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Air-borne ultrasound application in the convective drying of strawberry

Juliana Gamboa-Santos[a], Antonia Montilla[a], Juan Andrés Cárcel[b], Mar Villamiel[a], Jose V. Garcia-Perez[b*]

[a] Instituto de Investigación en Ciencias de la Alimentación (CIAL) (CSIC-UAM). CEI (CSIC+UAM). Nicolás Cabrera, 9, E-28049 Madrid, Spain.

[b] Grupo de Análisis y Simulación de Procesos Agroalimentarios (ASPA). Departamento Tecnología de los Alimentos, Universitat Politècnica de València. Camí de Vera s/n, E-46022 Valencia, Spain.

*Author to whom correspondence should be addressed: Jose V. Garcia-Perez

Abstract

The use of non-thermal technologies, such as power ultrasound, is mostly suitable for the drying of thermolabile food materials. Thereby, the air-borne ultrasonic application as a means of improving the convective drying of strawberry has been explored in this work. Experiments were conducted by setting the acoustic power applied (0, 30 and 60 W) and the air temperature (40, 50, 60 and 70 ºC). The desorption isotherms and the shrinkage pattern were also experimentally determined. In order to describe the drying kinetics, a diffusion model considering both convective transport and shrinkage was used.

The increase in both the applied acoustic power and temperature gave rise to a significant reduction of drying time (13-44%). The application of power ultrasound involved a significant ($p<0.05$) improvement in the effective moisture diffusivity and the mass transfer coefficient, the effect being less intense at high temperatures. The results reported here highlight the fact that ultrasonic application during convective drying is a promising supporting technology with which to reduce the drying time needed for heat sensitive products, such as strawberry.

Key-words: Non-thermal processing; ultrasound; strawberry; modeling; effective diffusivity; mass transfer coefficient

1. Introduction

Over many decades, convective drying using hot air has been considered as the conventional dehydration method for foodstuffs since it extends shelf life and makes the low cost transportation and storage of the dry material easier. Despite being the most widely-addressed technique, hot air drying is considered one of the most energy intensive industrial operations. Thus, it is estimated that thermal dehydration processes account for up to 25% of the industrial energy consumption in developed countries (Chen & Mujumdar, 2008).

In order to understand the drying process and be able to improve it, mass transfer phenomena have been studied and the controlling resistances taken into account (Bon et al., 2007; Giner, 2009; Ozuna et al., 2011; Barati & Esfahani, 2013). Water transfer is mainly controlled by the rate of the water movement inside the materials (internal resistance, IR) and the convective transport from the solid surface to the air (external resistance, ER). The internal resistance is characteristic of the food material, while the external one depends mostly on the thickness of the diffusion boundary layer (Cárcel et al., 2007). Despite the great efforts made to improve the drying process, it is known that optimal requirements for the heat and mass transfer do not necessarily ensure the final products are of optimal quality.

During hot air drying, product quality loss is linked to the use of high temperatures and long drying times. Thus, the limitations to a conventional drying process could be partially overcome by using additional energy sources, such as microwave (Li et al., 2011), infrared radiation (Rastogi, 2012) or power ultrasound (US) (Cárcel et al., 2012; Chandrapala et al., 2012), which should help to reduce both drying time and temperature. In the case of microwave or infrared radiation, there is a risk of product overheating, which has to be considered when the drying of heat-sensitive products is addressed. On the contrary, US waves mainly produce mechanical effects and their air-borne application can intensify the water removal without introducing a high amount of thermal energy during drying (Riera et

al., 2011). This represents a great improvement in the field of non-thermal processing and environmentally-friendly, energy-saving technologies. In fact, it is acknowledged that US technology is a good example of how to ensure sustainability (Gallego-Juárez, 2010). Moreover, the fact that applying power US in gas media only produces a low thermal effect means that its application in the drying of heat-sensitive materials is of interest (Awad et al., 2012; Cárcel et al., 2012; Chemat et al., 2011). The ultrasonic effects in gas-solid systems are mainly linked to the rapid series of alternative compressions and expansions promoted by the ultrasonic waves in both the solid particle ("sponge effect") and the surrounding air. This mechanical force can create microscopic channels that allow an easier inner water movement (De la Fuente-Blanco et al., 2006), as well as microstreaming and high turbulence at the interfaces (Cárcel et al., 2012). Additionally, the phenomenon of cavitation could provoke the removal of the most strongly attached water molecules (Soria & Villamiel, 2010). Recent studies have reported how air-borne US application in food drying is greatly affected by both the operational parameters and product properties (Ozuna et al., 2011). These studies have addressed the US application in the drying of lemon (García-Pérez et al., 2009) and orange peel (Ortuño et al., 2010; García-Pérez et al., 2012), olive leaves (Cárcel et al., 2010), potatoes (Ozuna et al., 2011) and carrots (Cárcel et al., 2011), among others. However, to the best of our knowledge, there have been no previous studies into the ultrasonically assisted convective drying of berries. Strawberries are fruits which enjoy wide consumer acceptance not only due to their palatability but also to their nutritive value and bioactivity (Giampieri et al., 2012), making strawberries one of the largest fruit crops (Doymaz, 2008).

The aim of this paper was to assess the influence of the air temperature and the application of ultrasound on the convective drying kinetics of strawberry. For that purpose, experimental results were analyzed and modeled using the diffusion theory

2. **Materials and Methods**

2.1. Samples preparation

Fresh strawberries (*Fragaria x ananassa Duch*) were purchased from a local market in Valencia (Spain) and stored at 5 °C for a maximum of 3 days until drying. After washing in tap water, draining with blotting paper and removing the external impurities, strawberries were cut into 2.5 ± 0.5 mm thick slices along their longitudinal axis.

2.2. Moisture content

The moisture content of fresh strawberries was determined at 70 °C and 80 mbar vacuum level until constant weight (AOAC, 1990c).

