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Influence of ultrasound application on both the osmotic pretreatment and subsequent convective drying of pineapple (*Ananas comosus*)

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Abstract

Ultrasound application represents an alternative means of improving heat and mass transfer. This study explored the combined application of ultrasound (US) during both the osmotic dehydration (OD) pretreatment and the convective drying of pineapple. For that purpose, fresh and pretreated samples (20 or 40 min, with (55.5 kW/m^3, 40 kHz) and without ultrasound application) in an osmotic solution of sucrose (40 % w/w) were dried (40 ºC and 70 ºC) with (21.8 kHz, 31 kW/m^3) and without ultrasound application. A diffusion model permitted to quantify the influence of the factors studied (time of pretreatment, ultrasound application during pretreatment, drying temperature and ultrasound application during drying) in drying kinetics. The increase in drying temperature and the application of ultrasound during drying significantly accelerated the drying process by reducing both the internal and the external mass transport resistance. On the contrary, the osmotic pretreatments reduced the drying rate by increasing the external resistance.

Keywords ultrasonic, kinetics, diffusivity, moisture transport, external resistance, convective drying.

1. Introduction

Pineapple (*Ananas comosus*) is a tropical fruit with high concentrations of sugars and nutrients, such as mineral salts (calcium, phosphorus, magnesium, potassium, sodium, copper and iodine), vitamins (C, A, B1, B2 and niacin) and fibers (Megías-Pérez, Gamboa-Santos, Cristina, Villamiel, & Montilla, 2014). However, postharvest losses represent a substantial problem (Prusky, 2011), not only from an economical point of view but also from an environmental one. In this sense, drying is an alternative means of extending the shelf life and availability, providing products with improved value (Isquierdo et al., 2013; Mujumdar & Law, 2010) that can be used simply as ready-to-eat foods or as ingredients in snacks, breakfast cereals, bakery goods and desserts (Karam, Petit, Zimmer, Djantou, & Scher, 2016). Of the various techniques, convective drying is one of the most commonly used (Silva & Corrêa, 2005) for its simplicity. However, it requires the exposure of the food to hot air for a long period that can lead to partial or total degradation of nutrients and changes in the essential sensory characteristics of the product, such as color, appearance and mechanical properties (Megías-Pérez et al., 2014). Moreover, the fact that the drying process is a lengthy one makes it costly as regards energy consumption (Onwude, Hashim, & Chen, 2016).

Osmotic dehydration (OD) consists of the immersion of a solid in a hypertonic solution. As a consequence, the solid loses water and gains solutes (Sagar & Kumar, 2010). Compared with convective drying, this process saves energy (Ahmed, Qazi, & Jamal, 2016), increases the retention of color and flavor (Salazar-López, Jiménez, Salazar, & Azuara, 2015), improves mechanical properties (Ramallo, Hubinger, & Mascheroni, 2013) and allows products with reduced water activity to be obtained (Corrêa, Pereira, Vieira, & Hubinger, 2010). However, due to the fact that mass transfer is driven by diffusion and capillary flow, it requires a long processing time (Ahmed et al., 2016). Moreover, the products obtained present an intermediate level of moisture content.

The combination of an OD pretreatment and subsequent convective drying is a compromise solution that could combine the advantages of both processes (Sagar & Kumar, 2010). Thus, the alterations in the food tissue promoted by OD reduce the subsequent drying time and limits the decrease in quality produced by hot air drying (Ahmed et al., 2016; Vega-Gálvez, Lara, Flores, Di Scala, & Mondaca, 2012). However, while this combination can shorten the total drying time, the process is still quite long.

The use of ultrasound is a promising technique for the purposes of improving mass transport, with its effects depending on the media in which it is propagated. Thus, in liquid media, the main effect is cavitation (Azoubel, Amorim, Oliveira, Maciel, & Rodrigues, 2015; Corrêa et al., 2016). The asymmetric implosions of bubbles produced close to the solid surface can generate microjets in the direction of the surface and intense micro stirring at the interface (Ozuna, Puig, García-Pérez, & Cárcel, 2014b). In a solid medium, the sound waves cause quick alternating compressions and expansions in the solid, analogous to a sponge being continually squeezed and released (Cárcel, Benedito, Rosselló, & Mulet, 2007; Fernandes, Rodrigues, Gaspareto, & Oliveira 2006). The consequence of this phenomenon, called the ‘‘sponge effect’’, is that of releasing the native liquid from the inner part of the solid to the surface, thereby promoting the entry of the surrounding fluid (Cárcel et al., 2007). In gas media, ultrasound provokes alternating pressures and oscillating velocities that produce an intense microstirring at the boundary layer of air-solid interphases (García-Pérez, Ortuño, Puig, Cárcel, & Pérez-Munuera, 2012).

For these reasons, ultrasound has been widely used to intensify mass transport phenomena in solid-liquid systems, such as OD processes (Cárcel et al., 2007; Fernandes, Linhares, & Rodrigues 2008; Kang et al., 2016; McDonnell, Lyng, Arimi, Allen, 2014; Siucinska, Konopacka, Mieszczakowska-Frac, & Polubok, 2016), improving both moisture loss and solute gain. The influence of ultrasound waves on a quality parameter, such as structure, has also been widely studied. As regards solid-gas systems, ultrasound has emerged as an interesting alternative in order to intensify convective drying processes, reducing both the drying time and the amount of energy required (Cárcel, Garcia-Perez, Riera, E. Mulet, 2011; Frias, Peñas, Ullate, & Vidal-Valverde, 2010; Gamboa-Santos et al., 2014; García-Pérez et al. 2012; Kowalski, Pawlowski, Szadzinska, Lechtanska, & Stasiak, 2016; Nascimento, Mulet, Ascheri, Carvalho, & Cárcel., 2016; Rodríguez et al., 2014). Moreover, ultrasonically assisted drying opens up the possibility of reducing the drying temperature, thus improving the final product quality (Gamboa-Santos et al., 2014).

However, there is no research regarding the application of ultrasound in both of these combined techniques: an OD pretreatment followed by convective drying. For this reason, the goal of the present study was to evaluate the influence of the application of ultrasound on osmotic pretreatment and on the subsequent drying of pineapple.

