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Additional Information

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2 Moisture loss kinetics and microstructural changes in eggplant (*Solanum melongena* L.)  
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5 during conventional and ultrasonically assisted convective drying  
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1  
2 **ABSTRACT**  
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4 The overall aim of this study was to assess the moisture loss kinetics and the structural  
5 changes induced by both conventional and ultrasonically assisted convective drying of  
6 eggplant tissue. Three sets of drying experiments (at 40 °C and 1 m/s) were carried out:  
7 conventional air drying and ultrasonically assisted drying at two different levels of  
8 applied ultrasonic power, 45 and 90 W. The microstructure of the dried samples was  
9 studied by Scanning Electron Microscopy.  
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19 The application of ultrasound during the convective drying of eggplant led to a  
20 significant reduction of the drying time. The ultrasonic effect was dependent on the  
21 power applied, thus, the higher the power, the faster the moisture loss. The  
22 microstructure of eggplant endocarp was greatly affected during conventional air  
23 drying, probably due to the long drying times. This microstructure was better preserved  
24 after the application of a moderate ultrasonic power (45 W), due to the shorter drying  
25 time and the mild mechanical effects of ultrasound on the endocarp cells.  
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39 Key-words: ultrasound, dehydration, modeling, microstructure  
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## 1. INTRODUCTION

Eggplant is a relevant crop in North America, Asia and the Mediterranean area. Its limited shelf life is one of the main restrictions on the trade of eggplant as a fresh product. Dehydration constitutes an alternative with which to provide more stable eggplant products, which may be shipped to foreign markets or used the whole year round (Akpinar and Bicer, 2005).

Convective drying is the most traditional dehydration method used to preserve foods; it mainly consists of forcing air through the product to be dried. This drying process involves chemical, physical, structural and nutritional changes, linked to the water loss and the high temperatures applied (Concellón et al., 2007; Hernando et al., 2008), which affect the product quality. In such a way, Hung and Duy (2012) reported the reduction of bioactive compounds content in eggplant by hot air drying. Actually, the structural changes are more intense in high porosity products, such as eggplant.

The convective drying of eggplant has already been reported in literature (Akpinar and Bicer, 2005; Wu et al., 2007; Doymaz, 2011; Doymaz and Göl, 2011; Garcia-Perez et al., 2011), but only a few works have addressed the effect of drying on the product's structure. Thus, Chaves and Avanza (2004) studied the shrinkage of eggplant slabs during hot air drying and Doymaz and Göl (2011) addressed the effect of blanching prior to hot air drying. Otero et al. (1998) tested the effects of high-pressure-assisted freezing and conventional air-freezing on the microstructure of eggplant tissue. Other authors have added enzymes and calcium to eggplant tissue in order to test how this protects the microstructure during drying (Banjongsinsiri et al., 2004).

On the other hand, as the convective drying process is one of great relevance on an industrial level, it has been rigorously addressed in literature (Mulet et al., 2005;

1  
2 Doymaz, 2011; Doymaz and Göl, 2011). Despite the strenuous efforts made to improve  
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4 it, the loss of product quality and the high energy demand are still considered as big  
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6 challenges that have to be met (McMinn and Magee, 1999). In order to shorten the  
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8 drying time or decrease the air drying temperatures, the combination of additional  
9  
10 energy sources with forced air have been tested, such as microwave and infrared  
11  
12 radiation (Orsat et al., 2007). In this sense, high power ultrasound is of great interest due  
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14 to the fact that its effects on kinetics are based on mechanical mechanisms more than on  
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16 heating effects, which leads to a shorter drying time without significantly heating the  
17  
18 product. Thus, ultrasonically assisted convective drying allows the use of milder drying  
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20 temperatures than conventional drying. Both aspects, drying time and temperature  
21  
22 reduction, are considered relevant in order to better preserve the product quality during  
23  
24 drying. The potential of the application of high power ultrasound to several fruits and  
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26 vegetables during their drying has been reported (Da-Mota and Palau, 1999; Gallego-  
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28 Juarez et al., 1999; Garcia-Perez et al., 2007; Garcia-Perez et al., 2009). Actually, these  
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30 works have focused on gaining insight into the effects of ultrasound on the mass  
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32 transport phenomena. However, the same ultrasonic mechanisms that accelerate the  
33  
34 mass transfer process may also induce some kinds of changes to the product structure.  
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36 In this sense, structural changes have already been reported for other ultrasonically-  
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38 assisted food processes, such as brining (Sanchez et al., 2001) and meat ageing (Stadnik  
39  
40 et al., 2008). Therefore, the microstructural studies are of great interest in order to  
41  
42 evaluate the application of ultrasound in convective drying processes on an industrial  
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44 scale.

