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Effects of high-intensity ultrasound on drying kinetics and antioxidant properties of passion fruit peel

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ABSTRACT

The aim of this study was to evaluate the effect of temperature and ultrasound application on drying kinetics and antioxidant potential of passion fruit peel. To this end, drying experiments (1 ms^{-1}) were carried out at 40, 50, 60 and 70 °C without and with ultrasound application (21,7 kHz, 30.8 kW/m^3). Two diffusion models based on Fick's second law were used to mathematically describe the drying kinetics considering or not the external moisture transport resistance. The antioxidant capacity and the total phenolic content of dried passion fruit peels were assessed. The increase in temperature and the application of ultrasound significantly reduced the drying time. Modeling showed that the application of ultrasound increased both the effective diffusivity and the mass transfer coefficient, particularly at the mildest temperatures tested, 40 and 50 °C. Under these conditions, ultrasound application also reduced the loss of total phenolic content and maintained the antioxidant activity of dried passion fruit peel.

1. Introduction

Brazil is a country known for the cultivation of tropical fruits and has become one of the main producers of passion fruit, the most significant proportion of which is commercialized as juice. This generates a considerable amount of residues, due to the peels and seeds which represent 65–70% of the raw material (Oliveira et al., 2002). The disposal of this by-product incurs elevated economic and environmental costs.

The search for effective and non-toxic natural compounds with antioxidant activity has been intensified in recent years (Lobo et al., 2010). This option can represent a means of reusing the waste from the processing of the fruit which is both highly beneficial and economically advantageous. In fact, passion fruit contents low fractions of proteins (4.6%) and fat (0.6%) (Hernández-Santos et al., 2015) but it has been proven that is rich in fibers (35–90% of dry matter) and compounds with antioxidant activity. In this sense, flavonoids such as quercetin, luteolin or cyanidin 3-O-glucoside (Farid et al., 2010) with high antioxidant activity (Raju et al., 2013) have been identified and several authors have proposed their use as a source of intermediate food ingredients for the development of functional foods (Contreras-Calderón et al., 2011; Infante et al., 2013; López-Vargas et al., 2013; Martínez et al., 2012; Oliveira et al., 2002; Quaresma et al., 2009).

The drying of raw matter is a common stage prior to the extraction of the antioxidant compounds, not only allowing the raw matter to be stabilized making the storage easy but also preventing water interference in the extraction process (García-Pérez et al., 2012). Hot air drying is one of the most commonly used methods of vegetable drying. However, physical and chemical changes take place during the drying process, affecting the quality of the dehydrated product in terms of its nutritional characteristics and texture. The long processing time needed and the elevated temperatures usually employed are the main factors which not only influence quality parameters, such as the vitamin content (Labuza, 1984) and the antioxidant activity (Ahmad-Qasem et al., 2013), but also make drying one of the most energy demanding operations (Mujumdar and Devahastin, 2000). The application of high intensity ultrasound during drying can intensify the operation, reducing processing time and/or

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Nomenclature

Symbol, description, units

a_w	Water activity
C_f	Final content (polyphenols, antioxidant capacity)
C_i	Initial content (polyphenols, antioxidant capacity)
E_a	Activation energy, kJ/mol
D_e	Effective moisture diffusivity, m^2/s
D_o	Pre-exponential factor, m^2/s
k	Mass transfer coefficient, kg water/m^2s
L	Thickness of passion fruit peel, m
W	Moisture content, kg water/kg dry matter
W_{eq}	Equilibrium moisture content, kg water/kg dry matter
W_o	Initial moisture content, kg water/kg dry matter
R	Universal gas constant, kJ/mol K
Sh	Sherwood number
S^2_{ex}	Variance of the experimental data
S^2_{calc}	Variance of the calculated data
T_a	Absolute temperature, K
t	Time, s
x	Moisture transport direction
λ_n	Eigenvalue
ρ_{ss}	Density of dry solid, (kg d.m./m^3)
φ_{air}	Relative humidity of drying air

decreasing the treatment temperature (Cárcel et al., 2014). The high frequency ultrasonic wave causes a mechanical stress inside solid products and produces micro stirring at solid–gas interfaces that can affect both internal and external moisture transport (Cárcel et al., 2012, 2014; Gallego-Juárez et al., 2007), the porous structures being more prone to the effects of ultrasound than the denser ones (Ozuna et al., 2014). In this sense, passion fruit peel presents a similar porous structure to orange peel, mainly in the albedo layer, which could be suitable for ultrasonically assisted drying (García-Pérez et al., 2012).