2.3. Airborne US dryer

Strawberries were dried by using an ultrasonic-assisted convective dryer (**Figure 1**). The prototype was initially a current pilot-scale convective dryer, with its drying chamber subsequently modified to generate US waves (García-Pérez et al., 2006a; Riera et al., 2011). The ultrasonic device includes a cylindrical vibrating radiator driven by a piezoelectric transducer (21.8 kHz), which generates a high-intensity ultrasonic field in the air medium, where the samples are placed. A high power US generator, an impedance matching unit and a digital power meter (WT210, Yokogawa Electric Corporation, Japan) regulate and measure the electrical parameters of the acoustic signal (voltage, intensity, phase, frequency and power). The air parameters (velocity and temperature) were controlled through a PID algorithm and a PC supervised the whole drying process.

106 *2.4. Drying experiments*

107 An air velocity of 2 m/s was chosen for drying experiments of strawberry slabs,
108 according to previous studies carried out in the same dryer (Cárcel et al., 2007; García-Pérez
109 et al., 2006a and 2009). The temperature ranged between 40 and 70 °C (**Table 1**), which
110 could be considered mild drying temperatures. Two levels of ultrasonic energy were set by
111 applying specific electric powers to the transducer (30 and 60 W). Convective drying
112 experiments were run under the same experimental conditions but without applying US (0
113 W), thus being denominated "nonUS" drying experiments in the following sections. At least
114 three replicates of each experimental condition were carried out. A summary of the
115 processing conditions tested is shown in **Table 1**.

116 In the drying experiments, samples (73.5 ± 3.5 g) were randomly distributed in the
117 drying chamber to minimize the influence of the heterogeneity of the generated acoustic field.
118 For that purpose, samples were placed inside the vibrating chamber suspended in a metallic
119 frame that allows free air flow around each individual piece. Sample weight was
120 automatically recorded at 3 min intervals during the whole drying process.

121

122 *2.5. Desorption isotherm*

123 The water desorption isotherms were obtained from fresh strawberries. Milled
124 samples (3.08 ± 0.05 g) were partially dehydrated in a conventional air-forced oven at 50 °C
125 for different times (from 0.5 to 17 h). This allowed obtaining samples with a wide range of
126 final water content (0.2-11.2 kg water (W)/kg dry matter (DM)). The partially dried samples
127 were kept at 25 °C for 24 h in closed containers to achieve a homogeneous moisture
128 distribution. Then, the water activity (a_w) was measured in a standardized conductivity

hygrometer NOVASINA TH-500 (Air Systems for Air Treatment, Pfäffikon, Switzerland) at 25 °C. The device was previously calibrated using the following salts: LiCl, $MgCl_2$, $Mg(NO_3)_2$, NaCl, $BaCl_2$ and $K_2Cr_2O_7$ following the calibration procedure of the equipment manufacturer. Once a_w was determined, the sample moisture content was measured in triplicate (AOAC, 1990c). A total number of 30 water activity/moisture content experimental points were obtained. The well-known Brunauer, Emmet and Teller sorption isotherm model (Brunauer et al., 1938) was the equation used to describe the relationship between experimental a_w and moisture (Eq. 1). The BET model was fitted to the experimental data by using the SOLVER optimization tool available in Microsoft EXCEL™, identifying the model parameters (the monolayer moisture content, W_m, and the energy constant, C), which minimized the sum of the squared difference between the experimental and calculated moisture content.

$$W = W_m \frac{Ca_w}{(1-a_w)(1+(C-1)a_w)} \quad (1)$$

where W is the average moisture content (kg W/kg DM), a_w the water activity, W_m the monolayer moisture content (kg W/kg DM) and C the BET's model parameter (dimensionless).

2.6. Determination of Shrinkage

The product shrinkage was estimated using cubic samples of strawberries (8.5 mm), dried at 70 °C using an air velocity of 2 m/s and without US application (0 W). This kind of sample was chosen assuming an isotropic shrinkage and in order to improve the accuracy of the estimation. For that purpose, during drying, three samples were randomly collected and weighed every 30 min, measuring their moisture content (AOAC, 1990c) and volume. The

toluene displacement method was used to measure the volume (toluene density 0.867 g/mL at 20 °C) using a volumetric standard picnometer (48.89 mL) and an analytical balance (PB 303-5, Mettler Toledo) (García-Pérez et al., 2011). From the measurement of the volume, the length of the mass transport characteristic dimension (L), which coincides with the half-length of the cube side, was calculated by considering the samples maintained their cubic geometry. The relationship between L and the moisture content was considered in the mass transport modeling.

2.7. Modeling the drying kinetics

The diffusion theory was considered to describe the one-dimensional water transfer during drying. The governing equation (Eq. 2) for infinite slab geometry takes into account both the solid isotropy and a constant effective moisture diffusivity (D_e) during drying (Simal et al., 2003).

$$\frac{\partial W_p(x,t)}{\partial t} = D_e \frac{\partial^2 W_p(x,t)}{\partial x^2} \quad (2)$$

where W_p is the local moisture content (kg W/kg DM), x the mass transport direction (m) and t the time (s).

The model solution was addressed by considering that the sample volume did not remain constant during drying due to the phenomenon of shrinkage, which is especially noticeable in high-porosity products, such as fruits and vegetables (Schössler et al., 2012). Thus, mass transport was addressed as a moving boundary problem considering the half length of the infinity slab (L, m) to be moisture dependent, which was experimentally determined as explained before. For initial and boundary conditions, a homogeneous moisture content distribution in the solid (Eq. 3) and the solid symmetry (Eq. 4) was

considered. Moreover, the external resistance (ER) to mass transfer was taken as significant (Eq. 5) due to the low air velocity used, as reported in literature in previous studies (García-Pérez et al., 2009).

$$t = 0 \qquad W_p(x,0) = W_0 \tag{3}$$

$$t > 0; x = 0 \qquad \frac{\partial W_p(0,t)}{\partial x} = 0 \tag{4}$$

$$t > 0; x = L \qquad -D_e \rho_{ds} \frac{\partial W_p(L,t)}{\partial x} = k(a_w(L,t) - \varphi_{air}) \tag{5}$$

where ρ_{ds} is the dry solid density (kg DM/m^3), k is the mass transfer coefficient (kg W/m^2/s), a_w is the water activity on the solid surface and φ_{air} is the relative humidity of the drying air.