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46 The overall aim of this study was to assess the moisture loss kinetics and the structural  
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48 changes induced by both the conventional and the ultrasonically assisted convective  
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2 drying of eggplant tissue. This strategy aims to identify any common ground existing  
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4 between the effects induced by the ultrasonic application on both material structure and  
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6 mass transfer kinetics.  
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## 10 11 12 **2. MATERIALS AND METHODS**

### 13 14 **2.1. Drying experiments**

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16 Cylindrically shaped samples (height 2 cm and diameter 2.4 cm) were obtained from the  
17  
18 flesh of eggplants purchased in local markets (*Solanum melongena* var. Black Enorma).  
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20 For obtaining peeled samples, eggplant was sliced (thickness 2 cm) and cylinders were  
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22 taken out using a 2.4 cm hole puncher. The moisture content of the fresh eggplant was  
23  
24 determined by placing samples at 70 °C in a vacuum oven (absolute pressure 26.7 kPa,  
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26 Vaciotem-T, JP Selecta, Spain) until reaching constant weight, following AOAC  
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28 standards (AOAC, 1997).  
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34 Drying experiments were conducted in an ultrasonically assisted convective drier,  
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36 which has already been described in the literature (Garcia-Perez et al., 2009; Garcia-  
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38 Perez et al., 2011). An air borne ultrasonic device constitutes the drying chamber  
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40 (volume 2.4 L), it includes an aluminium vibrating cylinder (internal diameter 100 mm,  
41  
42 height 310 mm and thickness 10 mm) driven by a piezoelectric composite transducer  
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44 (21.7 kHz). Drying air goes through the vibrating cylinder where samples are placed.  
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46 Conventional convective drying experiments (AIR) were carried out on eggplant  
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48 cylinders, keeping the air velocity (1 m/s) and temperature (40 °C) constant.  
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50 Ultrasonically assisted (AIR+US) convective drying experiments were carried out at  
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52 two different power levels (specific electric power applied to the ultrasonic transducer),  
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54 45 and 90 W, and maintaining the same air velocity and temperature as in conventional  
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2 drying experiments (AIR). Thus, ultrasonic power densities of 18.5 (AIR+US-45W) and  
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4 37.0 W/L (AIR+US-90W) were tested. Before drying, samples were sealed using plastic  
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6 film and kept cold (4 °C) until drier was properly fitted to experimental conditions  
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8 (average storage time 10 minutes). In every case, the AIR and AIR+US experiments  
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10 were carried out at least three times and prolonged until the samples lost 80% of the  
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12 initial weight.  
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## 19 **2.2.Drying process modelling**

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21 A diffusion model based on the 2<sup>nd</sup> Fick's law was used to describe the moisture loss  
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23 kinetics of eggplant cylinders (Mulet et al., 2005; Hadrich and Kechaou, 2009). Eq. 1  
24  
25 shows the differential equation of diffusion for isotropic solids and finite length  
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27 cylindrical geometry considering the effective moisture diffusivity to be constant (Simal  
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29 et al., 1998):  
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$$34 \frac{\partial W_p(r, x, t)}{\partial t} = D_e \left( \frac{\partial^2 W_p(r, x, t)}{\partial x^2} + \frac{\partial^2 W_p(r, x, t)}{\partial r^2} + \frac{1}{r} \frac{\partial W_p(r, x, t)}{\partial r} \right) \quad (1)$$

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38 Where  $W_p$  is the local moisture (dry basis, kg water/kg dry matter),  $t$  is the time (s),  $D_e$   
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40 is the effective moisture diffusivity ( $m^2/s$ ) and  $x$  and  $y$  represent the axial and radial  
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42 pathways for mass transport, respectively.  
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46 The hypotheses assumed to solve Eq. 1 are listed as follows:  
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- 48 • The initial moisture content and temperature are uniform inside the sample due  
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50 to the previous tempering period of the sealed samples.
- 51 • Sample volume does not remain constant during drying due to the shrinkage  
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53 brought about by the water loss. Thus, mass transport should be addressed as a  
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55 moving boundary problem.  
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- The solid symmetry in both radial and axial pathways.
- A significant external resistance to water transfer due to the low air velocity (1 m/s) (Garcia-Perez et al., 2009), which forces the water flux between the solid surface and the air flow to be considered in both axial and radial pathways.