2. Materials and Methods

2.1 Material

The pineapple (*Ananas comosus*) used in this study was the new hybrid 73-114, known as Golden Pineapple or MD2. The fruits were produced in Costa Rica and purchased in a local market in Valencia, Spain. The level of ripeness of the fresh fruits chosen was as homogenous as possible and they presented a soluble solid content of 13 ± 1 °Brix (Refractometer Shibuya mod. A.C.R 121A 0-32%).

2.2 Sample preparation

The selected fruits were washed and peeled. Due to the fact that the sugar content could vary from one end of the pieces to the other (Ramallo & Mascheroni, 2012), both ends of the fruits were discarded and only the middle part of the pineapples was used for the experiments. Disk-shaped samples (20 mm diameter, 5 mm thickness) were obtained with the aid of a stainless steel cork borer and immediately used. The moisture content of the fresh and dried samples was measured (AOAC, 2007) in triplicate.

2.3 Experimental conditions

The experimental design consisted of combining osmotic pretreatments with convective air drying experiments. Ultrasound was applied in both operations, the solid-liquid system of the osmotic pretreatments and the solid-gas system of convective drying. All of the experimental conditions tested are shown in Table 1. The details of each process are described below.

2.3.1 Osmotic pretreatment

Because the aim of this work was to compare the results with those obtained by other authors, the chosen conditions for osmotic dehydration were in the average range of the previously used in the literature (Carcel et al., 2007; Garcia-Noguera et al., 2010; Silva et al. 2014). In fact, the osmotic dehydration assisted by ultrasound is usually performed in a short time operation (Fernandes et al, 2008) being enough to cause modifications in the fruit, as pineapple, that could improve the further drying. Moreover, too high solution concentration make difficult the ultrasonic wave transmission avoiding its effects to be significant (Fernandes and Rodrigues, 2008). Thus, OD was performed by immersing the pineapple samples in an ultrasonic bath (ATU S.L., Manises, Spain) containing 27 L of a hypertonic solution of commercial sucrose (40 % w/w). The ratio of fruit to solution was set at 1:300 (w:w). Using this low proportion made the influence of the dilution of the solution during processing negligible. Two immersion times were tested, 20 and 40 min and the temperature was maintained constant (25±1 ºC) during treatments by recirculating a cooling fluid around an external jacket of the ultrasonic bath. The OD was carried out assisted (55.5 kW/m^3, 40 kHz) or not by ultrasound. The ultrasonic power applied was the maximum of the equipment with the aim to maximize the ultrasonic effects. In fact, these conditions have been previously tested in other solid-liquid treatments, such as meat brining or cod desalting (Ozuna et al., 2014b), obtaining a significant influence in the mass transfer. After the OD, the samples were removed from the syrup, rinsed in distilled water to eliminate the solution adhered to the surface, and blotted with tissue paper to remove the water from the surface (Corrêa et al. 2010). OD led to changes in not only the dry matter content (DMC, Equation 1) but also in the water content (WC, Equation 2), both of which were calculated (Cárcel et al. 2007).

$$\mathrm{DMC} = \frac{\mathrm{DM_{fin}} - \mathrm{DM_0}}{\mathrm{DM_0}} \tag{1}$$

$$\mathrm{WC} = \mathrm{W_{fin}} - \mathrm{W_0} \tag{2}$$

where DM_{fin} and DM_0 corresponds to the dry matter content after (fin) and before (0) osmotic pretreatments, respectively. In this sense, W_0 and W_{fin} are the water content (kg water/kg dry matter) of the fresh samples and after the pretreatment.

2.3.2 Convective drying

The drying system used in the convective drying experiments is presented in Figure 1 (García-Perez et al., 2012). The desired drying air conditions are provided by means of a fan and an electrical heating unit, managed with a PID control algorithm. The air is driven through a drying chamber made up of an aluminum cylindrical vibrating element (internal diameter 100 mm, height 310 mm and thickness 10 mm). In each run, forty samples were placed in a sample holder and inserted into the chamber. This sample holder allows free air to flow around each sample. The cylindrical chamber, driven by a piezoelectric composite transducer (21.8 kHz), makes the system able to generate a high-intensity ultrasonic field with an average sound pressure of 154.3 dB (measured when applying the maximum power capacity of 31 kWm^{-3} and stagnant air conditions). In these conditions, previous studies have showed that ultrasound application can produce a significant reduction of drying time (Carcel et al., 2012; 2011). A scale was coupled to the system for measuring the sample mass at preset times.

The drying experiments at constant air velocity (1.0 ± 0.1 m/s) were carried out at two temperatures, 40 and 70 ºC, without or with (21.8 kHz, 31 kW/m^3) ultrasound application (Table 1) until samples lost 80 % of their initial weight. Each condition was tested at least in triplicate, which means that more than 60 experimental drying runs were performed. At both drying temperatures tested, the equilibrium moisture content was estimated from the moisture content of the samples subjected to a lengthy drying process (>36 h).

2.4 Modelling the Drying Kinetics

Convective drying processes are governed by both the external and the internal mass transfer and are commonly modeled by means of diffusion models (García-Pérez et al., 2012). Due to the geometry of the samples used in this study, their behavior was assumed to be similar that of an infinite slab and so a unidirectional mass transport process was considered. Equation 3 presents a unidirectional diffusion equation based on Fick's law (Crank, 1975).

$$\frac{\partial W(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff} \frac{\partial W(x,t)}{\partial x} \right) \quad (3)$$

where W(x,t) is the water content (kg water/kg dry matter) at instant t (s) at a given point x (m), D_{eff}, the effective diffusivity (m^2/s). The initial moisture content of the samples was considered uniform (Equation 4) and the solid was taken to be symmetrical (Equation 5). No shrinkage of samples was taken into account in the model.

$$W(x,0) = W_0 \quad (4)$$

$$\frac{\partial W(0,t)}{\partial t} = 0 \quad (5)$$

A common boundary condition in convective drying operations is that of considering the external mass transport resistance as negligible compared with the internal (Isquierdo et al., 2013). However, the low air velocity used in this study, 1 m/s, makes both external and internal mass transport resistances significant. For this reason, the coupled internal and external mass transport at the surface of the material was taken into account from Equation 6 (García-Pérez et al. 2012).

$$-D_{eff}\rho_{ds}\frac{\partial W(L,t)}{\partial x}=k\left(a_w(L,t)-\varphi_{air}\right) \qquad (6)$$

where ρ_{ds} is the dry solid density (kg dry mater/m^3), L is the half thickness of sample, k is the external mass transfer coefficient (kg water/m^{2}s), a_w is the water activity at the solid surface and φ_{air} is the relative humidity of the drying air in contact with the wet material. For that, the sorption isotherm of pineapple published by Falade et al. (2004) was taken into account.

