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Combined effects of ultrasound and pulsed-vacuum on air-drying to obtain unripe banana flour

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ABSTRACT

In order to increase the water migration rate during unripe banana drying process, two pre-treatments were applied. Experiments were performed as following: 20 min of ultrasound (US) + air-drying at 50 °C; 20 min of US + 60 min of pulsed-vacuum (PV) + air-drying at 50 °C; 25 min of US + air-drying at 60 °C and 25 min of US + 60 min of PV + air-drying at 60 °C. Experimental data were adjusted to five models and the Midilli model resulted to fit best experimental data with $r^2 > 0.999$, RMSE < 0.0119 and $\chi^2 < 0.00012$. Increasing in water effective diffusivity, at the two falling rate periods, were observed due to the application of US, whereas the combined technique of US + PV did not improve the water migration, at both air-drying temperatures. The results revealed drying time savings of (28 and 18) % at (50 and 60) °C, respectively.

Industrial relevance: In this work, ultrasound and ultrasound-pulsed vacuum pre-treatments prior to air-drying were applied as an alternative to produce unripe banana flour (UBF). This study indicates that the drying kinetics increased due to the application of ultrasound, preserving the resistant starch content of the final product. Hence, this technology diminishes the drying time and consequently reduces the energy costs, in comparison with to the conventional process. Therefore, the UBF rich in resistant starch content can be considered a functional ingredient that promotes dietary intake of unavailable carbohydrates, which may reduce the risks of non-communicable diseases.

1. Introduction

Banana takes important place in the production of agricultural crops from several countries, especially those located in the tropics. India is the top of the producers list with 25 million tons of fruit; fifth place is Brazil with 7 million tons. Banana is the second most produced fruit in Brazil, behind orange (FAO, 2012). In contrast, the accumulation of losses in the production of banana reaches 40% (EMBRAPA, 2007). The main causes of these losses are inadequate techniques for harvesting and post-harvesting; failures in the distribution and the difficulty in placing the product on the market can also be highlighted as causes of losses. Bananas when unripe have high resistant starch (*RS*) content, (47–57) g/100 g based on dry basis (d.b.) (Fuentes-Zaragoza, Riquelme-Navarrete, Sánchez-Zapata, & Pérez-Álvarez, 2010). According to Menezes et al. (2011) some of the components of unripe banana flour (UBF) are resistant starch (49 g/100 g d.b.), available starch (28 g/100 g d.b.), dietary fiber (7.2 g/100 g d.b.), sucrose (0.96 g/100 g d.b.) and reducing sugars (0.85 g/100 g d.b.). UBF, rich in *RS*, has attracted interest because of its positive effect in the human health, since, increase the intake of unavailable carbohydrates, which may reduce the risk of non-communicable diseases (Giuntini et al., 2015; Hoffmann et al., 2016). Therefore, the production of UBF encourages consumption of food with positive properties and reduces post-harvest losses of the fruits. UBF is commonly produced by drying.

A pre-treatment to air-drying process can be used to reduce the initial water content or to modify the fruit tissue structure (Fernandes & Rodrigues, 2007). Ultrasound (US) can form micro-channels in the product due to the mechanical stresses associated with wave transmission. When the ultrasonic waves travel through the product it causes rapid series of alternative compressions and expansions, which are compared to a sponge squeezed and released repeatedly (Fuentes-Blanco, Sarabia, Acosta-Aparicio, Blanco-Blanco, & Gallego-Juárez, 2006). The ‘sponge effect’ helps to keep the micro-channels unobstructed for moisture movement promoting the moisture migration in the solid (Fuentes-Blanco et al., 2006; Yao, Zhang, & Liu, 2009). Thus, US has been used to improve mass transfer in food (Patero & Augusto, 2015). Azoubel, Melo, Rocha, and Sorelly (2010) and Fernandes and Rodrigues (2007) related US positive effects on water effective diffusivity for ripe banana air-drying process. In recent years, attempts have been made to dry stuffs until desirable moisture content, improving the

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Nomenclature

a	constant of Henderson & Pabis and Logarithmic model (−)
a_w	water activity (−)
b	constant of Midilli model (1/min)
c	constant of Logarithmic model (−)
C_P	specific heat (J/g K)
D_{eff}	water effective diffusivity (m^2/s)
F_o	Fourier number (−)
k	first order constant of semi-empirical drying models (1/min)
L	sample half- thickness (m)
m	mass (g)
MR	moisture ratio
n	constant of Page model (−)
p_{abs}	absolute pressure (kPa)
P_{US}	ultrasonic volumetric power (W/L)
RS	resistant starch (g/100 g)
t	time (min)
T	temperature (°C)
V	volume (L)
x	moisture content on wet basis (g H_2O/g)
X	moisture content on dry basis (g H_2O/g)
WG	water gain (g/100 g)

Subscripts

0	initial
e	equilibrium
f	flour
p	peak
US	ultrasound

energy efficiency and reducing quality degradation of food products. Some alternatives include: decreasing the drying temperature, shortening the drying time, etc. (Chen, Guo, & Wu, 2016). An interesting option is the use of ultrasound technology because of its lower energy consumption and lower temperature application that could reduce quality degradation of food (Chen et al., 2016; Fernandes & Rodrigues, 2007; Tiwari, 2015).

