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Effect of ultrasound on banana cv Pacovan drying kinetics

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ABSTRACT

The aim of this work was to study and to model the drying kinetics of fresh and ultrasonic pretreated banana cv Pacovan using the diffusional model (Fick's second law) and an empirical two parameters model (Page model). The pretreatment was carried out in an ultrasonic bath at 30 °C. The drying process was carried out in a fixed bed dryer at two different temperatures (50 and 70 °C) and 3.0 m/s air velocity. Page empirical model provided the best simulation of the drying curves. The diffusional model was used to describe the moisture transfer and the effective diffusivities of water were determined and were in the order of 10^{-9} m^2/s. These diffusivities increased with increasing temperature and with the application of ultrasound, while the process time reduced, which can represent an economy of energy, since air drying is cost intensive.

1. Introduction

Banana is the most consumed fruit in several countries (Swasdisevi et al., 2009) and its world production is increasing almost every year, reaching approximately 86 million tones in 2007 (FAO, 2007). Some tropical countries have large plantations, such as Brazil, where the variety Pacovan is the most consumed and produced in the northeast region.

The ripe banana is perishable and deteriorates rapidly after harvesting, hence the need to apply an appropriate post-harvest technology to prolong shelf life. Drying is among the most popular methods for the purpose (Demirel and Thuran, 2003; Karim and Hawlader, 2005; Nguyen and Price, 2007). However, conventional dehydration methods based on hot-air can deteriorate the quality of the final product. Thus, undesired food flavour, colour composition, vitamin degradation and loss of essential aminoacids may be produced (Jayaraman and Das Gupta, 1992; Mujumdar and Menon, 1995). In addition, conventional air drying is energy intensive and consequently cost intensive because it is a simultaneous heat and mass transfer process accompanied by phase change (Barbanti et al., 1994). A pretreatment can be used to reduce the initial water content or to modify the fruit tissue structure in a way that air drying becomes faster (Fernandes and Rodrigues, 2007).

Osmotic dehydration is the most reported pretreatment used prior to air drying (Antonio et al., 2008; Pani et al., 2008; Lombard et al., 2008; Fernandes et al., 2008; Azoubel et al., 2009). However, among emergent new technologies, ultrasonic dehydration is very promising because the process can be carried out at low temperatures, which reduces the probability of food degradation (Mason, 1998) and permits the removal of moisture content from solids without producing a liquid phase change. Its use in food industry is increasing as new uses are studied (Fernandes et al., 2008).

The ultrasonic pretreatment involves the immersion of the fruit in water or in a hypertonic aqueous solution to which ultrasound is applied. Ultrasonic waves can cause rapid series of alternative compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly (sponge effect). In addition, ultrasound produces cavitation, which may be helpful to remove strongly attached moisture. The sponge effect caused by ultrasound application may be responsible for the creation of microscopic channels in porous materials, such as fruits, that reduce the diffusion boundary layer and increase the convective mass transfer in the fruit (Tarleton, 1992; Tarleton and Wakeman, 1998; Fuente-Blanco et al., 2006).

The objective of this work was to investigate the use of ultrasound as a pretreatment and its effect on the drying kinetics of banana.

2. Materials and methods

2.1. Materials

Fresh bananas cv Pacovan were obtained in the local market of Juazeiro County, Brazil, in a maturity appropriated for processing

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(yellow with a few brown spots), according to Travaglini et al. (1993). Prior to the start of each experiment, the bananas were sanitized with running potable water, manually peeled and sliced to the thickness of 0.5 cm (3.21 cm average slice diameter). The initial total soluble solids content (determined by refractometry) was 21°Brix.

2.2. Ultrasound pretreatment

An experimental set consisting of four banana samples was immersed in distilled water and submitted to ultrasonic waves for 10, 20 and 30 min. These pretreatment times were chosen after results of kinetics studies carried out beforehand, in which it was observed that after 30 min the changes inferred in the drying process became insignificant. The water to fruit ratio was maintained at 4:1 (weight basis).

The experiments with ultrasound were carried out in separate 250 mL Erlenmeyer flasks to avoid interference between samples and runs, at 30 °C and an ultrasonic bath (Unique, model USC-2850A, Brazil) was used, without mechanical agitation. The ultrasound frequency was 25 kHz.

After removed from the water solution, samples from each group were drained, blotted with absorbent paper to remove excess solution, weighted and submitted to drying. The moisture content of the samples was gravimetrically measured using a vacuum oven at 70 °C for 24 h (Tecnal, TE-395, Brazil). The weight and moisture content data of each sample were used to calculate the water loss (*WL*) and solid gain (*SG*), according to the following equations:

$$WL(\%) = \frac{ww_o - (tw - ws)}{w_o} \times 100 \tag{1}$$

$$SG(\%) = \frac{ws - ws_o}{w_o} \times 100 \tag{2}$$

where *tw* is the total wet weight of the banana slice at the time of the sampling, g; *ws* is the total solids weight, g; ws_o is the initial weight of solids, g; ww_o the initial weight of water, g; and w_o the total initial weight of the sample, g. Each experimental run was performed in triplicate and the reported values are based on average values, the error being less than 0.5%.