The model was numerically solved by using an implicit difference method with the aid of MATLAB (The MathWorks, Inc., USA). Both the effective diffusivity (D_{eff}) and the external mass transfer coefficient (k) were identified as the values that minimize the squared sum of differences between experimental and calculated moisture content.

2.5 Statistics

The percentage of explained variance (var, Eq. 7) and the mean relative error (MRE, Eq. 8) were calculated in order to determine the goodness of the fit to the experimental data.

$$var=\left(1-\frac{S_{xy}^2}{S_y^2}\right)\cdot 100 \qquad (7)$$

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

where S_y and S_{xy} are the standard deviation of the sample and the estimates respectively, W_{ei} and W_{ci} are the experimental and calculated moisture contents (kg water/kg dry matter) and N is the number of experimental data.

Moreover, multifactor ANOVAs and least significance difference (LSD) intervals ($p<0.05$) were calculated to determine the significance of the influence of the factors studied (osmotic pretreatment, with and without ultrasound application and ultrasound application during convective drying) on the identified effective diffusivity and mass transport coefficient.

3. Results and discussion

The initial moisture content of the fresh pineapple used in this study was 5.2 ± 0.4 kg water/ kg dry matter. As stated before, some of the fresh samples were used in drying experiments, and others were osmotically pretreated before drying (Table 1).

3.1 Osmotic dehydration (OD)

As can be expected, the OD pretreatment promoted both an increase in the dry matter (DMC) of the samples as well as a decrease in their water content (WC). Thus, as is shown in Table 2, the obtained values were positive for DMC and negative for WC; the longer the treatment time, the greater the changes. For non-sonicated samples, the WC of samples pretreated for 40 min was 42 % than that obtained after 20 min of pretreatment. As regards the DMC, the average value of the samples pretreated for 40 min was 20% higher than in the case of those pretreated for 20 min. However, these differences were not significant ($p<0.05$) probably due to the markedly variable nature of the raw matter. Silva, Fernandes, & Mauro (2014) pointed out that the ratio between WC and DMC is a function of the fruit structure. In the same sense, Ramallo et al. (2013) observed that the mechanical properties of fresh pineapples with the same degree of ripeness were different due to the variability of the fruit.

For the same time of pretreatment, no significant differences were found between the DMC and WC of ultrasonically or non-ultrasonically pretreated samples, probably linked to the high natural variability observed. However, in the case of the pretreatments carried out for 40 min, the DMC and the WC of the samples pretreated with ultrasound application were 33% and 27 % higher, respectively. This means that, at this time, ultrasound application intensified both mass transport processes but natural variability of the pineapple used could mask the significance of this intensification. Moreover, the differences between ultrasonic pretreated samples for 40 min and those pretreated for 20 min were significant ($p<0.05$). Other references show a mass transfer enhancement during osmotic processes as a result of applying ultrasound (Cárcel et al., 2007; Fernandes et al., 2008; Garcia-Noguera et al., 2010; Ozuna et al., 2014b). However, the magnitude of the ultrasound effects depends on the product (Mulet, Cárcel, Sanjuán, & Bon, 2003). The influence of the liquid medium properties, that can hinder the ultrasonic energy transport from the generation source to the sample, and the fact that different materials are more or less prone to the effects of ultrasound, makes it necessary to evaluate the influence of the acoustic waves case by case (Cárcel, García-Pérez, Benedito, & Mulet, 2012). In this sense, the fibrous nature of the pineapple microstructure made the osmotic process less effective (Botha, Oliveira, & Ahrné, 2012). Therefore, a more intense ultrasound application could be necessary for the purposes of observing ultrasonic effects. In general terms, it was observed that the magnitude of the effects on mass transfer when ultrasound was applied during the osmotic pretreatments of pineapple was limited.

3.2. Convective Drying

Fresh pineapple samples and samples pretreated under different conditions (time and ultrasound application) were dried at two temperatures (40 and 70 ºC), without or with ultrasound application. Subsequently, the influence of these four parameters on the drying kinetics of pineapple was studied.

As expected, the temperature affected the drying kinetics of pineapple, which became faster as the temperature of the drying air rose (Figure 2). For example, to achieve a moisture content of 1 kg water/kg d.m, the un-pretreated samples dried at 70ºC without ultrasound application needed 63% less drying time than those dried at 40ºC (Table 3). The effect of temperature on drying rate is well-reported in the literature (Chua et al., 2007). The internal resistance to moisture transport decreases as the drying temperature goes up due to the higher water molecule mobility inside the food, while the external resistance decreases due to the growth in the water pressure gradient between the phases. Moreover, a high drying temperature provides energy to overcome the latent heat of phase change that takes place during moisture evaporation.

Ultrasound application during drying also intensified the drying rate at the drying temperature tested (Figure 2). Thus, as can be observed in Table 3, the drying time of un-pretreated samples dried at 40 ºC was 35% shorter when ultrasound was applied. García-Pérez et al. (2012) studied the drying of orange peel at 40°C and found reductions in the drying time of 45% when applying ultrasound (37 kW/m^3). When drying apple at 30 ºC, Rodríguez et al. (2014) found that the drying time was 54% shorter when ultrasound was applied (30.8 kW/m^3). The smaller drying time reduction observed in the case of pineapple can be explained by its lower porosity compared with orange peel or apple (Ozuna, Gómez, Riera, Cárcel, & Garcia-Perez. 2014a). The sponge effect produced by the successive compression and expansion of the solid materials, the creation of micro-channels or the microstirring at interfaces are some of the ultrasonic effects that can contribute to the reduction in both internal and external mass transport resistance (García-Pérez et al., 2012).

As stated in the previous section, the pretreatment produced a water loss and a gain in dry matter. Therefore, at the beginning of the drying experiments, the pretreated samples showed a lower initial moisture content than fresh samples (Figure 3). This fact also contributed to a shorter drying time. Thus, for example, fresh samples dried at 40 ºC without ultrasound application needed 7.1±0.1 h to obtain a moisture content of 1 kg of water/kg dry matter while the samples pretreated for 20 min without ultrasound application only needed 5.5±0.2 h (Table 3), meaning a net drying time decrease of 22 % (1.6 h).

