by the highly porous structure caused by the water sublimation at -10ºC, due to the fact that the sample shrinkage is almost negligible (Stawczyk et al., 2007), which makes the water transfer faster. The effect of the temperature was also observed in the W_e; thus, in AIR samples, the lower the temperature, the higher the identified W_e (Table 2). Therefore, the samples dried at -10ºC rehydrated more and faster than those dried at 10ºC.

The application of US during drying increased the D_{er} in the rehydration, but this increase was not significant ($p>0.05$), probably due to the highly variable nature of eggplant (Table 2). The reason for this higher value of D_{er} could be linked to the generation of microchannels in the dried samples produced by US application that make it easier for the water to be absorbed during the subsequent rehydration (Mulet et al., 2011). Moreover, US application was found to have no significant ($p>0.05$) influence on W_e (Table 2). Therefore, this indicates that although US application caused a faster water inlet (higher D_{er}) it did not lead to greater water absorption (no influence on W_e) during rehydration.

3.4. Hardness of rehydrated samples

The hardness of the fresh and rehydrated eggplant was measured by means of simple compression tests in order to quantify the influence of the drying conditions on the texture (Table 3). In general terms, fresh eggplant samples were significantly ($p<0.05$) harder (15.7±2.6 N) than the rehydrated ones (8.7±1.2 N). The hardness of AIR samples ranged between 8.3 and 10.4 N and between 6.5 and 10.3 N for the AIR+US ones. The softening of the rehydrated samples could be due to the structural degradation caused by the drying process (Puig et al., 2012) that constrains the recovery of the initial texture.

The drying conditions tested did not affect the hardness of the rehydrated samples. Thus, no significant ($p>0.05$) influence of either air velocity, temperature or US application was found on the experimental values measured (Table 3). Therefore, the possible changes produced by the drying temperature or US application in the internal structure of the samples, which, as shown before, affected the rehydration capacity, were not enough to influence the final hardness of the rehydrated eggplant.

3.5. Absorption capacity of olive oil

The absorption of olive oil in dried eggplant was so fast that it was completed in a few seconds. This made the experimental determination of the absorption kinetics non-feasible. Therefore, the absorption capacity (AC) of olive oil was estimated as the weight increase (as a percentage with respect to the initial weight) after 60 s of immersion.

In general terms, the air velocity and temperature used during drying did not cause significant ($p>0.05$) differences in the AC of eggplant (Figure 6). The application of US increased the AC, especially in eggplant samples dried at -10ºC; however, these differences were not significant ($p>0.05$), probably due to the highly variable nature of the experimental data, as already stated for other aspects in this paper. As an example, the AC of eggplant samples dried at -10ºC and 1 m/s without and with US application was 263.5±16.2% and 292.7±16.8%, respectively. At -10ºC, the high porosity generated by the formation of ice crystals and the subsequent sublimation (Voda et al., 2012) could also increase the AC of olive oil of these samples. Therefore, as occurred in the case of hardness, the structural changes produced by the different drying conditions tested, particularly the effect of the air drying temperature and US application, were not enough to produce significant changes in the AC of the olive oil in the dried samples. In any case, further research will be necessary to determine the influence of the drying conditions on the microstructure of dried eggplant.

4. Conclusions

In this study, the influence of different processing variables (air velocity, temperature and US application) on the kinetics of the LTD of eggplant was assessed, as were some quality aspects. The application of US increased the drying rate, shortening the drying time by as much as 87%. In addition, ultrasound decreased the influence of both air velocity and temperature on the LTD kinetics. As far as the quality aspects are concerned, the processing variables did not show a significant ($p<0.05$) influence either on the hardness of the rehydrated samples or on the absorption capacity of olive oil. The rehydration capacity was only significantly ($p<0.05$) influenced by the drying temperature. Therefore, US could be considered a feasible technology with which to intensify the low temperature drying of high quality foodstuffs. Further studies should elucidate if the kinetic improvement linked to the ultrasonic application is accompanied by an energy saving.

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Figure captions

Figure 1. Examples of polynomial fit to experimental drying kinetics of eggplant cubes. A: 1 m/s, -10ºC, 0 W (AIR); B: 2 m/s, -10ºC, 50 W (AIR+US).