Taking the previous hypotheses into consideration, the following initial and boundary conditions were fixed to solve Eq. 1:

$$W_p(r,x,0) = W_0 \quad \text{in } 0 \leq x \leq L; 0 \leq r \leq R \quad \text{at } t = 0 \quad (2)$$

$$\frac{\partial W_p(0,x,t)}{\partial r} = 0 \quad \text{in } r = 0; 0 \leq x \leq L \quad \text{at } t > 0 \quad (3)$$

$$-D_e \rho_{ss} \frac{\partial W_p(R,x,t)}{\partial r} = k(\varphi_e(R,x,t) - \varphi_{air}) \quad \text{in } r = R; 0 \leq x \leq L \quad \text{at } t > 0 \quad (4)$$

$$\frac{\partial W_p(r,0,t)}{\partial x} = 0 \quad \text{in } x = 0; 0 \leq r \leq R \quad \text{at } t > 0 \quad (5)$$

$$-D_e \rho_{ss} \frac{\partial W_p(R,x,t)}{\partial r} = k(\varphi_e(R,x,t) - \varphi_{air}) \quad \text{in } x = L; 0 \leq r \leq R \quad \text{at } t > 0 \quad (6)$$

Where: L is the sample half height (m), R the sample radius (m),  $W_0$  the initial moisture content,  $\rho_{ss}$  the dry solid density, k the mass transfer coefficient (kg water/m<sup>2</sup>/s),  $\varphi_e$  the water activity (Garcia-Perez et al., 2011) and  $\varphi_{air}$  the relative humidity of the drying air.

Eggplant shrinkage has already been reported in previous works, thus, Garcia-Perez et al. (2011) reported Eq. 7 using the toluene displacement technique, depicting the change in eggplant volume (V) as regards the average moisture content (W).

$$\frac{V}{V_0} = 0.929 \frac{W}{W_0} + 0.112; \quad r^2 = 0.99 \quad (7)$$

Where subscript 0 indicates the initial state.



1  
2 An implicit finite difference method was applied to solve the diffusion problem (Mulet  
3  
4 et al., 2005), as reported by Garcia-Perez et al. (2011). A computational procedure  
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6 written in Matlab code (The MathWorks, Inc., Natick, MA, USA) allowed the local  
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8 moisture distribution to be obtained and, by integration, the average moisture content of  
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10 the solid, as a function of drying time, effective moisture diffusivity and mass transfer  
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12 coefficient.  
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17 In order to evaluate the influence of the ultrasonic application on the overall mass  
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19 transport, it is of great importance to identify the kinetic parameters, the effective  
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21 moisture diffusivity ( $D_e$ ) and the mass transfer coefficient ( $k$ ), due to the fact that they  
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23 are related to the internal and external resistance to mass transfer.  $D_e$  determines the  
24  
25 water's ability to move inside the material (Castell-Palou and Simal, 2011). It is an  
26  
27 intrinsic and structural property of the material, but, due to its kinetic aspect, it is also  
28  
29 influenced by external factors, like temperature. According to the literature (Da-Mota  
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31 and Palau, 1999; Gallego-Juarez et al., 1999), the ultrasonic mechanisms should be  
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33 expected to speed up the water's mobility in the material and, as a consequence, the  $D_e$   
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35 should improve. In the case of parameter  $k$ , it determines the kinetic of the water  
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37 movement from the solid surface to the air flow.  $k$  is mainly controlled by the flow  
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39 turbulence, and obviously the boundary layer thickness. Ultrasonic waves produce great  
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41 turbulence in the interfaces leading to an increase in  $k$  value. Both parameters,  $D_e$  and  $k$ ,  
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43 were simultaneously estimated by fitting the proposed diffusion model to the  
44  
45 experimental drying kinetics. The fitting procedure consists of minimizing the squared  
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47 differences between the experimental and the calculated average moisture content  
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49 separately for the different experimental conditions assayed. For that purpose, the  
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51 SIMPLEX optimization method available in Matlab (fminsearch function) was used. In  
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2 order to determine the accuracy of the fit, the percentage of explained variance (%VAR,  
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4 Eq. 8) and the mean relative error (%MRE, Eq. 9) were calculated.  
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$$7 \quad \%VAR = \left[ 1 - \frac{S_{tW}^2}{S_W^2} \right] \times 100 \quad (8)$$