No significant differences in drying time were found in terms of the type of pretreatment applied. Neither the time during which the sample is immersed in the osmotic solution tested nor the application of ultrasound during the osmotic pretreatment used in this study significantly affected the length of the drying process needed to attain 1 kg water/kg dry matter (Table 3). However, other authors reported a clear influence of the osmotic pretreatment conditions, assisted (Deng & Zhao 2008; Fernandes et al., 2008) or not by ultrasound (Rahman & Mujumdar 2007), on the subsequent drying. In the case of pineapple used, the highly variable nature of the raw matter can mask the influence of the different pretreatment times, 20 and 40 min. As regards ultrasound application during osmotic pretreatment, the physical characteristics of the osmotic solution, such as viscosity, can make the ultrasonic wave transmission through it difficult, preventing them from reaching the samples with enough intensity to produce significant effects (Cárcel et al. (2012). Moreover, the structural properties of the material are decisive for the action of the ultrasound waves. In this sense, the fibrous structure of pineapple can also make it difficult for ultrasound to act (Ozuna et al., 2014a) and a more intense ultrasonic field could be necessary to induce significant effects (Carcel et al., 2007).

The changes in pineapple composition and structure produced by the osmotic pretreatment can affect the ability of product to be dried. In this sense, it was observed that the moisture content difference between pretreated and un-pretreated samples in drying experiments carried out at 70 ºC, which was significant at the beginning of the process, shrank as the drying time advanced (Figure 4). Under these drying conditions, the drying time of un-pretreated and pretreated samples was quite similar, regardless of the pretreatment carried out (Table 3). The influence of the pretreatment on the drying rate may be better observed when dimensionless moisture is considered, because the difference in the initial moisture content is not considered in the drying kinetics. Thus, as can be observed in Figure 5, the decrease in the dimensionless moisture content of un-pretreated samples during drying was slightly faster than that observed in the case of those pretreated for 40 min with ultrasound application.

All of these results indicated that, when drying at 70 ºC, the slight reduction in drying time induced by the pretreatment did not compensate for the time involved in performing it. The need for additional facilities with which to carry out the osmotic process must also be considered. Moreover, high temperature drying could produce a certain degree of caramelization of the added sugars that can establish additional barriers to the water's exit from the pineapple matrix.

The modelling of the experimental drying kinetics permitted the quantification of the actual influence of pretreatments on the drying kinetics.

3.3. Modelling the drying process

All of the experimental drying kinetics (more than 60 experimental runs) were modelled by using the model described previously (Equation 3). This model fitted the experimental results adequately, achieving percentages of explained variance of over 95% and mean relative errors of under 10% (Table 3). Moreover, the trend of the experimental and calculated moisture content evolution was quite similar (Figure 6).

The average effective diffusivity (D_{eff}) and the external mass transport coefficient (k) obtained for each experimental condition are shown in Table 3. The significance of the differences in the values obtained for the different pretreatments and drying conditions were also studied from the estimation of multifactor ANOVAs and Tukey HSD tests. To that end, D_{eff} and k were considered as the dependent variables and the time of pretreatment, ultrasound application during pretreatment, drying temperature and ultrasound application during drying as the factors.

The results showed that time and ultrasound application during pretreatments had no significant ($p<0.05$) influence on the D_{eff} values identified. Therefore, the water loss and sugar gain during the osmotic pretreatment did not significantly affect the internal movement of the moisture inside the pineapple samples during convective drying. On the contrary, the influence of both temperature and ultrasonic application during drying was significant ($p<0.05$). In the case of temperature, as was expected, the identified D_{eff} was significantly ($p<0.05$) higher at 70 ºC than at 40 ºC. Thus, the D_{eff} of un-pretreated samples dried at 70 ºC was 274 % higher than that identified at 40 ºC. As stated before, the increase in the drying temperature facilitates water mobility inside the samples (Chua et al., 2007).

The application of ultrasound also significantly ($p<0.05$) intensified the internal mass transport of moisture. Thus, in the case of un-pretreated samples dried at 40 ºC, ultrasound application increased the identified D_{eff} by 105 %. Previous papers reported the influence of ultrasound on the reduction of internal resistance to mass transfer, inducing effects such as the sponge effect or the creation of internal micro-channels (Cárcel et al., 2011). In the case of experiments carried out at 70 ºC, the increase in D_{eff} brought about by ultrasound application was 83 %. The fact that ultrasound has a milder effect on D_{eff} at higher temperatures has been previously described (Nascimento et al., 2016). One explanation for this may be linked with the relative importance of the energy provided by the ultrasound and by the drying air temperature. At low drying temperatures, the energy provided by ultrasound is significant compared with the energy provided by the air and ultrasound effects are of great magnitude. On the contrary, when hot drying air is used, the energy provided by the high temperature can partially or totally mask the effects provided by the energy supplied by ultrasound.

As for the external mass transport, it should be highlighted that all of the parameters studied (time of pretreatment, ultrasound application during pretreatment, drying temperature and ultrasound application during drying) had a significant ($p<0.05$) influence on the identified values of k. Thus, the k values were higher in drying experiments carried out at 70 ºC than in those carried out at 40 ºC. The higher temperatures make both the evaporation of water and its transport to the drying air easy.

The application of ultrasound during drying also significantly increased the k values, by around 75 % in those carried out at 40 ºC and around 70 % in experiments performed at 70 ºC. The creation of oscillating pressures and the micro-stirring at interfaces produced by ultrasound can help to reduce the boundary layer of diffusion and, therefore, decrease the external resistance to mass transfer (García-Pérez et al., 2012). In the drying experiments carried out without ultrasound application, not only at 40 ºC but also at 70 ºC, it was observed that k was lower in the case of pretreated samples. On the contrary, in the case of the drying experiments carried out with ultrasound application, the samples pretreated for 40 min showed lower values of k than those pretreated for 20 min. The application of ultrasound during pretreatment also reduced the identified k values, particularly in the case of samples dried at 70 ºC. This can be attributed to the sugar gain produced during OD pretreatment; the greatest gain came when ultrasound was applied and the pretreatment time was longer. Due to the short pretreatment times tested in the present study (20 and 40 min), this sugar gain can mainly be located at the surface of the samples. Therefore, the sugar concentration in this layer will be higher than inside the sample and can represent an additional barrier to the water transport from the inner sample layers to the drying air. At high drying temperatures, a certain degree of caramelization of this sugar can also help to make difficult the exit of internal moisture. Finally, the influence of ultrasound application during pretreatment on the microstructure of this external layer (Garcia-Perez et al., 2012) can also contribute to a reduction in k values.