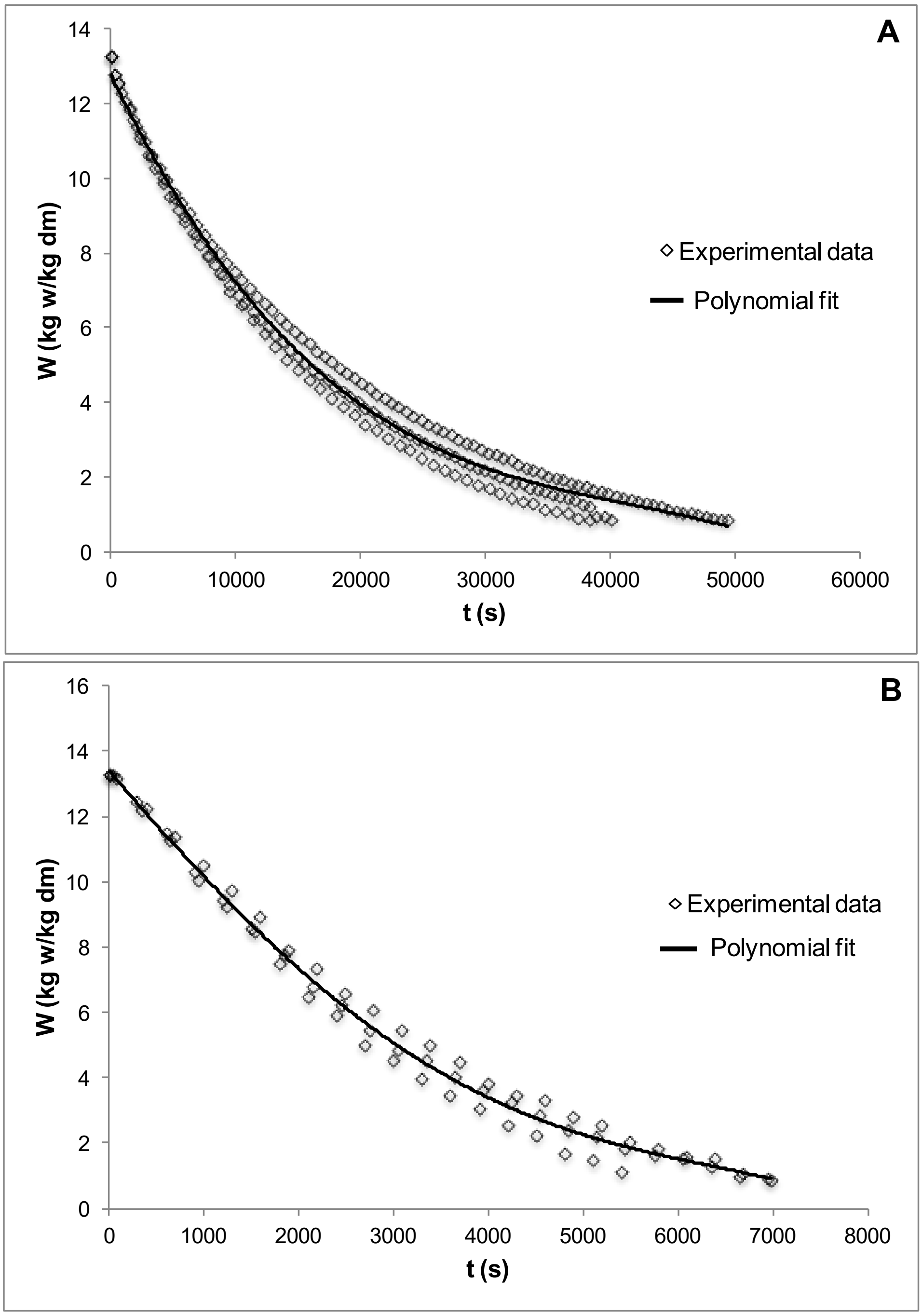
Figure 2. Drying kinetics of eggplant at different air velocities (1, 2, 4 and 6 m/s). A: 0ºC, 0 W (AIR); B: 10ºC, 50 W (AIR+US). Error bars show the differences between experimental data and the polynomial equation.

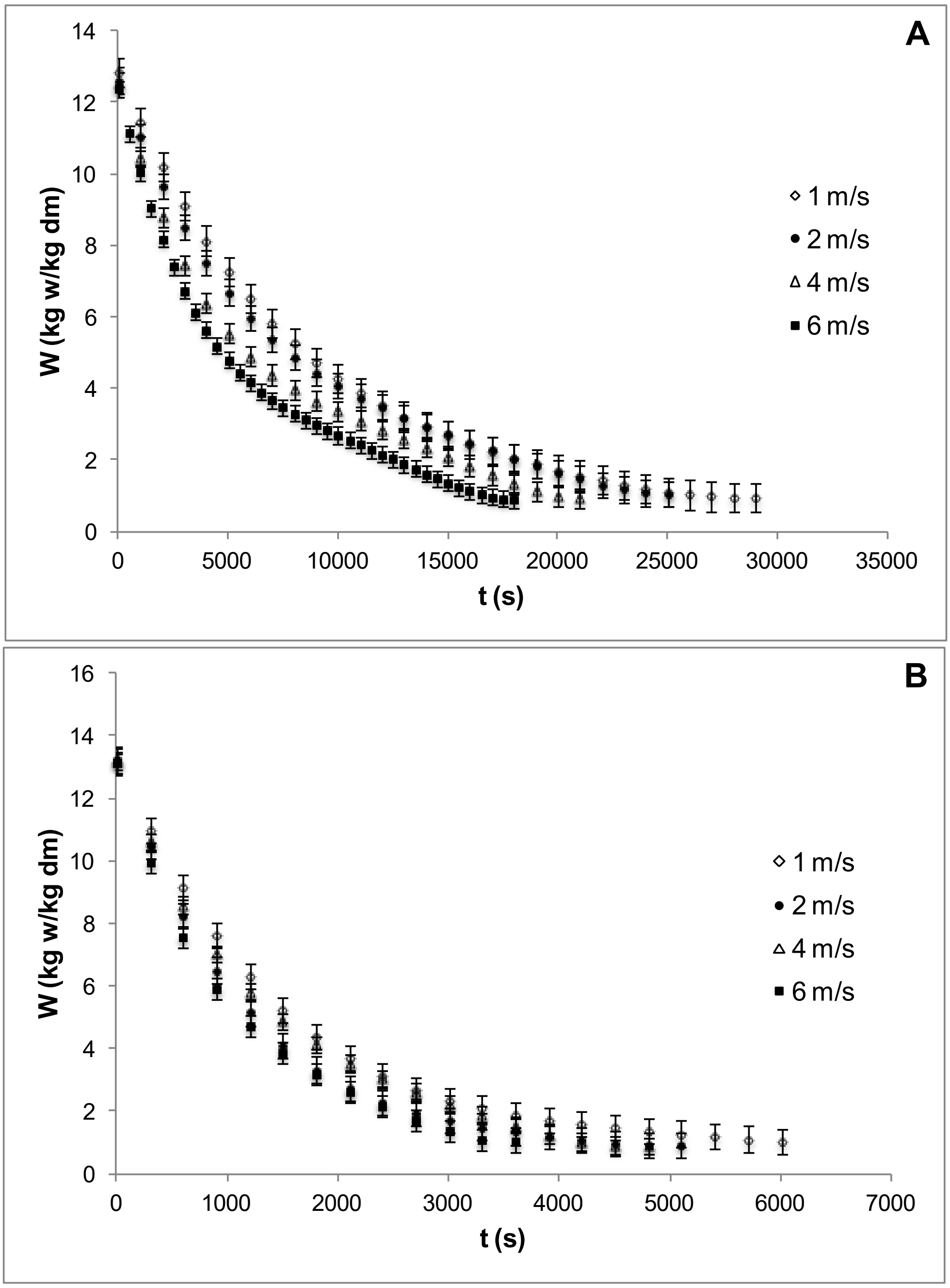
Figure 3. Drying kinetics of eggplant at different temperatures (-10, 0 and 10ºC). A: 1 m/s, 0 W (AIR); B: 1 m/s, 50 W (AIR+US); C: 2 m/s, 0 W (AIR); D: 2 m/s, 50 W (AIR+US); E: 4 m/s, 0 W (AIR); F: 4 m/s, 50 W (AIR+US); G: 6 m/s, 0 W (AIR); H: 6 m/s, 50 W (AIR+US). Error bars show the differences between experimental data and the polynomial equation.