$$8 \quad \%MRE = \frac{100}{N} \left[ \sum_{i=1}^N \frac{|W_{ei} - W_{ci}|}{W_{ei}} \right] \quad (9)$$

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18 where  $S_W^2$  and  $S_{tW}^2$  are the variance of the sample and the estimation, respectively,  $W_{ei}$   
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20 and  $W_{ci}$  are the experimental and calculated average moisture contents and N the  
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22 number of experimental points in the drying kinetic.  
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### 2.3. Microstructural analysis

The microstructure of fresh, AIR and AIR+US (45 and 90 W) dried samples was studied using Cryo-SEM and SEM techniques. AIR dried samples were considered a control sample in order to identify the influence of power ultrasound on the structure of dried samples.

#### Low Temperature Scanning Electron Microscopy (Cryo-SEM)

Unpeeled samples containing both flesh and skin were used for the Cryo-SEM analysis.

This permitted a study into the effect of the drying conditions on the different eggplant

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2 tissues (external and internal) to be carried out. The experimental set-up involves a  
3  
4 cryostage CT-1500C (Oxford Instruments, Witney, UK) coupled to a Jeol JSM-5410  
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6 scanning electron microscope (Jeol, Tokyo, Japan). Samples were immersed in slush N<sub>2</sub>  
7  
8 (at -210 °C) and then quickly transferred to the cryostage at 1 kPa, where sample  
9  
10 fracture took place. The sublimation was carried out at -95 °C and the final point was  
11  
12 determined by direct microscopic observation (5 kV). Once again in the cryostage unit,  
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14 the sample was gold-coated using an ionization current of 2 mA and applying vacuum  
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16 (0.2 kPa) for 3 min. A scanning electron microscope was used to carry out the  
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18 observation at 15 kV, using a working distance of 15 mm and at -130 °C.  
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### 23 Scanning Electron Microscopy (SEM)

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25 For the SEM study, cubic (3x3x3 mm) samples of the eggplant flesh were obtained with  
26  
27 a stainless steel cutter. The samples were fixed in a solution of 2.5% glutaraldehyde in  
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29 0.1 M (pH 7.3) cacodylate buffer for 24 h at 4°C, dehydrated in a series of 10, 20, 40,  
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31 60, 80 and 100% ethanol (ethanol:water, v/v) every 20 min, rinsed in acetone and  
32  
33 ultradehydrated by critical point with CO<sub>2</sub> (1100 psi, 31.5 5 °C) in a POLARON E3000  
34  
35 instrument. Then, they were gold-coated using POLARON E6100 Equipment (10-  
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37 4mbar, 20 mA, 80 s) and observed through a Jeol JSM 6300 Scanning Electron  
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39 Microscope (15 kV, 15 mm).  
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## 48 **3. RESULTS AND DISCUSSION**

