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Influence of power ultrasound application on drying kinetics of apple and its antioxidant and microstructural properties

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ABSTRACT

The effect of drying air temperature and power ultrasound (US) application on the drying curves of apples (var. Granny Smith) and on the quality (total polyphenol (TPC) and flavonoid (FC) contents, the antioxidant activity (AA) and microstructure after drying) have been evaluated. Drying curves were studied at air temperatures of 30 °C, 50 °C, and 70 °C; without ultrasound (AIR) and using two levels of ultrasonic power: 18.5 kW/m^3 (AIR + US1) and 30.8 kW/m^3 (AIR + US2), being the drying time significantly ($p < 0.05$) reduced as these two operational variables increased. A diffusional model, taking into account the influence of drying temperature and US power on both the diffusion and the external mass transfer coefficients allowed the accurate simulation of the drying curves (MRE = 5.8 ± 2.1%). TPC and FC were affected by drying temperature and US application. In AIR samples, the increase of drying temperature led to lower losses of TPC, FC, and AA. The US application (AIR + US1 and AIR + US2) involved lower TPC and FC losses in comparison to AIR samples only at 30 °C. The use of US promoted notorious changes in the microstructure (SEM observation) of apple samples, in comparison to the samples dried without US at all the temperatures considered, due to the stress developed by ultrasonic waves.

1. Introduction

Apples constitute a major part of fruit production and there is a growing tendency to its consumption in the world, in the form of fresh fruit, juice or dried products including snack preparations, integral breakfast foods and other varieties (Biedrzycka and Amarowicz, 2008). Apples also ranked the second for total concentration of phenolic compounds, and perhaps more importantly, apples had the highest portion of free phenolics when compared to other fruits (Boyer and Liu, 2004), being the Granny Smith variety, one of the polyphenol-richest apple cultivars (66.2–211.9 mg/100 g fresh weight) with flavonoids (catechin and proanthocyanidins) as the major class of apple polyphenols (Vrhovsek et al., 2004; Biedrzycka and Amarowicz, 2008). Nowadays, consumers demand for high quality products which keep the fresh-like characteristics of flavor, texture, color but more important the nutritional content, along with an equitable or extended shelf life. Unfortunately, apple processing, either juice obtaining or drying leads to a significant loss of the phenolic content and also its antioxidant activity (Van der Sluis et al., 2002).

Recently, an increase of the concerning about the health's benefits of apple consumption has encouraged the research of the effects of processing on product attributes in order to minimize the quality degradation. Several processing methods have been studied in the recent years in order to assess its influence on the quality loss of the final product. With this aim, microwave heating (Picouet et al., 2009), high pressure (Landl et al., 2010), cold-break (Le Bourvellec et al., 2011), straight pressing (Van der Sluis et al., 2002), among others, have been used for apple juice or puree obtaining. Apple drying has been widely addressed in literature. Convective drying is the most frequently used dehydration operation in food and chemical industry, is used to assure the food stability, minimizing the microbiological and physicochemical activity by means of the reduction of water activity (Krokida et al., 2003); however, drying causes changes in the nutritional value, physical properties and microstructure of fruits and vegetables and their products (Chen et al., 2011). Heras-Ramírez et al. (2012) and Vega-Gálvez et al. (2012), among others, have studied the effects of drying conditions, such as temperature, air velocity and drying time, on the degradation of thermolabile compounds, such as polyphenols and flavonoids, and its antioxidant activity in apples. Other authors have reported those changes in different vegetables: orange peel (Garau et al., 2007), quinoa seeds (Miranda et al., 2010), carrots (Eim et al., 2013), tomatoes (Mechlouch et al., 2012), and garlic (Calín-Sánchez et al., 2013).

Not only the nutritional quality is affected by the drying process, but also the microstructure is modified by water removal.

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Nomenclature

A	area at the solid surface for the mass transfer (m^2)
C	concentration (mg/g d.m)
D_e	effective water diffusion coefficient (m^2/s)
h_m	external mass transfer coefficient (kg H_2O/m^2 s)
L	half of the length (m)
n	number of experimental data
M	mass of water in the control volume (kg)
m	mass flux per area (kg/m^2 s^1)
MRE	mean relative error (%)
P	power level (kW/m^3)
S_x	standard deviation (sample)
S_{yx}	standard deviation (calculated)
T	temperature (K)
t	time (s)
V	volume (m^3)
var	percentage of explained variance (%)
W	average moisture content (kg H_2O/kg d.m)
x, y, z	spatial coordinates (m)
ρ_{dm}	dry matter density (kg d.m/m^3)
φ	relative humidity

Subscripts

0	initial
∞	drying air
cal	calculated
e	equilibrium at surface
exp	experimental
f	final

The microstructural analysis of foodstuffs has been widely described in literature by Ramírez et al. (2011), Vega-Gálvez et al. (2012), Eim et al. (2012) among others, as an effort to relate microstructural changes with macroscopic alterations during the drying process.