Experimental sorption isotherm (Eq. 1) at 25 ºC was used to roughly estimate the water activity (a_w) at the sample surface (Eq. 5) for the different drying conditions tested. While, the experimentally estimated shrinkage pattern contributed to model the reduction of the characteristic dimension (L) during drying. Eq. (2) was solved by considering both the initial and the boundary conditions already depicted and by applying an implicit finite difference method (Mulet et al., 2005). For that purpose, a programming code was written in Matlab R 2009d (The MathWorks, Inc., Natick, MA), which provided the local moisture distribution in the slab as well as the average moisture content (W). The model was fitted to the experimental drying kinetics by using the optimization tool *fminsearch function* (SIMPLEX method) available in Matlab. Thus, the D_e and k were simultaneously identified by minimizing the sum of the squared differences between the experimental and the calculated average moisture content.

192 In order to evaluate the fit of the models, the explained variance (VAR) and the mean
193 relative error (MRE) were computed from Eqs. (6) and (7) (Cárcel et al., 2011).

$$VAR = \left[1 - \frac{S_{tw}^2}{S_w^2}\right] \times 100 \quad (6)$$

$$MRE = \frac{100}{N}\left[\sum_{i=1}^{N} \frac{\left|W_{expi} - W_{calci}\right|}{W_{expi}}\right] \quad (7)$$

194

195 where S_w^2 and S_{tw}^2 are the variance of the experimental moisture data and the estimation,
196 respectively, W_{expi} and W_{calci} are the experimental and calculated average moisture contents
197 and N is the number of experimental data.
198 The Arrhenius equation was used (Sablani & Rahman, 2008) in order to quantify the
199 influence of the temperature on the D_e values (Eq. 8).

$$D_e = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (8)$$

200

201 Where D_0 is the pre-exponential Arrhenius factor (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol/K) and T is the temperature (K).

202 Analysis of variance (ANOVA) (Statgraphics 5.1 software) was carried out to identify
203 the significance (95%) of the influence of US application and air temperature factors on D_e
204 and k, while, Least Significance Intervals (LSD) were determined to identify significant
205 differences in the means.

206

207

3. **Results and discussion**

3.1. Experimental drying data

The strawberries presented an average initial moisture content of 9.55 ± 0.27 kg W/kg DM, which was considered as the critical moisture content due to the lack of a constant rate period under these experimental conditions. **Figure 2** shows the effect of temperature and power US on the experimental drying kinetics.

The temperature increase gave rise to substantially shorter drying times, which was noticeable at all the US powers applied. Thus, in order to reach an average moisture content of 0.3 kg W/kg DM, samples dried without applying US (0 W) at 40, 50, 60 and 70 °C needed 5.3, 4.6, 4.4 and 3.3 h, respectively. In the case of ultrasonically assisted drying assays at 60 W, the drying times ranged from 4.6 h at 40 °C to 2.2 h at 70 °C.

As can be observed in **Figure 2**, not only the temperature, but also the application of US affected the drying kinetic. At every temperature tested, the use of US improved the drying rate, and the higher the ultrasonic power applied, the faster the drying. Thus, for example, at 60 °C, the drying time needed to reach a moisture content of 0.3 (kg W/kg DM) was reduced from 4.4 h (0 W) to 2.5 h by applying an ultrasonic power of 60 W. Average drying time reductions brought about by applying US ranged from 13 to 44%. García-Pérez et al. (2009), Ortuño et al. (2010), Ozuna et al. (2011) and Cárcel et al. (2011) reported drying time reductions of about 30% in carrots, 53% in lemon peel, 45% in orange peel and 40% in potatoes under the same drying conditions (40 °C, 1 m/s and ultrasonic powers of up to 90 W). Even more substantial drying time reductions have been found in the case of eggplant, in which the application of an ultrasonic power of 90 W gave rise to a decrease of 72% in the drying time (García-Pérez et al., 2011). The internal structure of the different products could be the reason for the difference observed. Thus, eggplant has a highly

232 unconsolidated tissue with a porous structure (Wu et al., 2007), which, consequently, is more
233 heavily influenced by US application than other vegetables and fruits, such as strawberry.
234 Despite there being no previous references to air-borne US application in strawberry
235 drying, García-Noguera et al. (2010) reported the osmotic dehydration of strawberry assisted
236 by US as a pretreatment in order to improve the effectiveness of the subsequent drying. These
237 authors found that the drying time of strawberry halves was shortened by about 50% when
238 the samples were previously treated with US (25 kHz) in a 50% sucrose solution (30 °C for
239 30 min) prior to drying (60 °C, 0.5 m/s and 16% air relative humidity). In the same study,
240 they also tested the ultrasonic pre-treatment in distilled water, which resulted in a reduction in
241 the air-drying time of 18% as compared to the untreated samples. In this case, the US effects
242 are linked to structural changes in the fruit tissue brought about mainly by the cavitation
243 produced in liquid media. Among other factors, it was reported that US increased the sucrose
244 added to strawberry, changing, therefore, the nature of the fresh product and so, the drying
245 behavior.
246