### 49 **3.1. Moisture loss kinetics**

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51 Under every condition tested, the drying of eggplant cylinders took place in the falling  
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53 rate period (Figure 1), thus, the initial moisture content was considered to coincide with  
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55 the critical moisture content. The drying experiments were prolonged until samples lost  
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2 80% of their initial weight, which gives a moisture content of close to 3 dry basis. The  
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4 experimental results showed that the conventionally dried samples (AIR) needed  
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6 approximately 25,000 s (7 hours) to reach this moisture content. In the case of the  
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8 ultrasonically assisted drying experiments (AIR+US), the drying time was only 13,000 s  
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10 (3.5 hours) when 45 W were applied to the ultrasonic transducer and 6,500 s (1.8 hours)  
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12 for an applied power of 90 W. Then, by applying power ultrasound at the tested powers  
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14 (45 and 90 W), the drying time was shortened by 50% and 75%, respectively. This  
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16 aspect is highly relevant in terms of the global efficiency of industrial drying, since the  
17  
18 shortening of the drying time not only enhances the energy efficiency of the drying  
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20 stage but also the industrial production capacity. Therefore, ultrasound may be  
21  
22 considered as a novel technology which has the potential to be applied in convective  
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24 drying processes of agri-food products on an industrial scale. Moreover, bearing in  
25  
26 mind the low heating capacity of ultrasound, a specific application in the drying of heat  
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28 sensitive products or in low temperature drying processes is of even greater interest.  
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32 In previous works carried out on other products, such as carrot, lemon peel (Garcia-  
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34 Perez et al., 2009) or persimmon (Garcia-Perez et al., 2007), the ultrasonic application  
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36 was less efficient at shortening the drying time than in the case of eggplant. This fact  
37  
38 could be explained considering that high porosity products, like eggplant, are more  
39  
40 prone to the mechanical effects produced in the material (Garcia-Perez et al., 2009).  
41  
42 Ultrasound produces alternative expansions and compressions in the materials where  
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44 ultrasonic waves are travelling through. The continuous mechanical stress makes it  
45  
46 easier for water to flow out due to the fact that the molecules are forced to move to the  
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48 sample surface. This effect is called the “sponge effect” due to its similarity to when a  
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50 sponge is squeezed and released. The highly porous nature of eggplant (Boukouvalas et  
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2 al., 2006) means it has a low structural resistance to the mechanical effects and this  
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4 could be the main reason for the fact that ultrasonic application is highly effective in  
5  
6 eggplant tissue.  
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9 Modelling contributed not only to the quantification of the ultrasonic effects, but also  
10  
11 helped to separate them into external and internal resistance to mass transport. The  
12  
13 results of the modelling are shown in Table 1. Explained variance values higher than  
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15 99% and mean relative errors lower than 2% were obtained for the proposed diffusion  
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17 model. Both statistical parameters highlight a close fit of the experimental drying  
18  
19 kinetics. Therefore, the assumptions considered in the diffusion model resolution seem  
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21 adequate to characterize mass transport during eggplant drying under these experimental  
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23 conditions.  
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29 The effective moisture diffusivity for conventional drying kinetics (AIR,  $D_e=4.91 \cdot 10^{-10}$   
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31  $m^2/s$ ) was similar (Table 1) to other values reported for this product in literature  
32  
33 (Akpınar and Bicer, 2005; Doymaz, 2011). Thus, Doymaz and Göl (2011) reported, for  
34  
35 the drying of eggplant slices (0.5 and 1 cm thickness) at 2 m/s and temperatures ranging  
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37 from 50-80 °C, effective diffusivities from  $0.93$  to  $8.84 \cdot 10^{-10}$  ( $m^2/s$ ). The application of  
38  
39 power ultrasound led to a significant increase of  $D_e$  ( $p<0.05$ ), involving a reduction of  
40  
41 the internal resistance to mass transfer. Thus, the  $D_e$  value of eggplant for ultrasonically  
42  
43 assisted drying at 90 W (AIR+US-90W) is almost one order of magnitude higher than  
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45 the value obtained in conventional drying experiments (AIR). As already mentioned,  
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47 this fact could be linked to the “sponge effect”, that is the alternative expansions and  
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49 contractions of the material, produced by ultrasound. The effects of power ultrasound  
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51 were dependent on the power applied. The  $D_e$  identified for the ultrasonically assisted  
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53 drying experiments performed at 45 W (AIR+US-45W) showed an intermediate value  
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2 between those obtained in AIR and AIR+US-90W experiments. The higher the applied  
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4 power, the greater the effects produced by ultrasound. This fact has already been  
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6 observed in the ultrasonically assisted drying of other foodstuffs (Garcia-Perez et al.,  
7  
8 2009), and it was also observed in other ultrasonic applications, such as osmotic  
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10 dehydration (Carcel et al., 2007a) or brining (Carcel et al., 2007b).  
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14 As regards the influence of ultrasound on the external resistance to mass transport, the  
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16 modeling of the drying kinetics of eggplant cylinders (Table 1) showed a significant  
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18 ( $p < 0.05$ ) increase of  $k$  parameter when ultrasound was applied. Thus, the identified  
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20 value increased from 1.79 to  $3.29 \cdot 10^{-3}$  (kg w/m<sup>2</sup>/s) for AIR+US-45W experiments and  
21  
22 reached  $5.89 \cdot 10^{-3}$  (kg w/m<sup>2</sup>/s) for AIR+US-90W experiments. As already mentioned,  
23  
24 power ultrasound has the ability of improving the mass transfer coefficient ( $k$ ) due to  
25  
26 the reduction of the boundary layer thickness by a mechanical stirring of the gas  
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28 medium that ultrasonic waves produce at the interfaces. Ultrasonic applications involve  
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30 oscillating velocities, micro-streaming and pressure variation at the interfaces (Gallego-  
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32 Juarez et al., 1999), which greatly increase the turbulence leading to an improvement in  
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34 the water transport from the solid surface to the air medium.  
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38 The modeling of drying kinetics highlighted the fact that power ultrasound had a  
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40 significant effect on both internal and external water transfer during eggplant  
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42 dehydration. According to this, some kind of ultrasonic effect on both internal and  
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44 external eggplant structural tissues should be expected.  
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### 53 **3.2. Microstructure of fresh eggplant**