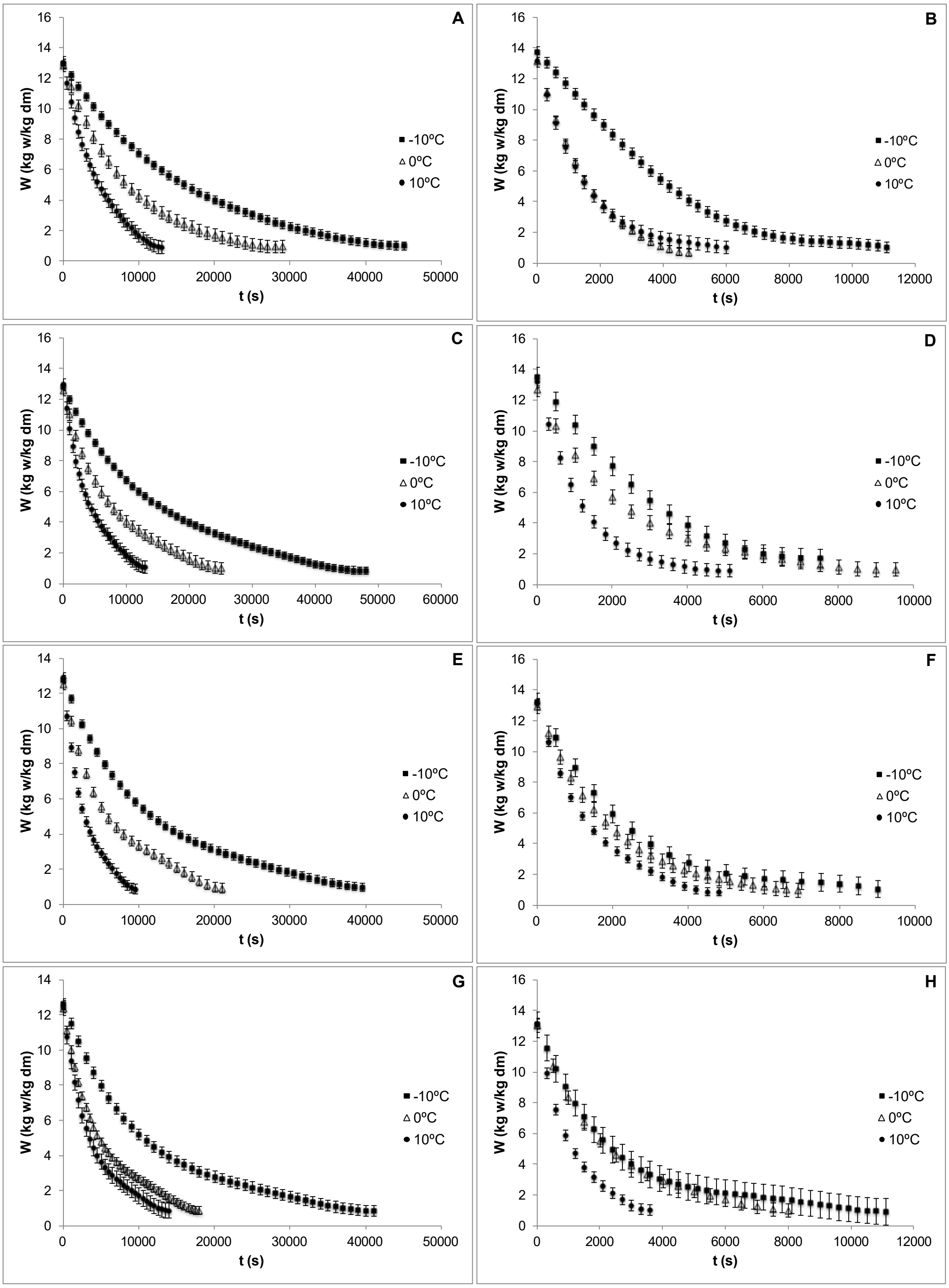
Figure 4. Drying kinetics of eggplant without (AIR, 0 W) and with (AIR+US, 50 W) US application. A: 4 m/s, -10ºC; B: 4 m/s, 10ºC. Error bars show the differences between experimental data and the polynomial equation.