247 *3.2. Shrinkage*

248 Under the experimental conditions here assayed, it was assumed that the US application
249 and the different air temperatures did not significantly affect the shrinkage; thus, this
250 phenomenon was monitored during the drying of strawberries at 70 °C in nonUS assays. As
251 previously mentioned in the *Materials and Methods* section, assuming the isotropy of the
252 material, strawberry cubes of 8.5 mm were used in order to assess the change of the side
253 length from the measurement of the total volume. From experimentally obtained results, a
254 linear relationship was obtained between volume (V/V_0) and moisture ratios (W/W_0) (**Figure**
255 **3**). According to the literature, similar relationships have been reported describing the

shrinkage in other vegetables and fruits (Koc et al., 2008; García-Pérez et al. 2011). Thus, the slope value (0.692) of this relationship (**Figure 3)** for strawberry drying was in the range previously reported by Ramallo & Mascheroni (2013) for pineapple samples dried at temperatures of between 45 and 75 °C (0.652-0.785). However, these values were lower than those found in the drying of eggplant (0.929-0.960) using hot air (García-Pérez et al., 2011) and a halogen moisture analyzer at 70-90 °C (Aversa et al., 2011). These differences might be linked to the different product structure and drying method, which can affect the collapse of the cell matrix.

From the afore-mentioned relationship, Eq. 9 was obtained to determine the change of the characteristic diffusion dimension (L) during drying and, afterwards, included in the modeling of the drying kinetics to provide a more realistic estimation of the effective moisture diffusivity.

$$L = \sqrt[3]{(0.692\frac{W}{W_0} + 0.325)L_0^3} \quad (9)$$

where subscript 0 refers to the initial time.

3.3. Desorption isotherms

The experimental desorption isotherm of strawberry determined at 25 °C is shown in **Figure 4**. According to Brunauer's classification (Brunauer et al., 1940), it may be classified as type III "Raoult's type" (Blahovec & Yanniotis, 2010): products with small amounts of water at low a_w and large amounts at high a_w levels (García-Pérez et al., 2008). Type III curves were also observed for other fruits (Lim et al., 1995; Mäskan & Gögüs, 1998; Vázquez et al., 1999).

277 The BET model was used for modeling the experimental relationship between the a_w
278 and the equilibrium moisture content in strawberry samples. Despite the high experimental
279 variability observed, the BET model reached high VAR (96.3%) and low RME (9.4%). The
280 accuracy of the model's fit is also shown in **Figure 4**. The BET parameters identified from
281 modeling the experimental data of the a_w and the moisture content in strawberry samples
282 were 0.316 kg W/kg DM for W_m and 3.63 for C. The W_m value was slightly higher than those
283 reported for cherries and blueberries by Yu et al. (1998) (0.12-0.13 kg W/kg DM) and Vega-
284 Gálvez et al. (2009) (0.08-0.13 kg W/kg DM), but lower (0.74-0.95 kg W/kg DM) than others
285 reported for strawberries (Moraga et al., 2004). In the case of the C value, Garau et al. (2006),
286 García-Pérez et al. (2008) and Molina-Filho et al. (2011) obtained similar data when studying
287 orange peel (2.4), lemon peel (1.4-4.9) and pumpkins (1.9-4.2), respectively. Since parameter
288 C is related to water molecule-food matrix interactions (Erbas et al., 2005), the results
289 obtained working on strawberries could be associated with a relatively low heat of sorption,
290 compared with values reported by Vega-Gálvez et al. (2009) for blueberries (C: 101.45 at 40
291 °C). In some of the previously-cited works (Moraga et al., 2004; Garau et al., 2006; García-
292 Pérez et al., 2008), GAB equations were simplified to BET models due to the fact that the K
293 constant of the GAB model was nearly equal to one; thus, they were used for the purposes of
294 comparison with the BET model parameters identified in this work.
295 The BET model here proposed will be used in the following section in the modeling of
296 the drying kinetics; it will help to quantify the convective water flux at the interface (Eq. 5).
297
298 *3.4. Mass transport*
299 **Table 2** shows the average effective moisture diffusivities (D_e) and the mass transfer
300 coefficients (k) identified from fitting the diffusion model for slab geometry to the

experimental drying kinetics of strawberry. The diffusion model, considering ER to mass transfer and shrinkage to be significant, provided an accurate description of experimental data. Regardless of the drying conditions, the obtained VAR values were over 99% and, in overall terms, the MRE were under 5%. Moreover, **Figure 5** illustrates, taking as an example the tests carried out at 70 °C (0, 30 and 60 W), the agreement between experimental and calculated data by the model.

The D_e values (from 0.763 to 2.293 x 10^{-10} m^2/s) shown in Table 2 were within the same order of magnitude of others previously reported for the convective drying of strawberries and also fell within the common range for foodstuffs (between 10^{-11} and 10^{-9}) (Doymaz, 2008). Furthermore, D_e values were close to those identified by García-Pérez et al. (2009 and 2012); Ozuna et al. (2011) and Cárcel et al. (2011) in the US-assisted drying of several fruits and vegetables.

3.4.1. Effect of temperature

As can be observed in **Table 2**, a rise in the drying temperature increased both the D_e and k parameters at every ultrasonic power level tested. From 40 °C to 70 °C, the D_e and k value were duplicated in both nonUS and US experiments. Similar results were obtained by Doymaz (2008) for the convective drying of strawberries between 50 and 65 °C (D_e from 4.95 x 10^{-10} to 1.09 x 10^{-9} m^2/s). D_e values reported by Doymaz (2008) were identified using a diffusion model which did not consider ER, thus, in a certain way, they also include the effect of temperature on external mass transport coefficients. Therefore, their direct comparison with the results reported here is complicated. If models that consider ER to mass transfer are taken into account, greater improvements in D_e have been identified. Thus, when drying carrot cubes, García-Pérez et al. (2006b) reported a D_e increase of 137% when the

temperature rose from 40 °C (1.93 x 10^{-10} m^2/s) to 70 °C (4.57 x 10^{-10} m^2/s). The temperature increase activates water molecules, speeding up the water transfer through the particle.

