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Ultrasound pre-treatment enhances the carrot drying and rehydration

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ABSTRACT

The present work aimed to describe the mechanisms involved in the enhancement of the drying and rehydration process of carrot slices caused by the pre-treatment using the ultrasound technology. For that, carrot slices of 4 mm of thickness were pre-treated for 30 and 60 min using an ultrasonic bath (41 W/L; 25 kHz). The convective drying process was performed at 40 and 60 °C with 2.0 m/s of air velocity, while the rehydration process was performed at 25 °C. The Henderson & Pabis model was used to describe the drying kinetics and the Peleg model to describe the rehydration process of the carrots slices. As a result, the drying and rehydration kinetics were described, at the different conditions of process, correlating the results with the main effects that the ultrasound cause as a pre-treatment (cell bloating and micro-channels) and the air-drying temperature. Depending on the length of the pre-treatment, the effects caused by the ultrasound in the following processes were different. In addition, it was corroborated that when the drying temperature is increased, less evidenced is the ultrasound effect. The ultrasound, when is applied for long times, enhanced the drying and further rehydration rate at low temperatures, due to the tissue damage. Moreover, vacuum-packed samples were pre-treated with ultrasound in order to exclude the water gain and to evaluate only the micro-channels formation effect. It was concluded that the ultrasound pre-treatment enhances the drying and rehydration processes; however, future optimization studies are recommended.

1. Introduction

The drying process is widely applied to obtain food products with longer shelf life, low cost of transportation and storage, as well as new ways of consumption. However, the conventional dehydration methods based on using hot-air for long times can deteriorate the quality of the final product (undesired food flavour, colour decomposition, vitamin degradation and loss of essential amino acids) (Chen & Mujumdar, 2009). Further, being a simultaneous heat and mass transfer process, accompanied by phase change, the food drying consumes a high amount of energy, with high costs and environmental impact. Consequently, high efforts are necessary to guarantee drying processes at mild conditions.

The water transfer during the drying process is controlled by two types of resistance — the internal resistance to the water movement inside the material and the external resistance between the solid surface and the air (Rosselló, Simal, Sanjuan, & Mulet, 1997). Internal resistance is a characteristic of the material, while external resistance depends on the thickness of the diffusion boundary layer (equipment and process conditions). One of those resistances frequently prevails, although checking their relative importance is necessary for establishing process conditions (Rosselló et al., 1997).

Under this context, different methods and drying pre-treatments have been applied to increase the mass transfer by reducing the product initial water content, by modifying the structure in a way that facilitates the water flow, or by changing the environmental conditions (Fernandes & Rodrigues, 2007). These methods include the application of vacuum (Deng & Zhao, 2008), centrifugal forces (Azuara, Garcia, & Beristain, 1996), electric pulses (Barba et al., 2015), electrical pre-treatments (Çakmak, Tekeoğlu, Bozkır, Ergün, & Baysal, 2016), modified atmosphere (Hawlader, Perera, & Tian, 2006), introducing compounds to accelerate the process (Leenaars, Huethorst, & Van Oekel, 1990) and using the ultrasound technology.

The ultrasound technology is an innovative technique to improve the conventional drying, being also used to enhance other mass transfer processes such as osmotic dehydration (Corrêa, Justus, De Oliveira, & Alves, 2015), hydration (Miano, Ibarz, & Augusto, 2016), and extraction (Fernández-Ronco, Gracia, Lucas, & Rodriguez, 2013). When ultrasound travels across a medium, it affects both internal and external resistances and could intensify the mass transfer process in the system (Yao, 2016).

The ultrasound technology can be applied using two different approaches in drying processes: ultrasound assisted drying (continuous way, during dehydration) or as pre-treatment. In addition, the ultrasound effects may be very different according to the physical state of

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the system (Gallego-Juarez, Rodriguez-Corral, Gálvez Moraleda, & Yang, 1999). When the ultrasound assisted drying is used, the mechanical waves travel through the air and product; micro-agitation in the solid–fluid interfaces can be produced in the immediate vicinity of the solid surface, reducing the external resistance and increasing the bulk transport within the fluid (Mulet, Cárcel, Sanjuán, & Bon, 2003). It takes places by the reduction of the diffusion boundary layer thickness, and the introduced pressure variations at solid/gas interfaces, which increases the surface moisture evaporation rate (Gallego-Juárez et al., 2007). However, applications in solid/gas systems, are less convenient due to the acoustic impedance mismatch and the energy absorption by air (García-Pérez, Cárcel, De La Fuente-Blanco, & Riera-Franco De Sarabia, 2006), as well as complexity in equipment designed.

On the other hand, when the ultrasound is used as a pre-treatment, the mechanisms of enhancement differ from the ultrasound assisted drying. In this case, the product is immersed in a liquid medium (distilled water or osmotic solution) with ultrasound application. After that, the product is conventional air-dried. This pre-treatment reduces the internal resistance during the drying process since the ultrasound causes structural changes on the products, such as micro-channels formation (Miano et al., 2016; Shamaei, Emam-Djomeh, & Moini, 2012).