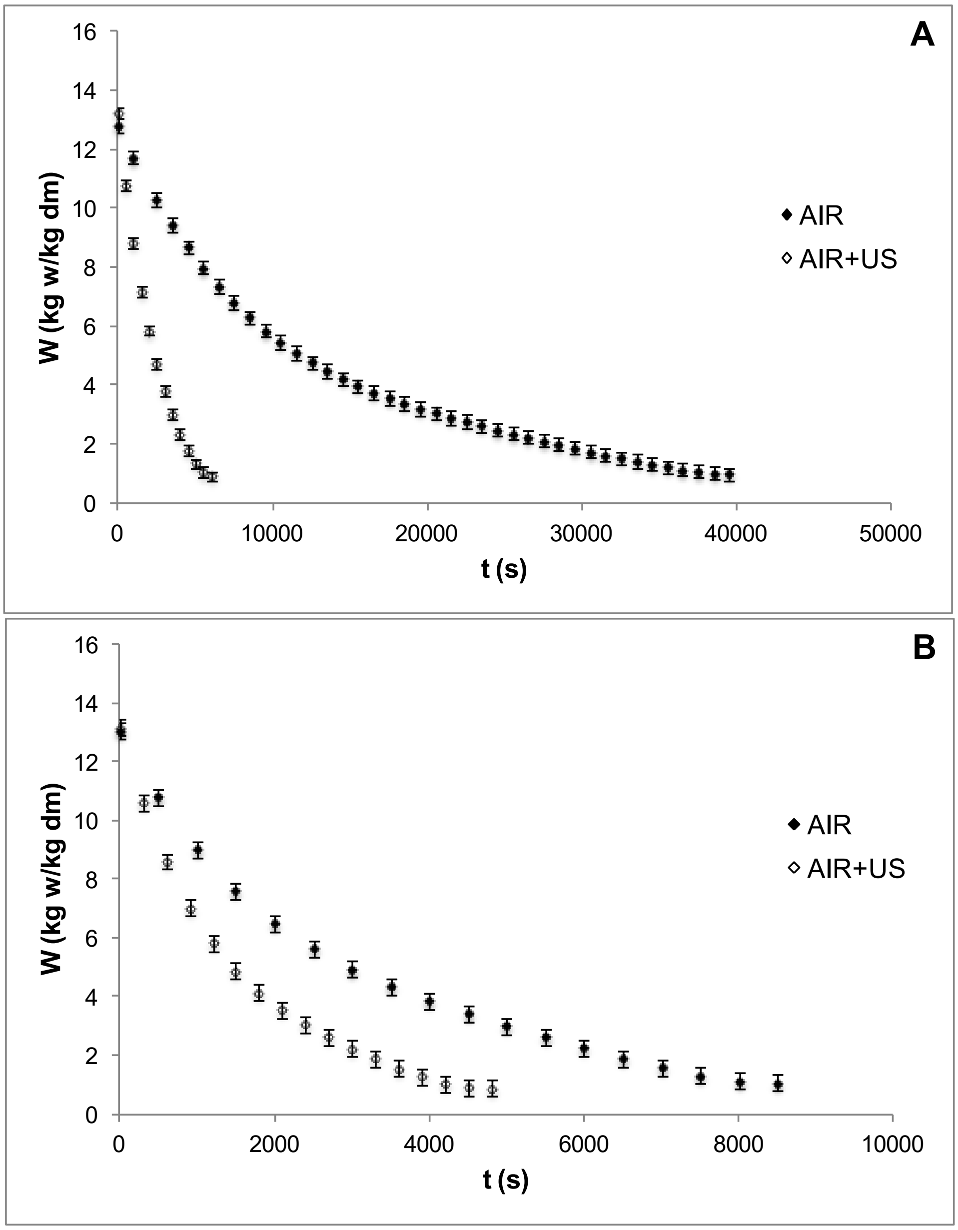
Figure 5. Rehydration kinetics of eggplant dried without (AIR, 0 W) and with (AIR+US, 50 W) US application and diffusion model. A: 1 m/s, 10ºC; B: 1 m/s, -10ºC; C: 6 m/s, 10ºC; B: 6 m/s, -10ºC.