The influence of temperature on D_e was quantified from an Arrhenius type relationship (Simal et al., 2005; Sablani & Rahman, 2008; Vega-Gálvez et al., 2008) (**Figure 6**). Linear correlation coefficients higher than 0.99 were found for the different assays carried out (0, 30 and 60 W). The E_a value calculated (25.3 ± 1.9 kJ/mol) in nonUS experiments (0 W) was within the range of those proposed for other products: 42.3 kJ/mol for peas (Senadeera et al., 2003); 28.4 kJ/mol for carrots (Doymaz, 2004); 21.9 and 32.3 kJ/mol for kiwi (Simal et al., 2005); 28.6-31.5 kJ/mol for papaya (Vega-Gálvez & Lemus-Mondaca, 2006), and 18.1- 43.2 kJ/mol for apple (Vega-Gálvez et al., 2008). The identified E_a values decreased to 21.9 ± 2.1 and 20.6 ± 1.8 kJ/mol for assays carried out applying 30 and 60 W respectively, as observed in the slopes of the linear relationships depicted in **Figure 6**. Thus, E_a values for nonUS and 60 W experiments were significantly different ($p<0.05$). Therefore, in a certain way, the ultrasonic power affected the strawberry drying, this aspect being addressed in the following section.

3.4.2. Effect of power ultrasound

The application of US increased the identified D_e and k values at every temperature tested (**Table 2**), the effect being dependent on the power applied; so, the higher the power applied, the larger the improvement of these parameters. In the case of D_e, the average increase was of 18 and 42% for 30 and 60 W, respectively. Similar improvements were reported for the US-assisted drying of other fruits and vegetables. Thus, in potatoes, the D_e values increased by 19% (30 W) and 41% (60 W), when dried at 40 °C (Ozuna et al., 2011). In the case of carrots, an increase of only 17% was obtained by applying 60 W at 40 °C

whereas average improvements of 62% and 100% were reported in lemon peel slabs dried at 40 °C and at 30 W and 60 W (García-Pérez et al., 2009). When studying other more porous materials such as eggplant, García-Pérez et al. (2011) reported improvements of up to 92 and 211%, by applying US at 30 and 60 W, respectively. As reported in the literature (Riera et al., 2011), the phenomenon of alternating expansion and contraction cycles produced by applying power US to the materials should be what mainly speeds up the inner water movement, which is manifested in the increase in D_e.

As already mentioned, the air temperature during drying influenced the effects of US on mass transport. Thus, the average improvement of D_e at low temperatures (40, 50 °C) was 25.8 and 52.3% at 30 and 60 W, respectively, which was reduced to 11.1 and 31.5% at high temperatures (mean for 60 and 70 °C, respectively). Likewise, the negative effect that high temperatures have on the influence of US has also been reported in the case of carrot cube drying (García-Pérez et al., 2006b). This phenomenon is linked to the fact that, at high temperatures and due to the large amount of thermal energy available in the medium, the ratio of energy provided by US over total energy could almost be negligible (Riera et al., 2011).

Power US application also affected the convective water transport. As illustrated in **Table 2**, the application of US increased the k value significantly ($p<0.05$) at any temperature assayed. The average k increase, compared to nonUS experiments, was 13% and 50% at 30 W and 60 W, respectively. US waves create turbulences, oscillating velocities and microstreaming at the interfaces, which leads to a reduction of the boundary layer thickness and so, to an increase in the k values (Puig et al., 2012). Previous works have confirmed the ability of US not only to improve the mass transfer at the interface but also to provoke structural changes on the product surface (Ortuño et al., 2010; Cárcel et al., 2011; Ozuna et al., 2011). For example, from microstructural observations during orange peel drying, Ortuño et al. (2010) observed the spread of waxy compounds over the cuticle surface, which was

374 linked to the great turbulence generated by US at the interface. Therefore, further work will
375 be needed to elucidate how US influences the quality of the material being dried.
376

377 ## 4. Conclusions

378 The results here reported highlight that air-borne ultrasonic application during the
379 convective drying of strawberries is a promising supporting technology to conventional
380 drying processes due to its ability to improve mass transport phenomena, so shortening
381 drying time. The effect of power US on strawberry drying was dependent on the ultrasonic
382 power and temperature applied. Thus, the more the ultrasonic power applied, the faster the
383 drying and the higher the drying temperature, the milder the ultrasonic effect. The modeling
384 pointed to the fact that US application had a significant effect on both the D_e and the external
385 k.
386

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392

393 **Nomenclature**

a_w	Water activity	
C	BET's model parameter	
DM	Dry matter	
D_e	Effective moisture diffusivity	m^2/s
D_0	Pre-exponential Arrhenius factor	
E_a	Activation energy	kJ/mol
k	Mass transfer coefficient	kg W/m^2/s
L	Mass transport characteristic dimension	m
N	Number of experimental points	
R	Universal gas constant	kJ/mol/K
S_w^2	Variance of experimental moisture	(kg W/kg DM)^2
S_{tw}^2	Variance of moisture estimation	(kg W/kg DM)^2
t	Time	s
T	Temperature	K
V	Volume	m^3
VAR	Explained variance	
W	Moisture content	kg W/kg DM
x	Mass transport characteristic direction	
ρ_{ds}	Dry solid density	kg DM/m^3
φ_{air}	Relative humidity of the drying air	

Subscripts

calc	Calculated
exp	Experimental
m	Monolayer
0	Initial
p	Local

394

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FIGURE CAPTIONS

Figure 1 Diagram of the ultrasonic assisted drier. 1. Fan, 2. Heating unit, 3. Anemometer, 4. Three-way valve, 5. Thermocouple, 6. Sample loading chamber, 7. Coupling material, 8. Pneumatic system, 9. Ultrasonic transducer, 10. Vibrating cylinder, 11. Trays, 12. Balance, 13. Impedance matching unit, 14. Digital power meter, 15. High power ultrasonic generator, 16. PC.