2.3. Drying

Drying experiments were carried out in a continuous flow fixed bed dryer (Sulab, Brazil) at constant air velocity of 3.0 m/s and at two air temperatures (50 and 70 °C). The dryer system consisted of vertical air flow through trays and was arranged as a closed circuit. To maintain constant air condition only one tray was used with a single layer of sample on it (approximately 90 g). For the air heating, three electric resistances were used (two of 1600 W and one of 800 W), which could work independently, controlled by a digital thermostat. A thermal-hygrometer (TESTO, model 635, Germany) was used to measure the dry bulb temperature and the drying air humidity. The air velocity was monitored using an anemometer (AIRFLOW, model LCS 6000, UK).

Samples had average initial moisture content (wet basis) of 67.33% (2.06 kg/kg dry basis) for fresh and 68.82% (2.21 kg/kg dry basis), 70.11% (2.34 kg/kg dry basis) and 70.8% (2.43 kg/kg dry basis) for the 10, 20 and 30 min ultrasound pretreated samples, respectively, which was gravimetrically measured using a vacuum oven at 70 °C for 24 h. Sample moisture content during the air-drying process was gravimetrically determined from the sample initial moisture content (before air-drying process). Sample weight was measured using a semi-analytical balance. Weighting intervals of 15 min were used during the first and the second hour of processing and then 30 min intervals until the dynamic equilibrium between the sample moisture content and drying air humidity was reached, when the sample weight became constant. The drying kinetics was studied by observing the drying curves for the considered air temperature.

A plate of thickness 2*L* having the uniform initial moisture X_o, submitted to drying at constant conditions can be described by Fick's unidirectional diffusional equation (Crank, 1975):

$$\frac{\partial X}{\partial t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \tag{3}$$

where *X* is the moisture content, kg H_2O/kg dry matter; *t* is the time, s; D_{eff} is the water effective diffusivity, m^2/s; and *x* is the length, m.

Using the following initial and boundary condition:

uniform initial moisture content: $X(z,0) = X_o$
symmetry of moisture: $\frac{\partial X}{\partial z}\big|_{z=0} = 0$
equilibrium moisture at surface: $X(L,t) = X_e$

And applying:

$$\overline{X} = \frac{1}{L}\int_0^L X(z,t)dz \tag{4}$$

Eq. (3) becomes:

$$\frac{\overline{X} - X_e}{X_o - X_e} = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[-(2i+1)^2\pi^2 D_{eff}\frac{t}{4L^2}\right] \tag{5}$$

where $\overline{X}$ is the average moisture content at time *t*, kg H_2O/kg dry matter; X_e is the equilibrium moisture content, kg H_2O/kg dry matter; X_o is the initial moisture content, kg H_2O/kg dry matter; *L* is the half of slab thickness, m.

The effective diffusivity (D_{eff}) was obtained by fitting the experimental data to Fick's diffusional model (Eq. (5)), applying the non-linear estimation resources of the Statistica (1995) software. Either the thickness of the fresh banana or the thickness of the ultrasonic pretreated banana was assumed the initial dimension.

One of the most useful empirical models is Page's equation (Page, 1949), which is an empirical modification of the simple exponential model. It was used to fit the experimental drying data and it is written in the form:

$$\frac{\overline{X} - X_e}{X_o - X_e} = \exp(-kt^n) \tag{6}$$

where *k* is the drying constant, *n* is the Page's parameter and *t* is the process time, (s).

The modeling was characterized by the average relative error *E* (Eq. (7)) calculation and the determination coefficient R^2.

$$E(\%) = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{V_e - V_p}{V_e}\right| \times 100 \tag{7}$$

where *N* is the number of experimental data, V_e is the experimental value and V_p is the calculated value. Values of *E* less than or equal to 10% are considered to fit the experimental data satisfactorily (Lomauro et al., 1985).

3. Results and discussion

3.1. Ultrasonic pretreatment

The effect of ultrasonic pretreatment on water loss (*WL*) and solid gain (*SG*) are presented in Table 1. During ultrasound, the fruit gained water and lost solids. Similar results were found by Fernandes and Rodrigues (2007) in the ultrasonic pretreatment of banana

Table 1
Water loss (*WL*) and solids gain (*SG*) after ultrasound pretreatment.