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55 The microstructure of raw eggplant is shown in Figures 2 (Cryo-SEM technique) and 3  
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57 (SEM technique). As can be observed, the epidermis is a continuous layer of rounded  
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2 cells, closely packed and covered by a uniform and non-porous waxy layer. In a cross  
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4 section of eggplant, under the epidermis, two main tissues may be observed (Figures 2A  
5 and 2B). An external layer named the epicarp, which has hardly any intercellular spaces,  
6  
7 contains anthocyanins that provide the typical purple color of the Mediterranean  
8  
9 eggplant varieties. It mainly consists of 4-5 layers of rounded cells (10-25  $\mu\text{m}$ ). Under  
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11 the epicarp, and practically taking up the remainder of the fruit flesh, is found a spongy,  
12  
13 white structure named the endocarp (Figure 2C and 2D). As the microstructural  
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15 observation progresses to the inner part of the fruit (following the radial direction), the  
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17 cells get progressively bigger and large intercellular spaces can also now be observed.  
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19 This tissue is characterized by tubular, interconnected cells and a high porosity was  
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21 observed, particularly in the more internal zones (Figure 2D). In the Scanning Electron  
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23 Microscopy (SEM) images, the cell walls from the different tissues and the intercellular  
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25 connections between them can be clearly distinguished. Figure 3 shows a computer  
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27 typesetting of two micrographs in which the whole tissue, from the external cellular  
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29 layers of the epicarp to the interior endocarp layers, can be observed. This image shows  
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31 the link between the epicarp and endocarp with an interconnection between cells  
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33 through the walls. These SEM observations also show the larger intercellular spaces that  
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35 exist in the internal tissue (endocarp), compared to the external one (epicarp and  
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37 epidermis).  
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48 In the following sections, the influence of the different drying methods on internal  
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50 (endocarp) and external (epicarp and epidermis) microstructure will be addressed.  
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### 3.3. Effects of drying on internal microstructure (endocarp)

The conventional convective drying experiments (AIR) involved microstructural changes in the endocarp showing a high degree of degradation and a compacting process, as can be observed in the images obtained by Cryo-SEM (Figure 4). These effects on the endocarp tissue of eggplant may be linked to the lengthy exposure to forced air at 40 °C in AIR experiments. The effects on the endocarp of the ultrasonically assisted dried samples (AIR+US) were, in overall terms, less important than in AIR samples, but this was dependent on the ultrasonic power applied. The cells of the endocarp of AIR+US-45W samples (Figure 4C) still maintained their individuality and intact cell walls were even found. As the intensity of the applied power increased, the drying effects became more intense. As a consequence, a highly compacted tissue appeared in AIR+US-90W dried samples (Figure 4D), although some spaces were also found to be occupied by air.

These microstructural changes in the endocarp can also be observed in the images obtained by the SEM technique (Figure 5). The SEM micrographs show that the cell walls of AIR+US-45W dried samples (Figure 5C) are better preserved compared to AIR dried samples, although the tissue is more compacted. In the AIR dried samples, individual cells can hardly be identified due to a generalized degradation of the tissue. The ultrasonic waves applied at the highest level of power (90 W) induced a great compaction of the internal tissue (Figure 5D), even bearing in mind the fact that the drying time was shorter (Figure 1).