Figure 2 Drying kinetics (2 m/s) of strawberry slabs at different temperatures applying different ultrasonic powers.

Figure 3 Variation of volume and moisture ratio for strawberry cubes during drying (2 m/s, 70 °C).

Figure 4 Experimental and calculated (BET model) sorption isotherm of strawberry samples at 25 °C.

Figure 5 Experimental (W_{exp}) vs. calculated (W_{calc}) moisture content of strawberry slabs dried at 70 °C applying an ultrasonic power of 0, 30 and 60 W.

Figure 6 Fit of Arrhenius equation (continuous line) to the identified moisture diffusivities for power-ultrasound assisted strawberry drying. Experiments carried out at 2 m/s applying different ultrasonic powers (0, 30 and 60 W).

Figure 1

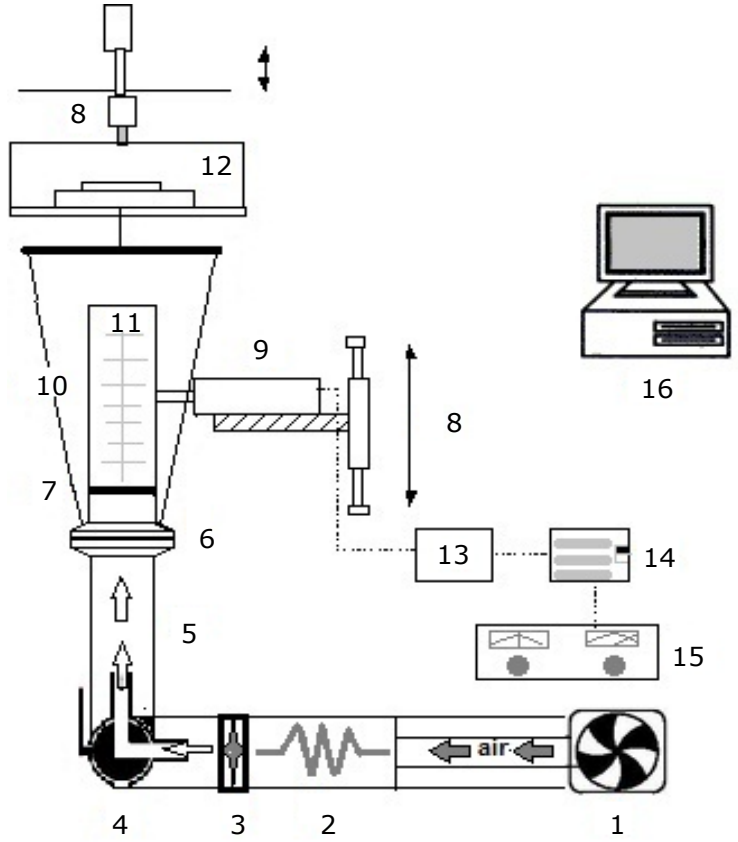
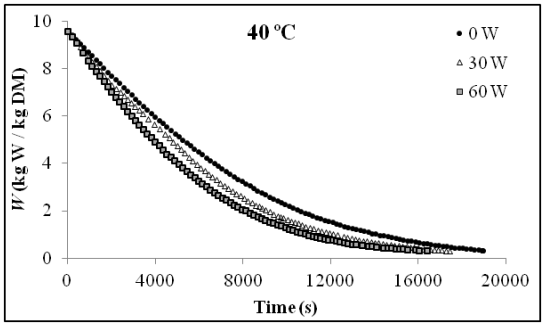
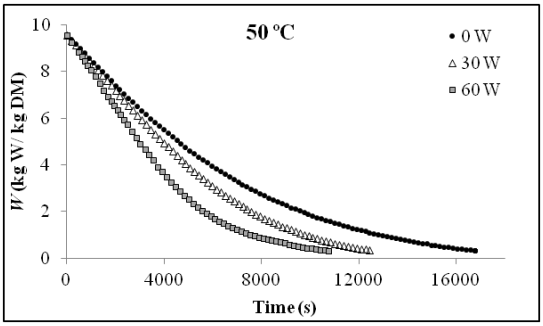
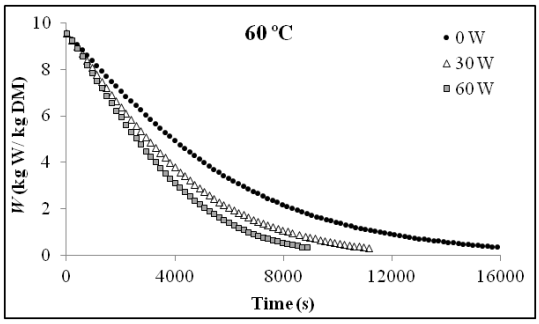


Figure 2


40 °C
• 0 W
△ 30 W
▫ 60 W
W (kg W / kg DM)
Time (s)
0
2
4
6
8
10
0
4000
8000
12000
16000
20000


50 °C
• 0 W
△ 30 W
▫ 60 W
W (kg W / kg DM)
Time (s)
0
2
4
6
8
10
0
4000
8000
12000
16000


60 °C
• 0 W
△ 30 W
▫ 60 W
W (kg W / kg DM)
Time (s)
0
2
4
6
8
10
0
4000
8000
12000
16000

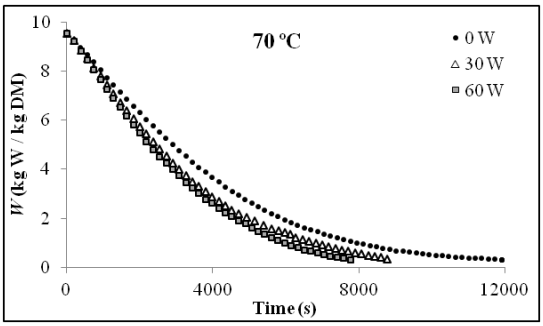

70 °C
• 0 W
△ 30 W
▫ 60 W
W (kg W / kg DM)
Time (s)
0
2
4
6
8
10
0
4000
8000
12000