Figure 6. Absorption capacity (AC) of olive oil in eggplant dried at 10ºC and different air velocities (A) and at 4 m/s and different temperatures (B) without US application (AIR samples).

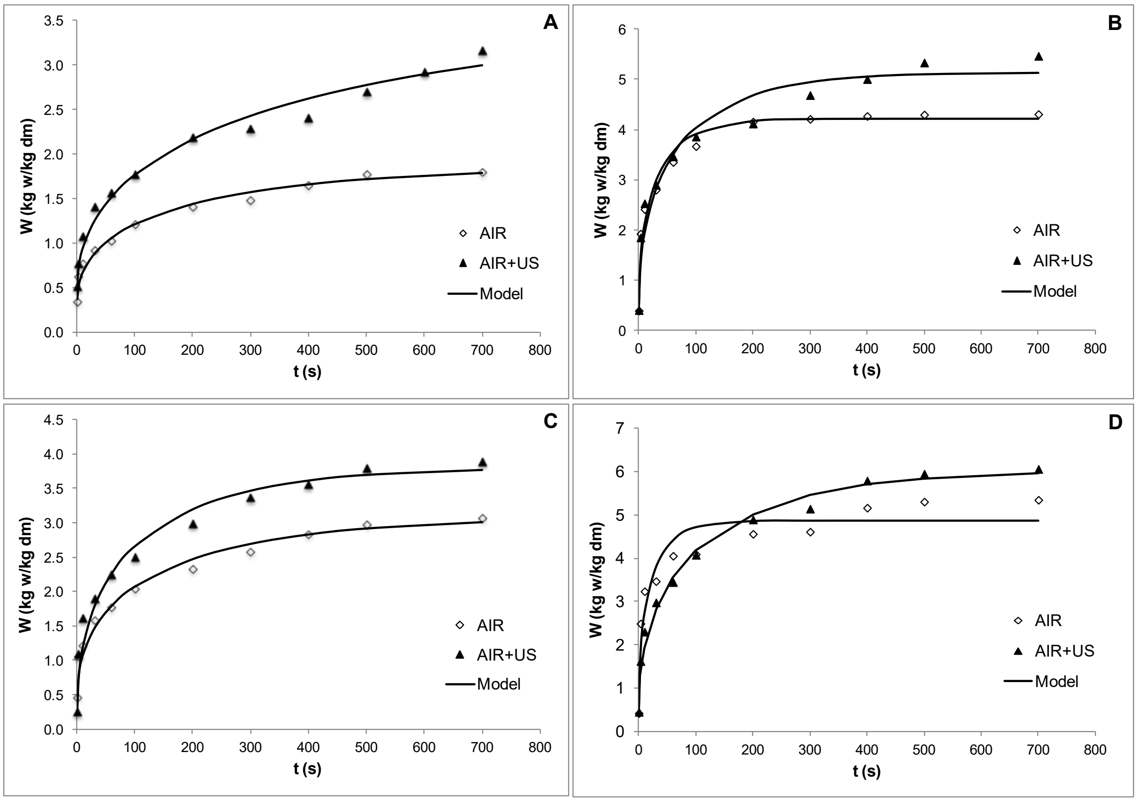

A
W (kg w/kg dm)
t (s)
Experimental data
Polynomial fit
B
W (kg w/kg dm)
t (s)
Experimental data
Polynomial fit