The alternating expansions and contractions brought about by the ultrasonic wave when travelling in a medium could promote the degradation of endocarp cells. The effect on the endocarp structure was dependent on the applied ultrasonic power. The higher the



1  
2 acoustic intensity used, the more intense were the compressions and expansions  
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4 produced by the ultrasound and the more marked the effect on the internal  
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6 microstructure. This could also be related with the fact that the effective moisture  
7  
8 diffusivity increased as more ultrasonic power was applied (Figure 1, Table 1).  
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11 When 45 W (50% of the maximum acoustic power tested) was applied (AIR+US-45W),  
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13 ultrasound was highly efficient in terms of the drying rate, since the drying time was  
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15 reduced by around 45% when compared to AIR experiments (Figure 1). Therefore, by  
16  
17 applying a mild ultrasonic power, the length of exposure to air drying was drastically  
18  
19 shortened, which reduced the structural damage associated with air (Figure 5C), thus  
20  
21 subjecting the endocarp cells to relatively weak compressions and expansions. When  
22  
23 the ultrasonic power was applied at the maximum level tested, 90 W (AIR+US-90W),  
24  
25 the compressions and expansions of the endocarp tissue were much more intense  
26  
27 inducing a greater compaction of the internal tissue (Figure 5D). This stress observed in  
28  
29 the internal microstructure could also make the moisture leave the matrix at a faster rate  
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31 and it could be responsible for the significant ( $p>0.05$ ) increase in the effective  
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33 diffusivity.  
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37 Therefore, if both the moisture loss kinetic and the internal microstructure are taken into  
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39 account, the ultrasonically assisted drying of eggplant at 45 W was the most favorable,  
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41 since by applying this mild ultrasonic power, the length of exposure to air drying was  
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43 significantly shortened.  
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### 3.4. Effects of drying on external microstructure (epicarp and epidermis)

The drying process also affected the external microstructure of eggplant. The conventional convective air drying (AIR) involved the separation of epicarp and epidermis (Figure 6B). The samples dried by ultrasound (AIR+US) did not show this effect, but wrinkles appeared on the epidermic surface due to the tissue compression (Figure 6C and 6D).

As regards the waxy compounds on the epidermis, they were not affected by the AIR drying experiments (Figure 7A). However, the ultrasonically assisted drying experiments (AIR+US) led to the waxy compound spreading over the epidermis (Figure 7B and 7C), causing the characteristic uniformity of this layer to be lost. Comparing the AIR+US-45W and 90W experiments, it can be observed that an increase in the applied ultrasonic power provoked a more intense spread of waxy compounds (Figure 7B and 7C).

The spread of waxy compounds showed that ultrasound did affect the external surface of the samples and, therefore, the solid-air interface. Ortuño et al. (2010) already observed the effect that applying power ultrasound during drying has on the waxy compounds of the orange peel epidermis. The observed effects are probably linked to the aforementioned stirring of the air medium mechanisms associated with ultrasound application (Gallego-Juarez et al., 1999). The oscillating velocities, micro-streaming and pressure variation at the interfaces should not only reduce the boundary layer thickness, thus improving mass transfer phenomena, as has been shown by the significant increase in the mass transfer coefficient of moisture (Table 1), but also contribute to the degradation of the interface microstructure.

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5 **4. CONCLUSIONS**  
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7 Ultrasonic application during the convective drying of eggplant led to a significant  
8 (over 70%) shortening of the drying time at the maximum ultrasonic power tested (90  
9 W). From the modeling, it was found that the reduction in the drying rate was linked to  
10 the improvement in both the mass transfer coefficient and the effective moisture  
11 diffusivity. The influence of ultrasound on internal and external mass transport was  
12 related with the effects on the internal (endocarp) and external (epicarp and epidermis)  
13 microstructure of the dried eggplant. Thus, the microstructure was better preserved by  
14 the application of a moderate ultrasonic power (45 W) than by conventional air drying,  
15 due to the shortening of the drying time and the weak mechanical effects of ultrasound  
16 on the endocarp cells. Therefore, the ultrasonically assisted drying of eggplant may be  
17 considered an efficient alternative to conventional convective drying as regards energy  
18 consumption (reduction of drying time) and quality in terms of the stability of the  
19 microstructure after processing.  
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## FIGURE CAPTIONS

**Figure 1.** Conventional (AIR) and ultrasonic assisted (AIR+US) convective moisture loss kinetics of eggplant cylinders (height 2 cm and diameter 2.4 cm) carried out at 40 °C and 1 m/s.