Treatment time (min)	*WL* (%)	*SG* (%)
10	−2.32	−0.48
20	−3.47	−2.13
30	−4.20	−2.40

cv Nanica. This was due to the concentration gradient, which favors a mass transfer of solids from the fruit to the liquid medium and a mass transfer of water from the liquid medium to the product. As a consequence, the moisture content of the fruit after the ultrasound step increased (5.17% in 30 min).

3.2. Drying

For comparison reasons, the dimensionless moisture content was calculated and its change during drying is presented in Figs. 1 and 2 (up to the dynamic equilibrium point). As expected, air temperature affected drying curves, decreasing the drying time of samples.

The mathematical modeling of the drying experimental data using Eqs. (5) and (6) for fresh and pretreated banana at both studied air temperatures are also shown in Figs. 1 and 2. Table 2 shows Page's parameters for the banana samples. It can be seen that the *k* parameter increased with the increase of the air temperature (except for the 10 min ultrasound pretreated sample). The same behavior was observed for the *n* parameter (except for the 30 min ultrasound pretreated sample). Azzouz et al. (2002) concluded that n was a function of air velocity and initial moisture content, while *k* was a function of air drying temperature and of the initial moisture content of grapes.

Page model clearly improve the simulation in comparison with the results obtained using the diffusional model, having the best fit to the experimental data, with calculated average relative error ranging from 1.89% to 12.76% and R^2 values greater than 0.99. This model has been used to accurately simulate the drying curves of potato (Akpinar et al., 2003), carrot (Doymaz, 2004), kiwi (Simal et al., 2005), among others.

Fick's parameters for fresh and pretreated banana are shown in Table 3. The effective diffusivities of water calculated using a dimensionless moisture ratio (Eq. (5) for the first 11 terms of the series) increased greatly with increasing temperature and it were higher for the pretreated samples. This confirms the observations of Fuente-Blanco et al. (2006) that the ultrasonic step affects the fruit tissue, making it easier for the water to

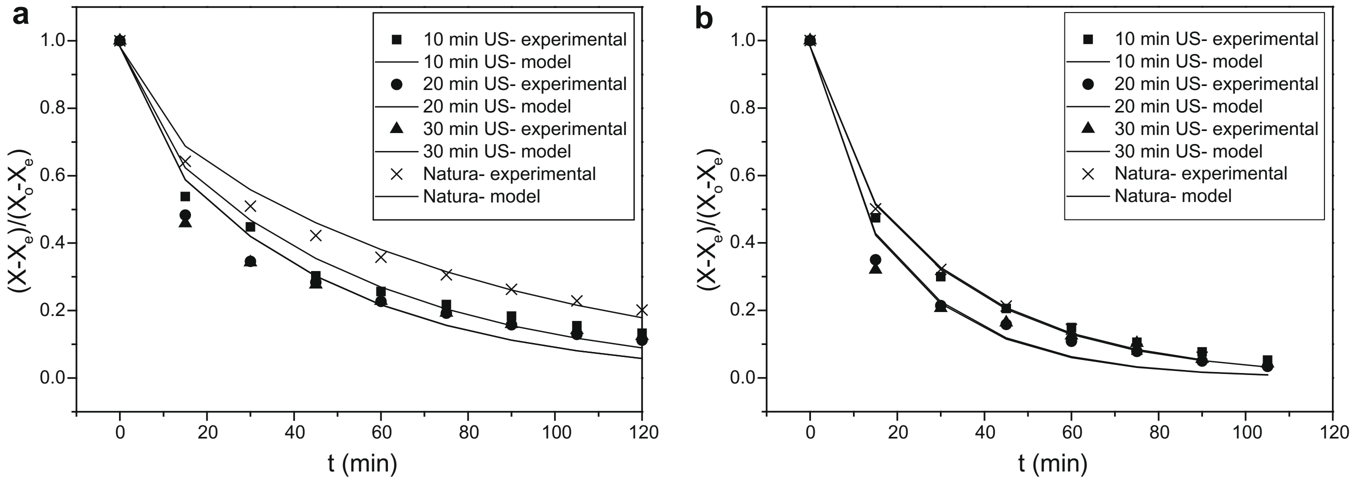

Fig. 1. Modeling of drying kinetics for natura and ultrasonic pretreated (US) banana using Fick model at 50 °C (a) and at 70 °C (b).