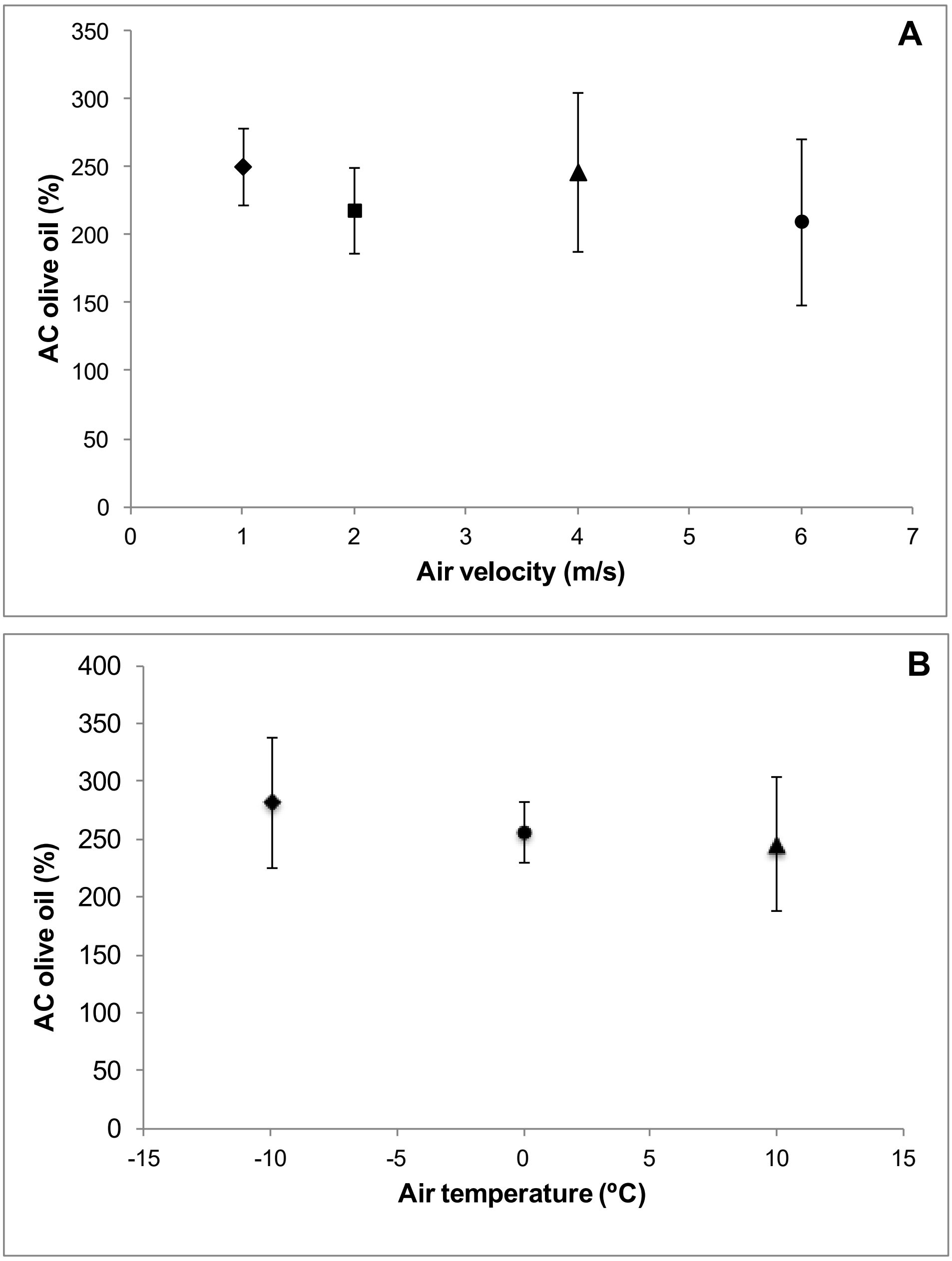

A
W (kg w/kg dm)
t (s)
1 m/s
2 m/s
4 m/s
6 m/s
B
W (kg w/kg dm)
t (s)
1 m/s
2 m/s
4 m/s
6 m/s


A
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
B
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
C
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
D
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
E
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
F
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
G
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC
H
W (kg w/kg dm)
t (s)
■ -10ºC
△ 0ºC
● 10ºC



A
W (kg w/kg dm)
t (s)
AIR
AIR+US
B
W (kg w/kg dm)
t (s)
AIR
AIR+US


A
B
C
D
W (kg w/kg dm)
t (s)
AIR
AIR+US
Model


A
350
300
250
200
150
100
50
0
AC olive oil (%)
0
1
2
3
4
5
6
7
Air velocity (m/s)
B
400
350
300
250
200
150
100
50
0
AC olive oil (%)
-15
-10
-5
0
5
10
15
Air temperature (ºC)