Therefore, from the modelling of the drying kinetics, it can be shown that the pretreatments reduced the convective drying kinetics, mainly increasing the external resistance to mass transfer. On the contrary, both ultrasound application during drying and the increase in drying temperature significantly reduced not only the internal mass transfer resistance but also the external.

4. Conclusions

The osmotic pretreatment of pineapple shortened the later drying process, however, this drying time reduction was, in general, not enough to compensate the additional time of the pretreatment. Moreover, and just from a kinetics point of view, the need of additional facilities can make not advisable the use of these pretreatments. Regarding the drying, the increase in drying temperature and the application of ultrasound during drying significantly accelerated the process. The modelling showed that these factors reduced both the internal and the external mass transport resistance. On the contrary, the osmotic pretreatments increased the external mass transport resistance. Therefore, if only processing time is taken into account, the application of ultrasound at the highest drying temperature tested provided the fastest and simplest process. However, additional studies must be carry out to determine the influence of studied variables in the final quality of the product.

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Table Captions

Table 1. Experimental conditions tested. Ultrasound intensity for pretreatment (55.5 kW/m^3, 40 kHz, 25ºC), ultrasound for drying (31 kW/m^3, 21.8 kHz)

Table 2. Dry matter (DMC) and water content (WC) changes after the osmotic dehydration of pineapple for different times and without or with ultrasound application

Table 3. Average drying time needed to obtain a moisture content of 1 kg water/kg dry matter, effective moisture diffusivity (D_{eff}) and mass transfer coefficient (k), identified by modelling the drying kinetics of pineapple using a diffusional and convective model.

Figure Captions

Figure 1. Scheme of the ultrasonic-assisted dryer. 1. Fan, 2. Heating unit, 3. Anemometer, 4. 3-Way valve, 5. Thermocouple, 6. Sample loading chamber, 7. Coupling material, 8. Pneumatic moving arms, 9. Ultrasonic transducer, 10. Vibrating cylinder, 11. Trays, 12. Balance. 13. Impedance matching unit, 14. Wattmeter, 15. High power ultrasonic generator, 16. PC

Figure 2. Evolution of the dimensionless moisture content of un-pretreated pineapple (P0) during drying at different temperatures (40ºC and 70 ºC; D40 and D70 respectively) and with (US) or without ultrasound application

Figure 3. Evolution of the moisture content during drying at 40 ºC without ultrasound application of both fresh pineapple (P0-D40) and also that osmotically pretreated without (P20-D40) or with (P20US-D40) ultrasound application for 20 min.

Figure 4. Evolution of the moisture content during drying at 70 ºC with ultrasound application of both fresh pineapple (P0-D70US) and that osmotically pretreated without ultrasound for 20 min (P20-D70US) or 40 min (P40-D70US).

Figure 5. Evolution of the dimensionless moisture content during drying at 70 ºC with ultrasound application of both fresh pineapple (P0-D70US) and that osmotically pretreated with ultrasound for 40 min (P40US-D70US).

Figure 6. Evolution of both the experimental moisture content and also of that calculated using the proposed diffusive model during the drying at 70 ºC without ultrasound application of pineapple samples pretreated for 20 min with ultrasound application (P20US-D70)

Table 1. Experimental conditions tested. Ultrasound intensity for pretreatment (55.5 kW/m^3, 40 kHz, 25ºC), ultrasound for drying (31 kW/m^3, 21.8 kHz)

Code	Osmotic pretreatment		Drying	
	Time [min]	Ultrasound application	Temperature [ºC]	Ultrasound application
P0-D40	Not pretreated		40	No
P0-D40US	Not pretreated		40	Yes
P0-D70	Not pretreated		70	No
P0-D70US	Not pretreated		70	Yes
P20-D40	20	No	40	No
P20-D40US	20	No	40	Yes
P20-D70	20	No	70	No
P20-D70US	20	No	70	Yes
P20US-D40	20	Yes	40	No
P20US-D40US	20	Yes	40	Yes
P20US-D70	20	Yes	70	No
P20US-D70US	20	Yes	70	Yes
P40-D40	40	No	40	No
P-40-D40US	40	No	40	Yes
P40-D70	40	No	70	No
P40-D70US	40	No	70	Yes
P40US-D40	40	Yes	40	No
P40US-D40US	40	Yes	40	Yes
P40US-D70	40	Yes	70	No
P40US-D70US	40	Yes	70	Yes

Table 2. Dry matter (DMC) and water content (WC) changes after the osmotic dehydration of pineapple for different times and without or with ultrasound application

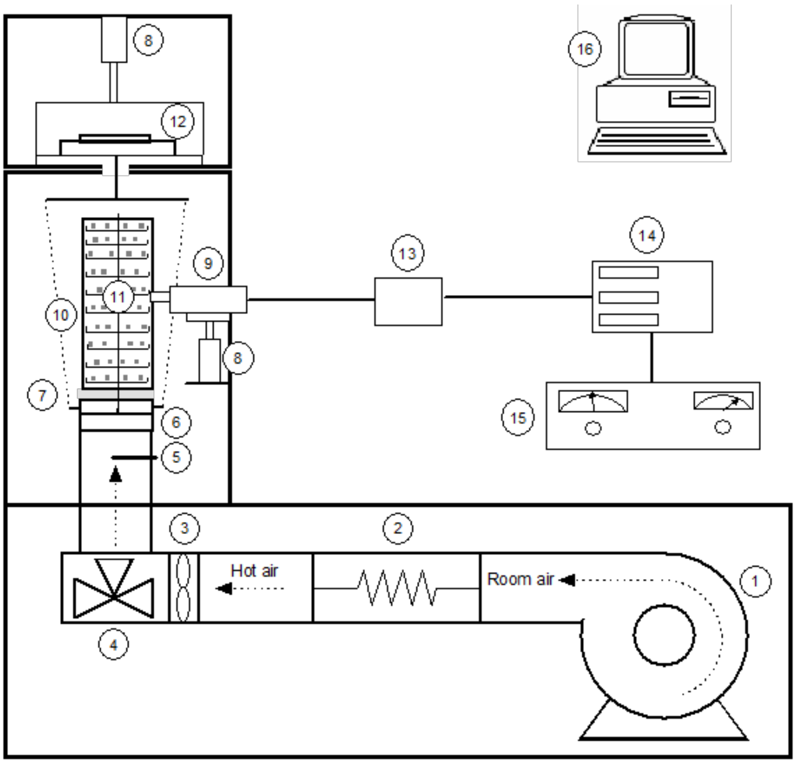
Osmotic treatment time (min)	**Ultrasound application**	**DMC (kg dry mater/ kg initial dry matter)**	**WC (kg water/kg initial dry mater)**
20	No	1.24±0.29^{a}	-0.26±0.08ab
20	Yes	1.04±0.20a	-0.21±0.04a
40	No	1.50±0.32ab	-0.37±0.07bc
40	Yes	1.99±0.13b	-0.47±0.04c