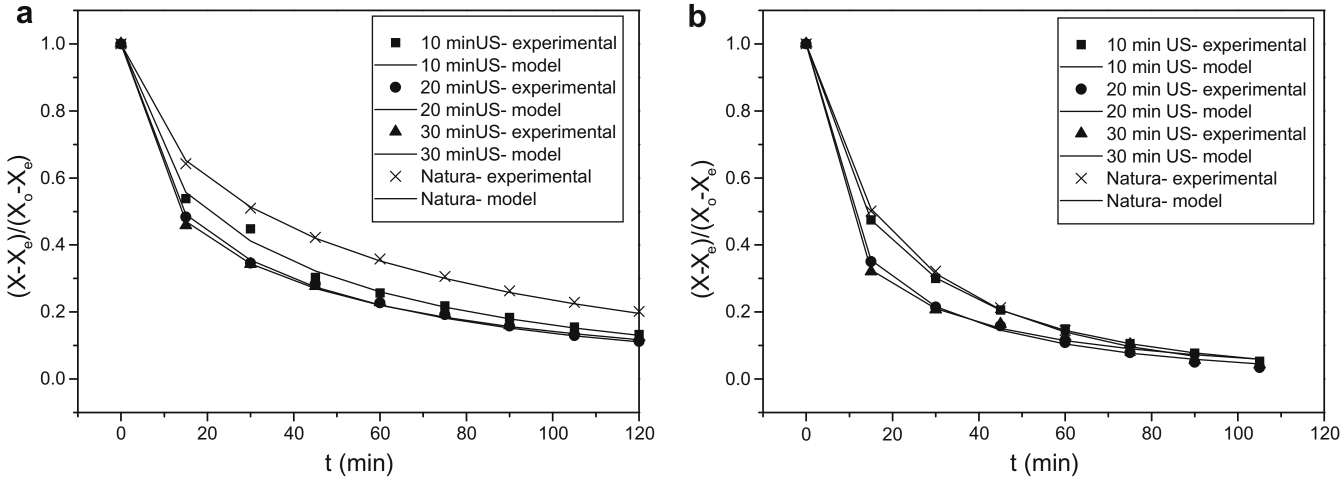

Fig. 2. Modeling of drying kinetic for natura and ultrasonic pretreated (US) banana using Page model at 50 °C (a) and at 70 °C (b).

Table 2
Page's equation parameters and statistical results for natura (N) and ultrasonic pretreated (US) banana.

T (°C)	k_N	n_N	R^2_N	E_N (%)	t_{US} (min)	k_{US}	n_{US}	R^2_{US}	E_{US} (%)
50	0.005	0.643	0.994	2.150	10	0.010	0.600	0.997	4.288
					20	0.018	0.540	0.999	8.337
					30	0.025	0.502	0.999	10.457
70	0.004	0.768	0.999	4.820	10	0.007	0.687	0.999	1.893
					20	0.023	0.562	0.999	7.990
					30	0.045	0.474	0.999	12.763

Table 3
Fick's equation parameters and statistical results for natura (N) and ultrasonic pretreated (US) banana.

T (°C)	$D_{eff\ N} \times 10^9$ (m^2/s)	R^2_N	E_N (%)	t_{US} (min)	$D_{eff\ US} \times 10^9$ (m^2/s)	R^2_{US}	E_{US} (%)
50	0.531	0.986	19.479	10	0.775	0.975	24.242
				20	0.926	0.962	32.983
				30	0.928	0.946	40.106
70	1.275	0.999	4.508	10	1.296	0.994	16.060
				20	1.800	0.981	30.351
				30	1.833	0.963	42.806

diffuse during air drying. This phenomenon may happen due to the process of formation of micro-channels during application of ultrasound and water could use the microscopic channels as an easier pathway to diffuse towards the surface of the fruit, contributing to the higher water diffusivity, as observed by Fernandes et al. (2008). These authors verified in microscopic images that the micro-channels were formed by the elongation and flattering of cell in some regions of the melons submitted to ultrasound, and that no cell breakdown was observed in the samples.

In a quantitative context, the changes in the value of diffusivity have great significance during the air drying stage. For example, if bananas are dried to a final moisture of 0.33 kg H_2O/kg dry matter (25%, wet basis), which is the maximum moisture value allowed to dried fruits, according to the Brazilian Legislation, it will take around 345 min to dry the untreated bananas at 50 °C (or 111 min at 70 °C), while by subjecting the fruit to a 20 min ultrasound pretreatment, in distilled water, the drying time will be reduced to 207 min at 50 °C (or to 106 min at 70 °C), because the increase in water diffusivity. Thus, processing time can be optimized to reduce air drying time to a minimum, reducing costs and increasing overall productivity, as observed by Fernandes and Rodrigues (2007) and Fernandes et al. (2009).

Comparison of diffusivities reported in the literature is difficult because of the different estimation methods and models employed together with the variation in food composition and physical structure. However, the obtained effective diffusivity values were in the same range as those reported in the literature for banana (Baini and Langrish, 2007; Nguyen and Price, 2007; Fernandes and Rodrigues, 2007).

4. Conclusions

Page model was considered the best for explaining the drying characteristics of banana, as it gave higher determination coefficients (R^2) and lower average relative error (E) values. The water effective diffusivity of the samples, which varied from 0.531 to 1.833×10^{-9} m^2/s, increased with increase in temperature and when the ultrasound stage was applied, leading to shorter drying periods and, thus, reduced process costs.

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