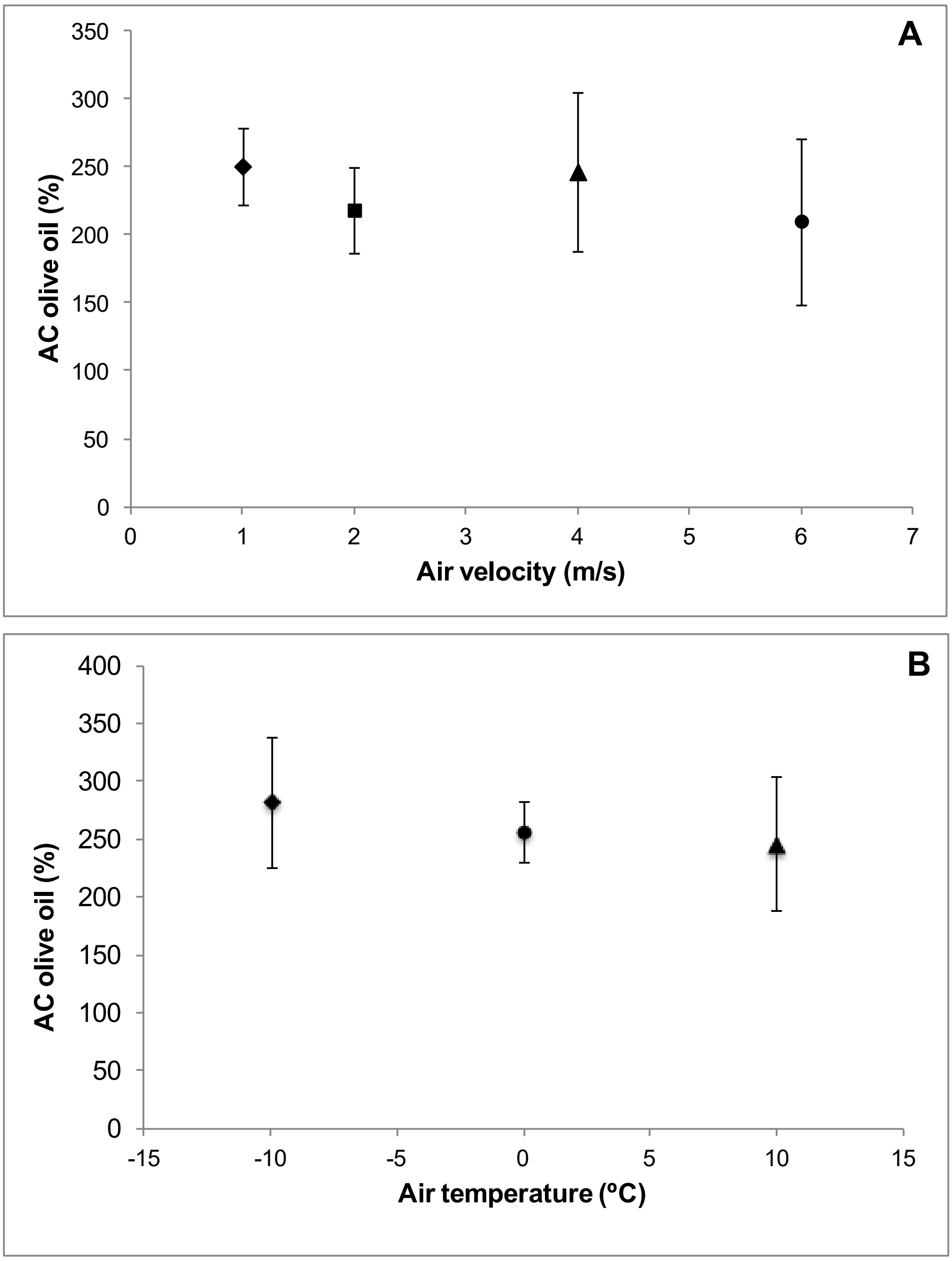

A
AC olive oil (%)
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
Air velocity (m/s)
B
AC olive oil (%)
400
350
300
250
200
150
100
50
0
-15
-10
-5
0
5
10
15
Air temperature (ºC)

Table 1. Modeling of drying kinetics of eggplant at different air velocities (1, 2, 4 and 6 m/s) and temperatures (10, 0 and -10ºC) without (AIR, 0 W) and with (AIR+US, 50 W) US application. Average values and standard deviation are shown for the effective moisture diffusivity (D_{ed}) and mass transfer coefficient (k). VAR (%) is the percentage of explained variance and MRE (%) the mean relative error. ΔD_{ed} and Δk report (as a percentage) the increase in a kinetic parameter as the result of ultrasound application.

			1 m/s	**2 m/s**	**4 m/s**	**6 m/s**
10ºC	AIR	D_{ed} (10^{-10} m^2/s)	4.5 ± 0.3^{a}	4.0 ± 0.4^{a}	5.7 ± 0.2^{a}	4.6 ± 0.6^{a}
		k (10^{-3} kg w/m^2s)	1.3 ± 0.2^{A}	1.6 ± 0.2^{A}	2.5 ± 0.4^{B}	2.5 ± 0.3^{B}
		VAR (%)	99.7	99.5	99.6	99.2
		MRE (%)	4.8	6.1	5.7	7.5
	AIR+US	D_{ed} (10^{-10} m^2/s)	16.5 ± 0.4^{b}	18.4 ± 0.5^{bc}	14.5 ± 0.4^{bc}	16.1 ± 0.5^{c}
		k (10^{-3} kg w/m^2s)	4.8 ± 0.4^{C}	5.2 ± 0.5^{CD}	5.2 ± 0.7^{DE}	6.1 ± 0.3^{E}
		VAR (%)	99.9	99.8	99.8	99.8
		MRE (%)	3.7	6.4	4.6	4.9
		ΔD_{ed} (%)	264	357	153	250
		Δk (%)	262	228	106	144
0ºC	AIR	D_{ed} (10^{-10} m^2/s)	2.2 ± 0.4^{a}	2.0 ± 0.4^{a}	2.3 ± 0.2^{a}	2.8 ± 0.4^{a}
		k (10^{-3} kg w/m^2s)	0.8 ± 0.1^{A}	1.0 ± 0.1^{AB}	1.4 ± 0.2^{BC}	1.8 ± 0.4^{C}
		VAR (%)	99.7	99.1	99.1	99.1
		MRE (%)	6.0	8.1	7.9	6.9
	AIR+US	D_{ed} (10^{-10} m^2/s)	10.8 ± 0.8^{ab}	10.7 ± 0.6^{b}	9.7 ± 0.2^{b}	7.2 ± 0.1^{b}
		k (10^{-3} kg w/m^2s)	3.7 ± 0.5^{D}	3.5 ± 0.6^{D}	3.6 ± 0.5^{D}	3.2 ± 0.3^{D}
		VAR (%)	99.6	99.3	99.6	99.5
		MRE (%)	3.7	7.9	10.8	8.2
		ΔD_{ed} (%)	389	435	324	157
		Δk (%)	383	251	153	79
-10ºC	AIR	D_{ed} (10^{-10} m^2/s)	1.4 ± 0.4^{a}	1.2 ± 0.1^{a}	1.3 ± 0.1^{a}	1.5 ± 0.2^{a}
		k (10^{-3} kg w/m^2s)	0.4 ± 0.1^{A}	0.5 ± 0.1^{A}	0.7 ± 0.2^{AB}	0.9 ± 0.2^{B}
		VAR (%)	99.8	99.5	99.6	99.7
		MRE (%)	4.1	6.4	7.6	4.1
	AIR+US	D_{ed} (10^{-10} m^2/s)	8.4 ± 0.8^{b}	11.1 ± 0.4^{b}	10.0 ± 0.3^{b}	10.9 ± 0.5^{b}
		k (10^{-3} kg w/m^2s)	1.5 ± 0.3^{C}	2.2 ± 0.3^{D}	3.1 ± 0.1^{E}	3.6 ± 0.8^{F}
		VAR (%)	98.7	99.5	99.9	99.7
		MRE (%)	7.6	4.6	3.8	4.3
		ΔD_{ed} (%)	485	824	645	631
		Δk (%)	227	322	313	271

Superscript letters (a, b, c) and (A, B, C, D, E, F) show homogeneous groups, established from LSD (Least Significance Difference) intervals ($p<0.05$) at every temperature, for D_{ed} and k, respectively.