Vacuum drying is another alternative method and is especially suitable for products that are prone to heat damage, like fruits and vegetables (Chen et al., 2016). The changes of pressure in the system produce strong drying forces responsible for mass transfer (Fito, Andrés, Chiralt, & Pardo, 1996).

Previous researchers already pointed out the advantages of the application of ultrasound prior to air-drying to improve the water effective diffusivity (D_{eff}). In this work, the application of ultrasound in combination with pulsed-vacuum pre-treatment was studied to verify the effect on the kinetics parameters of unripe banana air-drying. Studies using the combination of these two techniques and their relationship with air-drying for unripe banana have not been reported yet.

2. Materials and methods

2.1. Raw material

Unripe bananas (*Musa cavendishii*) variety *Nanicão* from Vale do Ribeira region (São Paulo, Brazil) were purchased from local market. As soon as fruits arrived to the laboratory, the soluble solids and firmness were determined, and processed immediately. According to Tribess et al. (2009), for this cultivar, to identify the first stage of maturation, the mean values of soluble solids should be close to (3.5 ± 0.8) °Brix and firmness (25.8 ± 2.4) N.

Soluble solids were determined by a refractometer and corrected for acidity and temperature values according to Zenebon and Pascuet (2008). A texture analyzer TA-XT2*iplus* was used to evaluate the firmness with a flat base of 6 mm diameter, at penetration velocity of 1 mm/s and penetrated until 20 mm deep. Initial moisture content was determined by gravimetric method at 70 °C under vacuum pressure (≤ 20 kPa) until constant weight (Zenebon & Pascuet, 2008). Soluble solids, firmness and initial moisture content were performed before processing, in triplicate.

2.2. Ultrasound pre-treatment

The experiments were conducted in a bath (UNIQUE, model USC-1850, Brazil) at 154 W and 25 kHz, without mechanical agitation. Before the pre-treatment was applied, the ultrasonic volumetric power was determined by calorimetric method (Cárcel, Benedito, Roselló, & Mulet, 2007) and following the methodology described by Kikuchi and Uchida (2011) and Vinatoru (2015), in quintuplicate. Ultrasonic bath was insulated to minimize heat transfer through the surroundings. In order to avoid that ultrasonic waves return to the transducer and to guarantee perfectly absorption in water, the equipment was tilted 30° and the walls and the bottom of the water bath were covered with aluminum paper. The equipment was filled with 2 L of distilled water at temperature of 26 °C and turned on for 5 min (300 s), while the water temperature was monitored with a thermocouple. The ultrasonic volumetric power was calculated by Eq. (1), considering the heating power as a result of the energy delivered by the US waves:

$$P_{US} = \left(mC_P\frac{dT}{dt}\right)\frac{1}{V} \quad (1)$$

wherein: P_{US} is the ultrasonic volumetric power; m is the mass of water; C_P is the specific heat of water; V is the bath volume; and dT/dt is the variation of temperature along the time.

Banana slices peeled and cut into slices of 5 mm thickness were submitted to ultrasound for (20 and 25) min. The water fruit ratio was maintained at 4:1 (weight basis) at ambient temperature and the experiments were carried out in duplicate. After ultrasound (US), pre-treatment samples were drained to remove the excess of water. Moisture content was determined in triplicate by gravimetric method at 70 °C under vacuum pressure (≤ 20 kPa) until constant weight (Zenebon & Pascuet, 2008). Initial and after pre-treatment weight and moisture content were used to calculate the water gain (*WG*) according to Eq. (2):

$$WG = \left(\frac{m_{US}x_{US} - m_0x_0}{m_0}\right) \times 100 \quad (2)$$

wherein: *WG* is the water gain; x is the moisture content based on wet basis; and the subscripts *US* and 0 correspond to after and before (initial) pre-treatment, respectively.

Banana slices before and after US pre-treatment were also photographed with an image capture system consisted of a light microscope and a digital camera (LEICA, model S6D, Germany). Images were captured at 40 × magnification.

2.3. Pulsed-vacuum pre-treatment

Pulsed-vacuum (PV) was carried out in a vacuum-convective drier (LABMAQ, model LM.ES-20, Brazil) at 50 kPa (p_{abs} = 51.325 kPa) at ambient temperature for 60 min. The experiments were performed out in duplicate. Moisture content by gravimetric method at 70 °C