In this work, the ultrasound technology was considered as a pre-treatment to the convective drying of carrot thin slices. The carrot is a product with multiple applications and properties, which constitutes a reference product in the evaluation of the effect of power ultrasound in assisted drying (García-Pérez, Cárcel, Benedito, & Mulet, 2007), previously ultrasound assisted blanching (Gamboa-Santos, Soria, Villamiel, & Montilla, 2013) and ultrasound as pre-treatment followed by hot air drying (Fijalkowska, Nowacka, Wiktor, Sledz, & Witrowa-Rajchert, 2016; Rawson, Tiwari, Tuohy, O'donnell, & Brunton, 2011; Sledz, Wiktor, Rybak, Nowacka, & Witrowa-Rajchert, 2016). Consequently, the focus of the present work was to describe and quantify the effect of using the ultrasound technology as pre-treatment and the consequent enhancement on the drying and rehydration process, describing the principal ultrasonic effects and the involved mechanisms.

2. Materials and methods

2.1. Raw material

Fresh carrots (Var. Flakee) were acquired in a local market (Piracicaba, SP, Brazil) and processed at the same day. The carrots were selected according to their optimum maturity state, colour, size and homogeneous characteristics. In order to guarantee the sample uniformity, the peeled carrots were cut in slices of 3 mm thickness and 37 mm of diameter.

2.2. Ultrasonic processing

The carrot samples (10 slices/replicate) were placed in 4 L of distilled water into an ultrasonic bath (Q13/25, Ultronique, Brazil) with a nominal power of 700 W, frequency of 25 kHz, and actual volumetric power of 41 W/L (calculated according to Cárcel, García-Pérez, Benedito, & Mulet (2012)). They were covered with a metal net to prevent the sample afloat. The control sample was defined as the slices without treatment of ultrasound. The other samples were processed for 30 min and 60 min of ultrasonic processing times. The process temperature was maintained at 23 °C using a heat exchanger connected to a thermostatic bath (Solaris 100,220 V, SP, Brazil). After the processing, the slices were removed from the ultrasonic bath and dried with paper towels to remove excess surface water, being then dried. All the treatments were carried out in triplicate.

To clarify which of the two reported effects produced by ultrasonic processing (micro-channels formation or water incorporation) is the main cause of the drying process improvement, the drying rate at 40 °C of three treatments were compared: samples without pre-treatment, ultrasound pre-treated samples and ultrasound pre-treated vacuum packed samples.

2.3. Convective drying experiments

Drying was performed at 40 and 60 °C with an air velocity of 2 m/s, using an oven with circulation and renewal air (MA 035, Marconi, Brazil). The carrot slices (5 slices — at each condition of treatment and replicate; Table 1) were placed on a metal net to allow the free movement of warm air through the entire surface of the samples. During the drying process, the samples were removed from the dryer every 5 min during the first 20 min, then every 10 min until 40 min and thereafter every 20 min until constant weight. The weight of the samples was measured using a precision scale (GEHAKA, BK4000, Brazil). The moisture at each time was then obtained by mass balance, considering the initial moisture. The initial moisture content was measured by placing small pieces of carrots at 105 °C using an infrared moisture analyser (Mettler LJ 16 and LP16, Japan). The drying process, for each temperature, was performed in triplicate.

Drying curves were plotted as function of the dimensionless water content (MR) versus time, computed according to the Eq. (1) (where M_t is the moisture content during the drying process time (t), M_o is the initial moisture and M_∞ is the equilibrium moisture). The initial moisture content of the fresh carrot (i.e., *in natura*) was always considered for all the calculi. Therefore, the ultrasound-pretreated samples started the drying process with MR values higher than one (due to the water absorption during the pre-treatment).

$$MR = \frac{M_t - M_\infty}{M_o - M_\infty} \tag{1}$$

2.4. Rehydration

After the drying process, the rehydration was evaluated because is an important process for drying products, and in order to compare and explain the possible structural alterations produced by the ultrasonic pre-treatment.

Rehydration was carried out at 25 ± 1 °C. The dried sample (5 slices) was rehydrated by immersion in 400 mL of distilled water, and the evolution of sample moisture over the time was determined by mass balance. For then, the slices were removed from the water, drained, superficially dried with absorbent paper, weighed and returned to the water. The evaluation was carried out every 5 min during the first 25 min, and then every 10 min until constant mass.

2.5. Mathematical fitting

Both drying and rehydration kinetics of all samples, with the different treatments, were evaluated using appropriated mathematical models.

In order to determine the best model for describing the drying kinetics behaviour, four empirical mathematical models (Table 2) were evaluated. These were selected considering its simplicity and expressive use in the literature.

Table 1
Codification of all performed treatments.

Treatment	Ultrasound pre-treatment time (min)	Air drying temperature (°C)
US0 min + D40 °C	0	40
US0 min + D60 °C	0	60
US30 min + D40 °C	30	40
US30 min + D60 °C	30	60
US60 min + D40 °C	60	40
US60 min + D60 °C	60	60

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