The ultrasound application may overcome some of the limitations of convective drying by increasing the drying rate at lower temperatures and so, the mass transfer phenomena (García-Pérez et al., 2007). The mechanical energy provided by the application of power ultrasound contributes to the reduction of both the internal and external resistances to the mass transfer, being the water transfer mainly improved by alternating expansion and compression cycles (sponge effect). Besides, high-intensity airborne ultrasound causes microstreamings at the interfaces that reduce the diffusion boundary layer, increase mass transfer, and accelerate diffusion (Gallego-Juárez et al., 2007). García-Pérez et al. (2009) reported this effect when different acoustic power densities (0–37 kW/m^3) were tested during a convective drying (40 °C, 1 m/s) of carrot cubes and lemon peel slabs. Besides, there is a limited heating effect of ultrasound on gas systems, which is relevant considering the preservation of thermolabile compounds during drying.

Therefore, the main objective of this study is to evaluate the influence of ultrasound application on the convective drying of apple at different temperatures. For this purpose, the drying curves have been studied by using a diffusion model and the total polyphenol and flavonoid contents, the antioxidant activity losses, and the microstructural changes due to the ultrasound application have been evaluated.

2. Materials and methods

2.1. Sample preparation

The Granny Smith apple used in this study was purchased in a local market. Fruits were washed, peeled, cored and cut into cubes (0.01 m edge). The initial average moisture (W_0) obtained by using the AOAC method No. 934.06 (AOAC, 2006) was of 5.64 ± 0.30 kg water/kg d.m. After cutting, cubes were processed immediately.

2.2. Drying experiments

Drying experiments were carried out in a convective drier assisted by power ultrasound, which has already been described in a previous work by Cárcel et al. (2011). The equipment consists of a pilot-scale convective drier with an aluminum cylindrical vibrating element (internal diameter 0.1 m, height 0.31 m and thickness 10 mm) working as the drying chamber. The cylinder is driven by a piezoelectric transducer (21.8 kHz); thus, the ultrasonic system is able to generate a high intensity ultrasonic field in the air medium with an average sound pressure of 154.3 ± 0.1 dB. The drier operates completely automatic, air temperature and velocity are controlled using a PID algorithm and samples are weighed at preset times by combining two pneumatic systems and a PLC (CQM41, Omron, Japan). Drying experiments were carried out at constant air velocity (1 m/s) and drying temperatures of 30 °C, 50 °C, and 70 °C, without ultrasound (AIR), and acoustically assisted applying two different acoustic powers of 18.5 ± 0.9 kW/m^3 (AIR + US1) and 30.8 ± 0.9 kW/m^3 (AIR + US2). An additional set of drying experiments was carried out at 40 °C and 24.6 ± 0.9 kW/m^3 in order to validate the simulation obtained by using the proposed diffusion model when different operational conditions to those of the parameter identification were used. All the drying experiments were carried out, at least, in triplicate and extended until a sample weight loss of 80% of the initial one was achieved.

2.3. Diffusional model

With the aim of obtaining a mathematical model representative of the moisture transport during the drying process, the Fick's second law was combined with the microscopic mass transfer balance and the process was considered to be isothermal. The governing equation for a differential element of cubic shape was formulated (Eq. (1)) considering liquid diffusion being the main transport mechanism.

$$D_e\left(\frac{\partial^2 W}{\partial_x^2}+\frac{\partial^2 W}{\partial_y^2}+\frac{\partial^2 W}{\partial_z^2}\right)=\frac{\partial W}{\partial_t} \quad (1)$$

A constant and effective diffusion coefficient (D_e), representative of the global transport process, might include molecular diffusion, liquid diffusion through the solid pores, vapor diffusion and all other factors which affect drying characteristics (Rodríguez et al., 2013). The governing equation (Eq. (1)) can be solved considering that the moisture distribution inside the solid was uniform at the beginning of the process (Eq. (2)). The boundary conditions considered were those related to the moisture distribution symmetry (Eq. (3)), and the external mass transfer at the solid surface (Eq. (4)) (Castell-Palou et al., 2012). Due to symmetry considerations, an eighth of the cube was modeled. In Fig. 1, the differential control volume for the mass transfer analysis has been depicted. The effect of solid shrinkage on transfer processes was taken into account