Table 2. Modeling of rehydration kinetics of eggplant dried at different air velocities (1, 2, 4 and 6 m/s) and temperatures (10, 0 and -10ºC) without (AIR, 0 W) and with (AIR+US, 50 W) US application. Average values and standard deviation are shown for the effective moisture diffusivity (D_{er}) and equilibrium moisture content (W_e). VAR (%) is the percentage of explained variance and MRE (%) the mean relative error.

			1 m/s	2 m/s	4 m/s	6 m/s
10ºC	AIR	D_{er} (10^{-8} m^2/s)	2.9 ± 0.9^{b}	1.2 ± 0.3^{b}	1.9 ± 0.2^{b}	1.2 ± 0.1^{ab}
		W_e (kg w/kg dm)	2.9 ± 0.4^{AB}	2.4 ± 0.4^{A}	4.5 ± 0.1^{C}	3.2 ± 0.2^{B}
		VAR (%)	98.3	97.9	97.3	97.9
		MRE (%)	4.3	6.6	8.1	6.0
	AIR+US	D_{er} (10^{-8} m^2/s)	0.5 ± 0.2^{a}	1.2 ± 0.2^{ab}	1.9 ± 0.6^{ab}	1.5 ± 0.1^{ab}
		W_e (kg w/kg dm)	3.1 ± 0.6^{B}	1.9 ± 0.3^{A}	3.5 ± 0.1^{BC}	3.8 ± 0.1^{BC}
		VAR (%)	98.1	97.8	96.1	96.8
		MRE (%)	6.9	8.3	8.6	9.6
0ºC	AIR	D_{er} (10^{-8} m^2/s)	1.1 ± 0.5^{a}	1.2 ± 0.3^{a}	0.9 ± 0.4^{a}	1.3 ± 0.2^{a}
		W_e (kg w/kg dm)	3.1 ± 0.2^{B}	2.9 ± 0.3^{AB}	3.1 ± 0.4^{B}	2.5 ± 0.2^{AB}
		VAR (%)	98.1	98.3	98.0	97.7
		MRE (%)	7.0	6.2	5.7	8.1
	AIR+US	D_{er} (10^{-8} m^2/s)	1.6 ± 0.5^{a}	1.4 ± 0.7^{a}	0.9 ± 0.3^{a}	1.4 ± 0.3^{a}
		W_e (kg w/kg dm)	2.5 ± 0.5^{A}	2.9 ± 0.3^{AB}	2.4 ± 0.4^{AB}	2.2 ± 0.4^{A}
		VAR (%)	94.8	97.6	96.4	97.3
		MRE (%)	7.9	6.0	7.8	5.6
-10ºC	AIR	D_{er} (10^{-8} m^2/s)	2.6 ± 0.2^{ab}	3.3 ± 0.9^{ab}	5.1 ± 0.5^{ab}	5.9 ± 0.9^{b}
		W_e (kg w/kg dm)	3.4 ± 0.2^{A}	3.3 ± 0.4^{A}	6.6 ± 0.4^{B}	4.7 ± 0.5^{A}
		VAR (%)	97.3	93.8	91.1	91.4
		MRE (%)	7.6	8.0	8.9	9.9
	AIR+US	D_{er} (10^{-8} m^2/s)	3.2 ± 0.9^{ab}	2.9 ± 0.8^{ab}	4.7 ± 0.5^{ab}	1.3 ± 0.1^{a}
		W_e (kg w/kg dm)	3.9 ± 0.7^{A}	3.2 ± 0.6^{A}	3.4 ± 0.4^{A}	6.5 ± 0.7^{B}
		VAR (%)	95.0	93.6	95.4	96.9
		MRE (%)	9.7	9.2	7.5	9.7

Superscript letters (a, b) and (A, B, C) show homogeneous groups, established from LSD (Least Significance Difference) intervals ($p<0.05$) at every temperature, for D_{er} and W_e, respectively.

Table 3. Hardness of rehydrated eggplant dried at different air velocities (1, 2, 4 and 6 m/s) and -10ºC without (AIR, 0 W) and with (AIR+US, 50 W) US application.

	1 m/s	**2 m/s**	**4 m/s**	**6 m/s**
AIR	8.3±1.6 [a]	9.0±1.4[a]	9.8±1.0[a]	8.6±0.9[a]
AIR+US	7.0±1.4 [a,b]	6.8±1.3[a,b]	10.3±0.3[a]	6.5±1.2[b]

Superscript letters (a) show homogeneous groups established from LSD (Least Significance Difference) intervals ($p<0.05$).