The aim of this study was to evaluate the effect of both the drying temperature and ultrasound application on the drying kinetics and antioxidant activity of passion fruit peel.

2. Materials and methods

2.1. Raw matter

Experiments were performed with passion fruit samples (Colombian origin) purchased in a local market (Valencia, Spain). Fruits were selected with a similar degree of maturity. Rectangular shaped samples of passion fruit peel ($0.044 \times 0.024 \times 0.007 \pm 0.001$ m) were obtained with the aid of a sharp blade. The initial moisture content was measured by placing samples in a vacuum oven at 70 °C and 200 mmHg until constant weight, following standard method n° 934.06 (AOAC, 1997).

2.2. Drying experiments

An ultrasonic assisted drier (Fig. 1), described in detail by Riera et al. (2011), was used to carry out the drying experiments. The system is provided with a vibrating cylindrical drying chamber driven by a piezoelectric transducer (21.8 kHz). An impedance matching unit permits the impedance output of the generator to be tuned to the transducer resonance frequency providing the system with a better electrical yield. A high intensity ultrasonic field (up to 154.3 dB) is produced inside the drying chamber while the drying air goes through it. The samples were randomly placed using a customized sample holder that allows a homogeneous air flow and ultrasonic treatment.

The drying experiments were carried out in triplicate at four different air temperatures (40, 50, 60 and 70 °C) without (AIR) and with ultrasound application (AIR + US; 21.7 kHz, 30.8 kW/m^3). In every case, an air velocity of 1 m s^{-1} was used. The dehydration process was stopped when samples lost 80% of their initial weight.

2.3. Modelling

For modelling purposes, it was assumed that the samples exhibited infinite slab behavior and, therefore, the flux of moisture during drying only takes place in one direction. Considering the effective moisture diffusivity as constant and the solid as isotropic, diffusion models based on Fick's second law were used to mathematically describe the drying kinetics according to Eq. (1).

$$\frac{\partial W(x,t)}{\partial t} = D_e \frac{\partial^2 W(x,t)}{\partial x^2} \tag{1}$$

Where W is the local moisture content (kg water/kg dry matter, d.m.); D_e is the effective moisture diffusivity (m^2/s); t is the time (s); and x is the direction of the water transport (m). Eq. (1) was solved by considering, as an initial condition, that the moisture content of samples was uniform at the beginning of the drying process. The external layer of passion fruit peel constitutes the natural barrier of the fruit against dehydration and, for this reason, it could be considered as a waterproof layer. Thus, the experimental moisture transport mainly took place from this waterproof layer to the opposite side of the sample, similarly to a symmetrical moisture transport in a slab twice as thick (Fig. 2). This fact was included in the model through the boundary conditions shown in Eq. (2).

$$\frac{\partial W(0,t)}{\partial x} = 0 \tag{2}$$

As regards the second boundary condition, two different situations were considered, which resulted in two different models. In a first approach, the external resistance to moisture transport was neglected (NER model), assuming that the moisture content of the solid surface achieves equilibrium when drying starts (Eq. (3)). Therefore, in this case, the kinetics was controlled by the movement of the moisture inside the solid.

$$W(L,t) = W_{eq} \tag{3}$$

where L is the thickness of the sample and W_{eq} is the equilibrium moisture content (kg water/kg d.m.). This equilibrium moisture content was estimated from the desorption isotherm of passion fruit peel obtained by Medeiros et al. (2006). The analytical solution of the NER model, integrated for the volume of sample, predicted the evolution of the sample's average moisture content during drying (Eq. (4)) (Crank, 1975).

$$W = W_{eq} + \left(W_0 - W_{eq}\right)\left[2\sum_{n=0}^{\infty}\frac{1}{\lambda_n^2 L^2} e^{-D_w \lambda_n^2 t}\right] \tag{4}$$