Figure 3

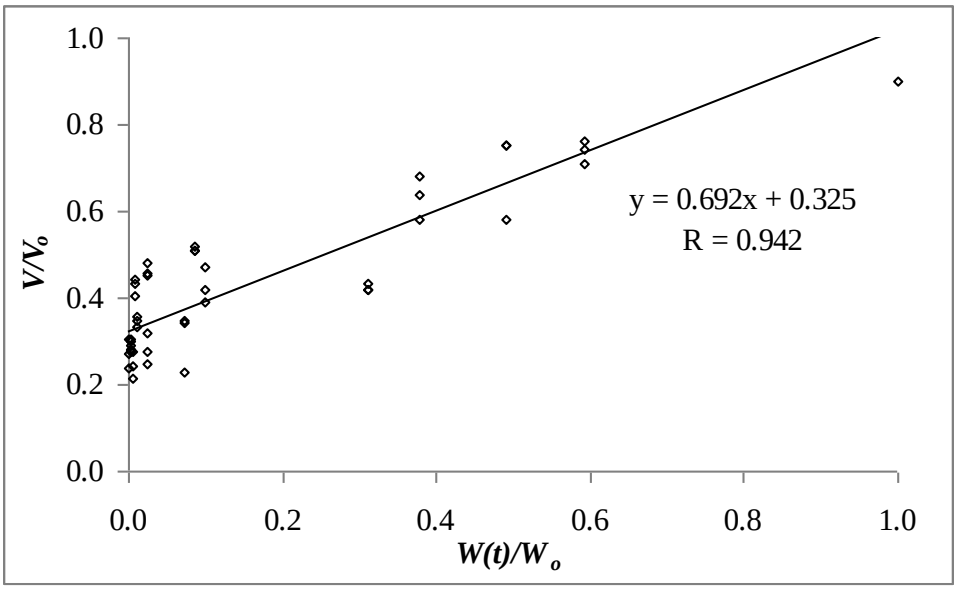


Figure 4

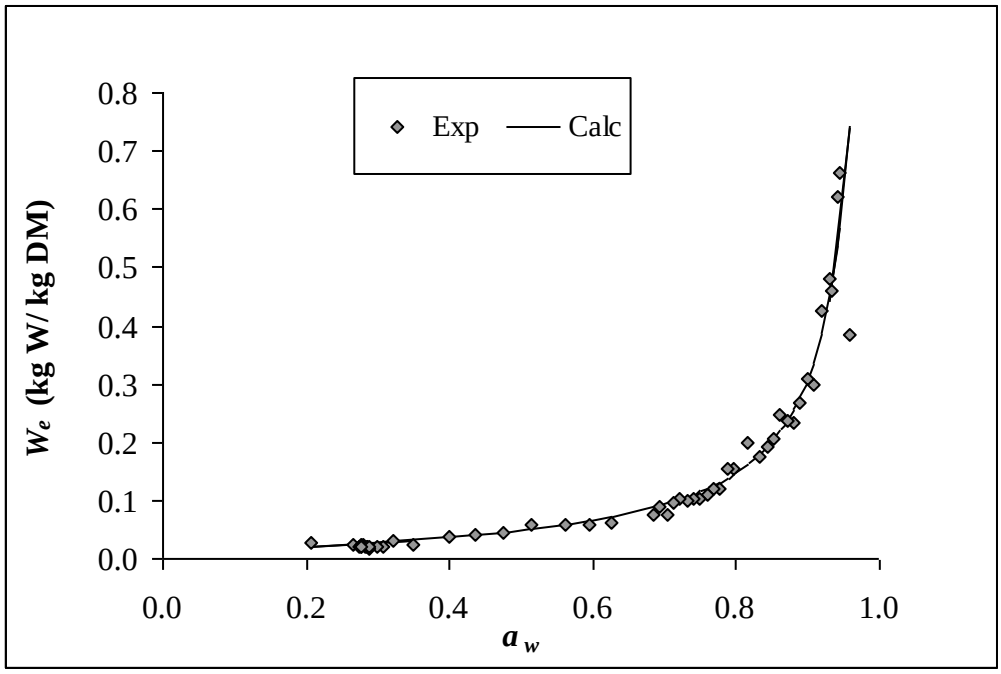


Figure 5

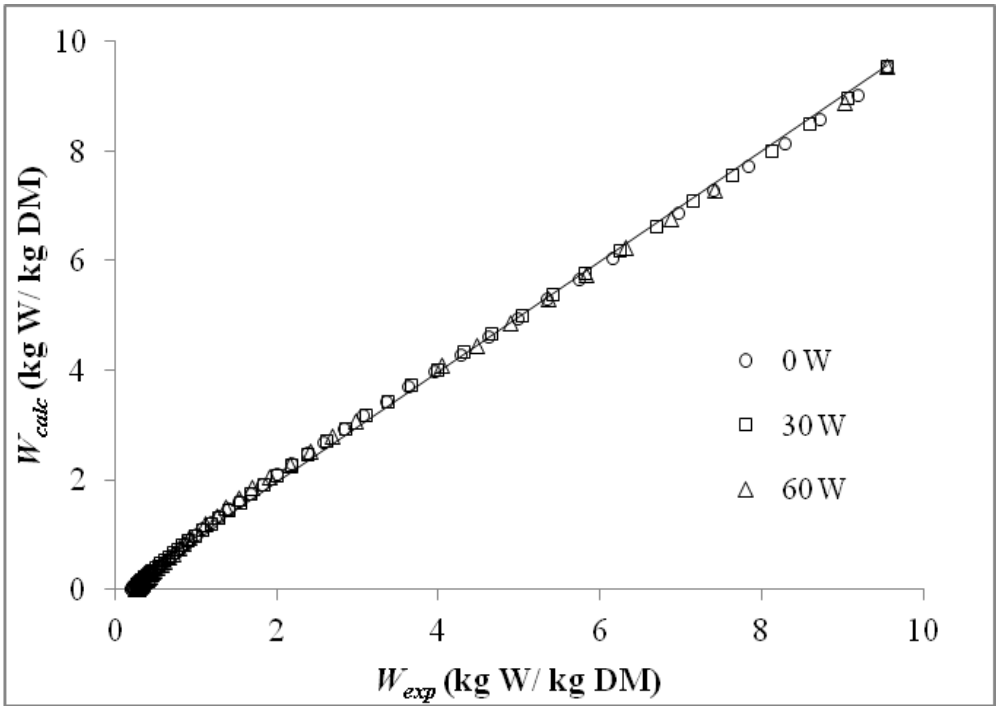


Figure 6

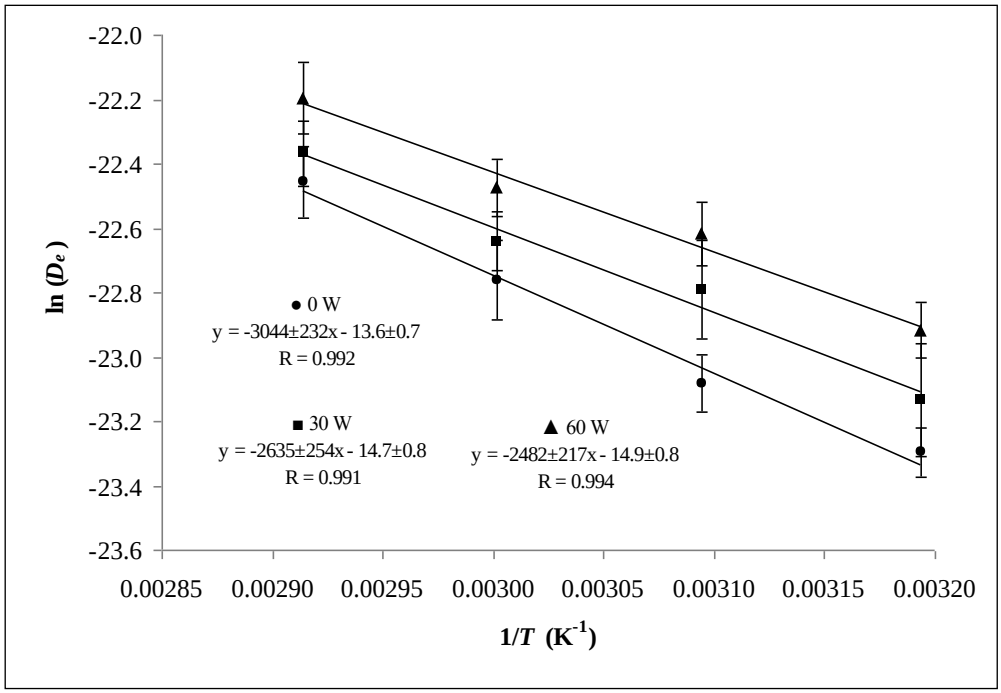

-22.0
-22.2
-22.4
-22.6
-22.8
-23.0
-23.2
-23.4
-23.6
ln (De)
0.00285
0.00290
0.00295
0.00300
0.00305
0.00310
0.00315
0.00320
1/T (K-1)
● 0 W
y = -3044±232x - 13.6±0.7
R = 0.992
■ 30 W
y = -2635±254x - 14.7±0.8
R = 0.991
▲ 60 W
y = -2482±217x - 14.9±0.8
R = 0.994

Table 1

Table 1 Processing conditions for ultrasonically assisted convective drying of strawberries

Assays	Temperature (°C)	US power* (W)
nonUS-40	40	0
US-40-30	40	30
US-40-60	40	60
nonUS-50	50	0
US-50-30	50	30
US-50-60	50	60
nonUS-60	60	0
US-60-30	60	30
US-60-60	60	60
nonUS-70	70	0
US-70-30	70	30
US-70-60	70	60

*Specific electric power applied to the transducer.

Table 2

Table 2 Modeling of drying kinetics of ultrasonically assisted drying of strawberry. Identified parameters and statistical analysis (Means ± SD)