**Figure 2.** Cryo-SEM. Cross section of raw eggplant (2A and 2B). Detail of endocarp cells next to epicarp (2C) and in the inner tissue (2D). epi: epidermis; ed: endocarp; ep: epicarp.

**Figure 3.** SEM. Raw eggplant. Computer typesetting of two cross sections of eggplant where epicarp (ep) and endocarp (ed) can be observed.

**Figure 4.** Cryo-SEM. Endocarp from raw eggplant (A) and dried eggplant samples: AIR (B), AIR+US-45W (C) and AIR+US-90W (D) samples.

**Figure 5.** SEM. Endocarpic tissue in raw eggplant (A) and in dried eggplant samples: AIR (B), AIR+US-45W (C) and AIR+US-90W (D).

**Figure 6.** Cryo-SEM. Raw eggplant (A) and dried eggplant samples: AIR (B), AIR+US-45W (C) and AIR+US-90W (D).

**Figure 7.** Cryo-SEM. Detail of the scattering of waxy compounds on the epidermis of dried eggplant samples: AIR (A), AIR+US-45W (B) and AIR+US-90W (C).

1 Table 1. Modelling of conventional (AIR) and ultrasonic assisted (AIR+US) convective  
 2 drying kinetics of eggplant cylinders (height 2 cm and diameter 2.4 cm) carried out at  
 3 40 °C and 1 m/s. Subscripts (A,B,C) and (X,Y,Z) show homogeneous groups  
 4 established from LSD intervals ( $p < 0.05$ ).

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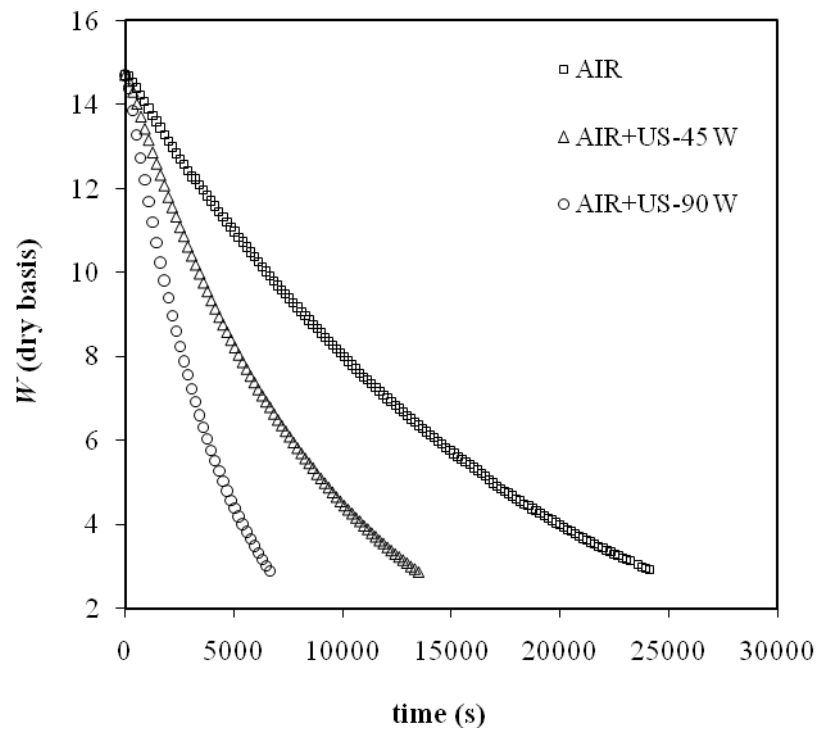
	$D_e$ ( $10^{-10}$ m <sup>2</sup> /s)	$k$ ( $10^{-3}$ kg w/m <sup>2</sup> /s)	%VAR	%MRE
AIR	4.91 <sub>A</sub>	1.79 <sub>X</sub>	99.99	0.45
AIR+US-45W	9.47 <sub>B</sub>	3.29 <sub>Y</sub>	99.90	1.03
AIR+US-90W	15.27 <sub>C</sub>	5.89 <sub>Z</sub>	99.92	1.12

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Figure 1



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