Letters (a, b, c,…) in each column show homogeneous groups established from Tukey test ($p < 0.05$) for drying time, D_{eff} and k, respectively

Table 3. Average drying time needed to obtain a moisture content of 1 kg water/kg dry matter, effective moisture diffusivity (D_{eff}) and mass transfer coefficient (k), identified by modelling the drying kinetics of pineapple using a diffusional and convective model.

Code	Drying time (h)	D_{eff} (m^2/s^{-1}) $\cdot 10^{10}$	k (kg water $\cdot m^{-2} \cdot s^{-1}$)$\cdot 10^4$	Var (%)	EMR (%)
P0-D40	7.1±0.1a	1.9±0.1a	6.3±0.2ab	99.67	14.55
P20-D40	5.5±0.2bc	2.1±0.4a	4.7±0.4a	99.50	10.02
P20US-D40	5.2±0.2bc	2.09±0.07a	4.77±0.2a	99.45	11.70
P40-D40	5.8±0.1c	1.86±0.06a	4.2±0.5a	99.80	6.30
P40US-D40	5.1±0.1bc	1.95±0.03a	4.7±0.3a	99.73	10.82
P0-D40US	4.6±0.7cd	3.9±0.5abc	11±1def	99.32	9.65
P20-D40US	3.3±0.4ef	4±1abcd	10±1bcde	99.57	7.20
P20US-D40US	3.7±0.4de	3.6±0.8abc	8±1abcd	99.67	6.15
P40-D40US	3.3±0.2ef	3.4±0.3ab	7.2±0.5abcd	99.53	11.72
P40US-D40US	3.2±0.5ef	3.7±0.5abc	7±2abc	99.67	10.84
P0-D70	2.6±0.1fg	7.1±0.5bcd	13.4±0.6ef	99.65	10.37
P20-D70	2.4±0.1fgh	6.2±0.2bcd	11.7±0.8def	99.83	4.19
P20US-D70	2.1±0.2ghi	7.2±0.6cd	10.3±0.4cde	99.79	5.99
P40-D70	2.1±0.2ghi	7.3±0.9cd	11 ±1def	99.80	5.13
P40US-D70	1.9±0.2ghi	7.±1d	10.8±0.9cde	99.76	7.62
P0-D70US	1.7±0.1ghi	13±2e	23±2h	99.77	6.08
P20-D70US	1.4±0.2hi	13±3e	18±5g	99.74	6.77
P20US-D70US	1.4±0.1i	15±3e	14±2ef	99.73	10.98
P40-D70US	1.4±0.2hi	12.7±0.4e	15±1fg	99.81	4.82
P40US-D70US	1.6±0.1hi	12±3e	13.8±0.7ef	99.78	8.39

Code: P"number" indicates the time of pretreatment applied (0, 20 or 40 min), when is followed by US indicates that the pretreatment was carried with ultrasound. D"number" is related to the temperature used during the convective drying (40 or 70 ºC) and the letters US indicate the application of ultrasound during drying. Letters (a, b, c,…) in each column show homogeneous groups established from Tukey test ($p < 0.05$) for drying time, D_{eff} and k, respectively



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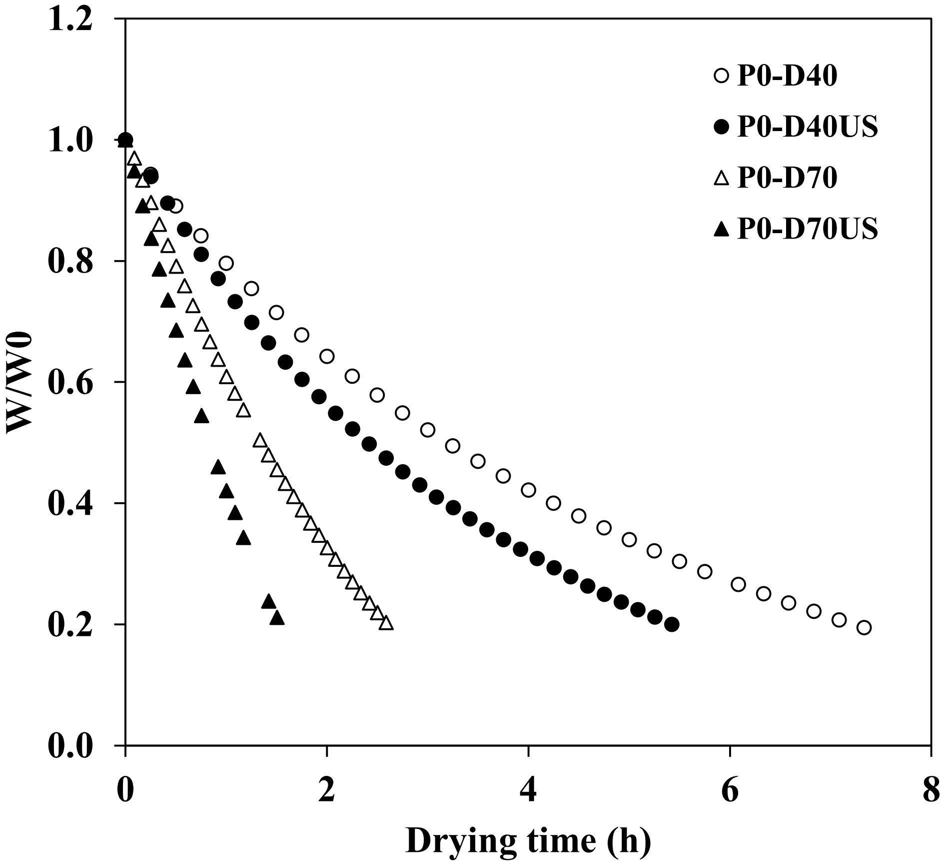