Assays	D_e $(10^{-10} m^2/s)$	k $(10^{-5} kg\ W/m^2/s)$	*VAR (%)*	*MRE (%)*
nonUS-40	0.763 ± 0.075^{a}	1.446 ± 0.256^{a}	99.74	3.79
US-40-30	0.898 ± 0.173^{ab}	1.380 ± 0.405^{a}	99.98	3.30
US-40-60	1.117 ± 0.086^{bc}	1.633 ± 0.160^{ab}	99.97	3.26
nonUS-50	0.947 ± 0.089^{ab}	1.630 ± 0.194^{ab}	99.97	4.25
US-50-30	1.267 ± 0.154^{cd}	1.750 ± 0.311^{abc}	99.90	4.23
US-50-60	1.500 ± 0.099^{de}	2.017 ± 0.180^{bcd}	99.97	3.84
nonUS-60	1.305 ± 0.123^{cd}	2.008 ± 0.234^{bcd}	99.85	4.09
US-60-30	1.470 ± 0.091^{def}	2.380 ± 0.150^{cde}	99.99	1.06
US-60-60	1.737 ± 0.089^{efg}	2.593 ± 0.170^{de}	99.98	2.98
nonUS-70	1.772 ± 0.112^{fg}	2.868 ± 0.202^{ef}	99.89	6.75
US-70-30	1.937 ± 0.101^{g}	3.277 ± 0.509^{f}	99.93	4.67
US-70-60	2.293 ± 0.110^{h}	3.387 ± 0.320^{f}	99.88	3.55

[1]Means with the same superscript letter (a-f) within the same column showed no statistically significant differences for their mean values at the 95% confidence level (LSD).