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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 °C and 70 °C) 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.

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, Jimenéz, 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

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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, 2014). 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 micro-stirring 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, & 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. Association of Official Analytical Chemist, 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.

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

Code	Osmotic pretreatment		Drying	
	Time [min]	Ultrasound application	Temperature [°C]	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

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 (Cárcel et al., 2007; Garcia-Noguera et al., 2010; Silva, Fernandes, & Mauro, 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 & 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 °C) 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, Puig, et al., 2014), 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, Eq. (1)) but also in the water content (WC, Eq. (2)), both of which were calculated (Cárcel et al., 2007).