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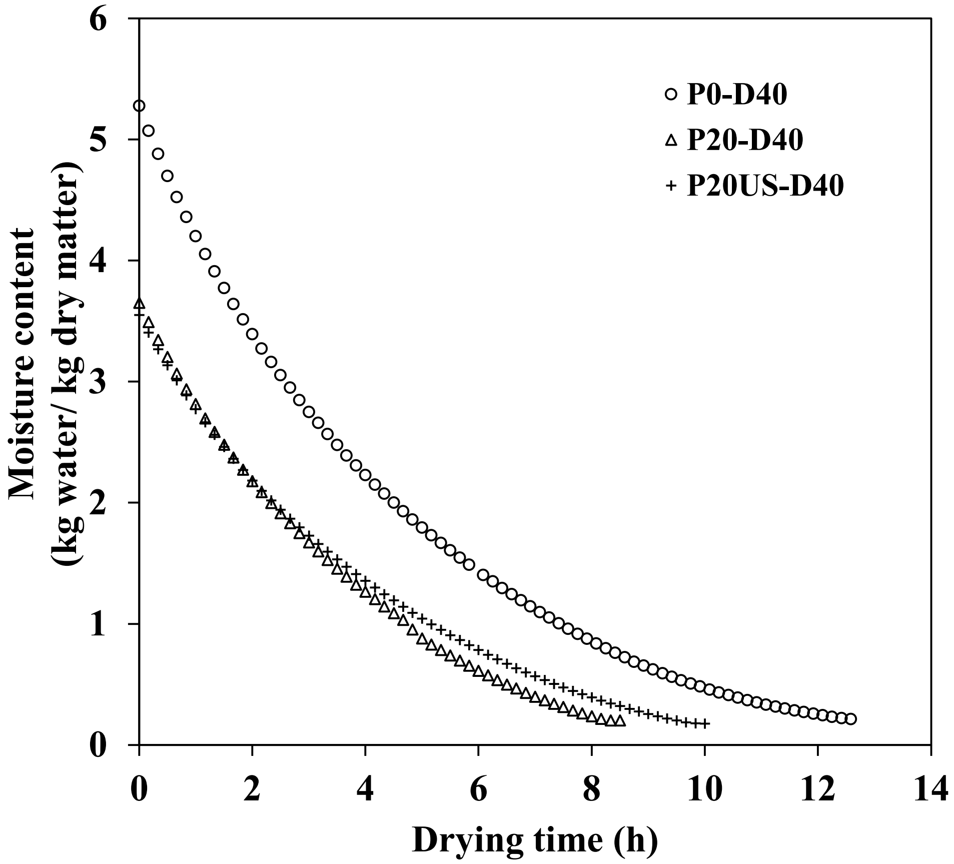


Figure 3. Evolution of the moisture content during drying at 40 ºC without ultrasound application of both fresh pineapple (P0-D40) and also that osmotically pretreated without (P20-D40) or with (P20US-D40) ultrasound application for 20 min.

