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FULL LENGTH ARTICLE

Mathematical models to describe thin-layer drying and to determine drying rate of whole bananas

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Abstract Banana is a fruit produced in most tropical countries. According to the literature, the post-harvest loss is about 40% of the production. To reduce the losses, an alternative is to dry the product. In this context, the main objective of this article was to describe the thin-layer drying of whole bananas. To describe the convective drying process, a mathematical model is normally used. In this article, several empirical models were selected to simulate experiments of thin layer drying accomplished with whole bananas at temperatures of 40, 50, 60 and 70 °C. In the selection, it was imposed that mathematical expressions must be obtained from each model to calculate the drying rate and also the process time. The process time ranged from 1200 (70 °C) up to 3265 (40 °C) min. The maximum drying rate occurs at the beginning of the process and varied between 1.95×10^{-3} (40 °C) and 3.60×10^{-3} (70 °C) min^{-1}. The statistical indicators (determination coefficient and chi-square) showed that Page and Silva et alii models were the best ones to describe the drying kinetics. These two empirical equations enable to write mathematical expressions for the drying rate and process time, and these expressions produced results which can be considered equivalent.

1. Introduction

Banana is a fruit produced in most countries with wet tropical weather. According to Baini and Langrish (2007), the world production of bananas is increasing almost every year, and reached approximately 100 million tons in 2004. In 2010, the main producer countries were India (32 million tons), China (10 million tons), Philippines (9 million tons), Ecuador (7.9 million tons) and Brazil with 7 million tons (FAO, 2011). Banana is one of the fruits most appreciated by consumers around the world, mainly due to its sensory characteristics. It is a calorific food, rich in carbohydrates and minerals, with medium quantity of sugar and vitamin A, and contains little protein (Gouveia et al., 2004). As Alsina et al. (2002) observed, bananas are important in the human nutrition because of their calorific value, and mainly as a source of minerals and vitamins. Besides the consumption "in natura", several products are obtained from banana, such as foods for children and

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dry products, as flour, flakes and also ''banana-passa'', that is the dried product.

According to Baini and Langrish (2007) and many other authors, the high moisture content of bananas makes them susceptible to mold growth. India, the world's largest banana producer, reported post-harvest losses as high as 35–45%, whereas Brazil reported a product loss of approximately 40%. As cooling is not a viable technique to prolong the shelf life of bananas, an alternative to this end is drying. According to Katekawa and Silva (2007), drying of bananas is used not only for preservation, but also to aggregate value to the product, as in chips and ''banana-passa''. Likewise, Janjai et al. (2009) also observed that banana is dried not only for preservation purposes, but also for modification of the taste, flavor and texture to meet consumer preferences and to increase the market value of the product.

Due to its nutritional and economic importance, several studies about banana are available in the literature, and some of them will be mentioned herein. Talla et al. (2004) developed mathematical models for density and shrinkage variation of banana during drying and validated these models through an experimental study on this fruit. Karim and Hawlader (2005) developed a mathematical model to describe heat and mass transfer processes during drying of banana, taking into account the shrinkage of the product. Nguyen and Price (2007) investigated the effect of the drying conditions on the drying kinetics of cylindrical pieces of banana in a temperature range from 30 to 70 °C, taking into account the effect of the slab thickness. In addition, the influence of the banana maturity and different harvesting seasons were also studied to confirm the effect of the morphology on the drying kinetics. In order to describe the heat penetration during a drying process, the latent heat of vaporization of water in the product must be known. Silva et al. (2012a) determined an empirical equation for the latent heat of vaporization of water in bananas, during their isothermal drying, as a function of moisture content and temperature. On the other hand, Da Silva et al. (2012a) proposed a drying model for bananas with variable effective mass diffusivity, and their study involved a numerical solution of the diffusion equation and an optimization algorithm based on an inverse method.

To describe the thin layer drying of an agricultural product, two main groups of models are frequently found in the literature. The first group corresponds to the empirical models (Turhan et al., 2002; Diamante et al., 2010; Kaleta and Górnicki, 2010; Mundada et al., 2011; Silva et al., 2012b) and second one corresponds to the diffusion models (Karim and Hawlader, 2005; Nguyen and Price, 2007; Da Silva et al., 2012a,2012b; Darvishi et al., 2013). Empirical models are important not only to describe thin layer water removal, but also to describe the heat penetration during this removal when hot air is used. In this case, heating is governed by the diffusion equation, that involves the drying rate in the energy balance (Karim and Hawlader, 2005; Mariani et al., 2008), and this rate can be determined by an empirical model. Generally, an empirical model is also used in the study of deep bed drying. In some methods of simulation, the deep bed is divided into several thin layers, and a set of equations is required to describe the process in each layer. Two of these equations are necessary to express the drying rate as a function of time, and also the drying time as a function of moisture content. Normally, empirical models are used with this finality (Aregba et al., 2006; Dantas et al., 2011). In this context, observing the importance of empirical equations in drying simulations, the objective of this article is defined as follows.

The main objective of this article was to describe the thin-layer drying kinetics of bananas, using empirical models. Hence, several models were selected and the selection obeyed the following criterion: from each selected model, mathematical expressions must be obtained to calculate the drying rate and also the process time.

2. Materials and methods

2.1. Experimental data of banana drying

Ripe banana *Musa acuminata*, subgroup Cavendish cv nanica was acquired in the local market, in the city of Campina Grande, State of Paraiba, Brazil. The experimental study was conducted during the months of August and September in 2011. The thin-layer drying experiments, using hot air, were conducted in the Laboratory of Storage and Processing of Agricultural Products of the Federal University of Campina Grande. The convective drier employed in this investigation (Fig. 1), with vertical flux, controller of temperature, controller of air velocity, and three drying trays, was developed and constructed in the local Department of Agricultural Engineering. Several ripe bananas were peeled and selected by their appearance and size, with no evidence of mechanical damage. Three sieves, each one with 1 whole banana, were placed in a convective dryer with vertical air flux. Thus, each drying process was performed in triplicate, with hot air at 40, 50, 60 and 70 °C. For each temperature T, care was exercised to select three bananas with the same dimensions (or very close) to minimize the size effect on the experimental data. Since three samples were dried simultaneously at each time and temperature, the mean value of the three experimental moisture contents was used for the drying characteristics. Average length L and diameter D of the product were measured before drying, with a digital caliper rule (Starret, Brazil, resolution of 0.05 mm), and the results are given in Table 1. This table also presents the average moisture contents in dry basis (initial X_i, final X_f and equilibrium X_{eq}) as well as drying time t. During the experiments, moisture content was measured by the gravimetric method using a digital balance (Marte, Brazil, precision of 0.01 g). The bananas were weighed at time intervals ranging from 5 min at the beginning of drying, to about 4 h at the end of

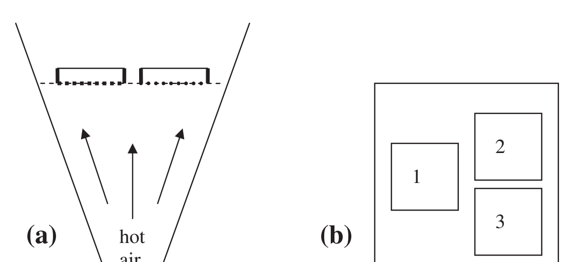

Figure 1 (a) Cross-section of the dryer showing the flux of air, the grid with an area of 40×40 cm^2 and trays for the samples. (b) The positions of the trays ($15 \times 15 \times 5$ cm^3) on the grid are changed cyclically during the interruptions of the drying process to weigh the bananas.