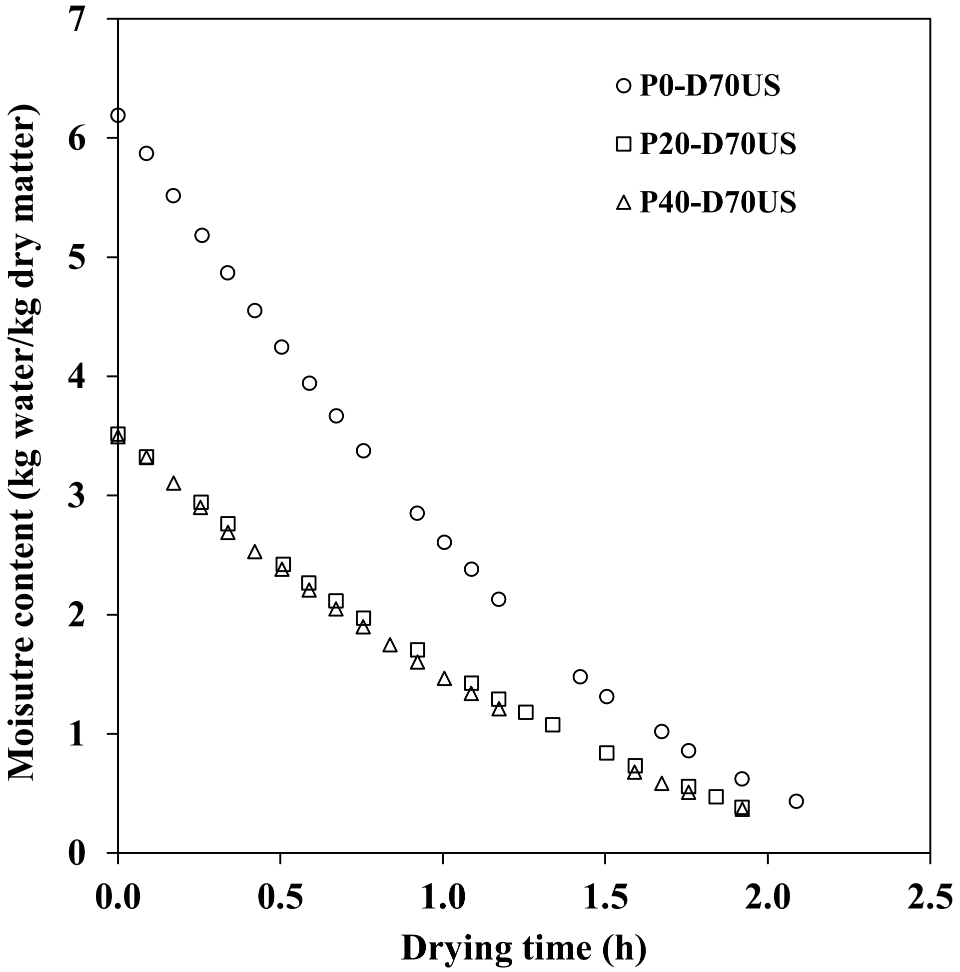
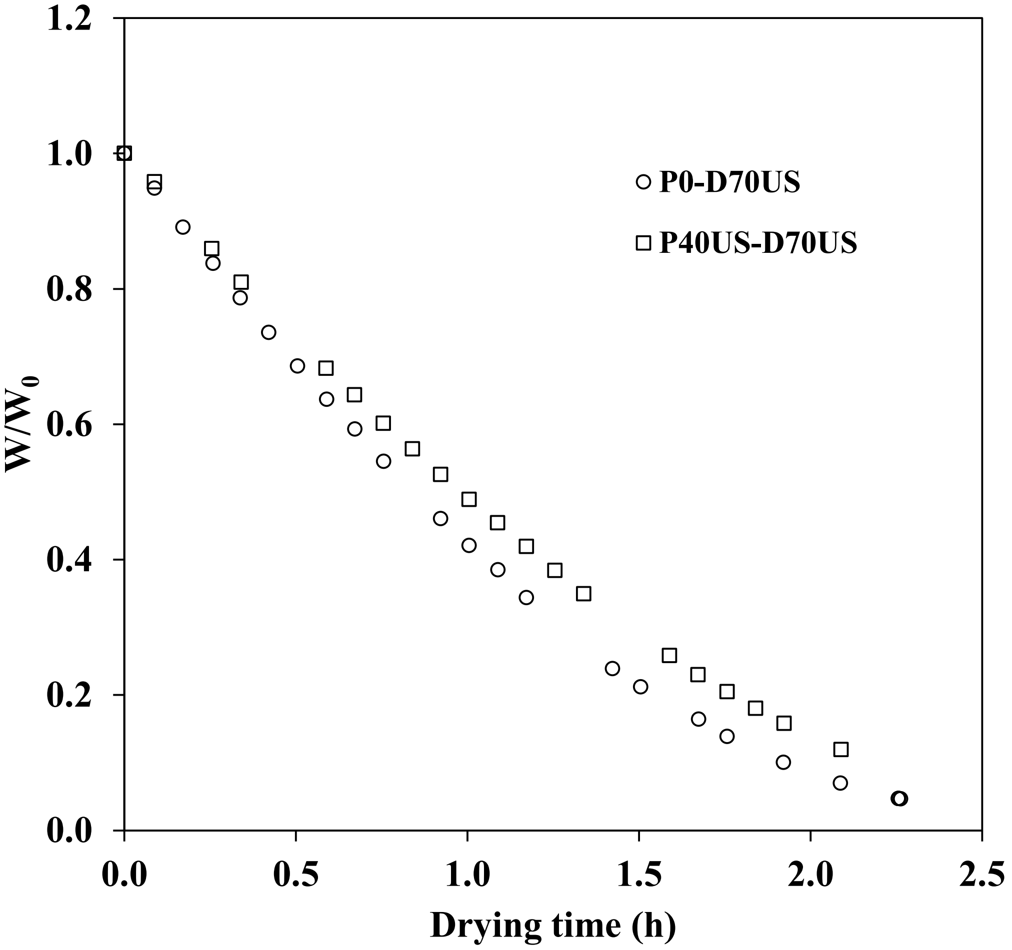


Figure 4. Evolution of the moisture content during drying at 70 ºC with ultrasound application of both fresh pineapple (P0-D70US) and that osmotically pretreated without ultrasound for 20 min (P20-D70US) or 40 min (P40-D70US).



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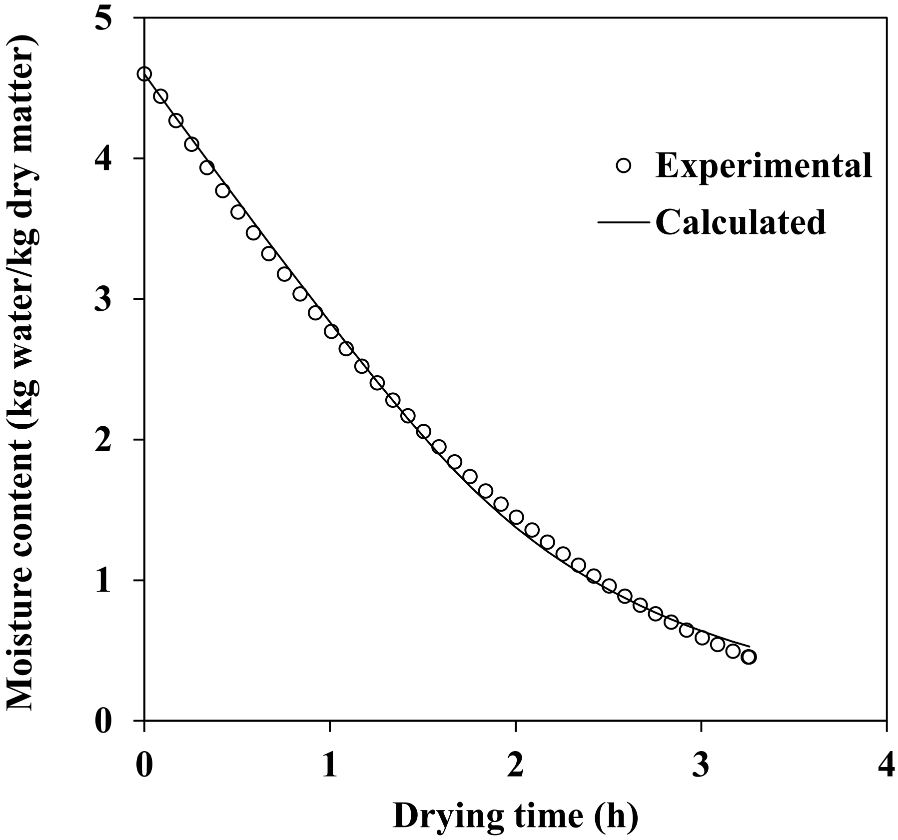

Figure 6. Experimental and calculated with the proposed diffusive model moisture content evolution during drying at 70 ºC without ultrasound application of pretreated for 20 min with ultrasound application pineapples samples (P20US-D70)