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Full Length Research Paper

Empirical models to describe thin layer drying of lima bean (*Phaseolus lunatus* L.)

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Lima bean is a legume produced and consumed in various countries. To reduce post harvest losses and to enable the storage for long periods, an alternative is to dry the product. To describe the drying process, a mathematical model is usually required. In this article, four empirical equations available in the literature were used to simulate thin layer drying kinetics of lima bean at temperatures of 40, 50 and 60°C. The four empirical equations were chosen based on their simplicity, involving only one or two fitting parameters. The statistical indicators showed that the Page and Silva et al. models were the best ones to describe the process. These two empirical equations has helped to deduce an analytical expression for the drying rate and these expressions produce results which can be considered equivalent.

Key words: Drying rate, mathematical model, grain, storage.

INTRODUCTION

Phaseolus lunatus L., commonly known as lima bean, is a legume produced and consumed in various countries (Da Silva et al., 2009). One of the major obstacles for the consumption of this product throughout the year is the storage loss caused by the growth of decay-causing microorganisms (Miyake and Hiramitsu, 2011). Cooling, immediately after the harvest, has been a widely used method for maximizing post-harvest life of fruits and vegetables (Da Silva et al., 2012). However, in the lima bean case, this mechanism diminishes the post-harvest degradation for a limited time. An efficient resource to reduce its degradation for a long period is to dry the product before the storage, usually by convection, using hot air (Da Silva et al., 2009). Thus, the grains can be stored for the desired period, and rehydrated before the consumption, recovering characteristics close to the fresh product. In addition, drying substantially reduces the weight and volume of the product, minimizing costs of packaging, transportation, and storage (Mujumdar, 1995). As mentioned previously, it is well known that the moisture content greatly affects the time of storage and the final quality of a product. Khakame et al. (2012) for instance, evaluated the effect of the grain moisture content and the time of maize storage on the efficacy of inert and botanical dusts, conventional and bacterial metabolite insecticides. According to the authors, the results showed that the grain moisture content significantly ($p < 0.05$) affected efficacy of grain protectants and superior control was achieved when it did not exceed 12% for inert dusts and 14% for pesticides. In this sense, it seems opportune to study the drying characteristics of the products to be stored.

To describe thin-layer drying of agricultural products, several mathematical models are available in the literature (Pinheiro et al., 1998; Kaleta and Górnicki, 2010; Silva et al., 2012a). Among these, the empirical models are frequently found in the literature to describe thin-layer drying processes (Diamante et al., 2010; Kaleta and Górnicki, 2010; Silva et al., 2012b; EL-Mesery and Mwithiga, 2012). These models are very simple and do not take into account the size nor the moisture distribution within the product. Empirical models are also important to describe the heat penetration by conduction during a drying process using

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hot air. According to Silva et al. (2012b), in this case heating is governed by the diffusion equation and, therefore, the description of the process involves the drying rate in the energy balance (Mariani et al., 2008). Naturally, this rate can be determined by an empirical equation. Furthermore, an empirical model can also be used to describe 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. Thus, one equation is necessary to express the drying rate as a function of the time and, normally, an empirical model is used (Aregba et al., 2006; Dantas et al., 2011).

As it is known, a safe storage begins immediately after the harvest, with the drying process. On the other hand, as mentioned above, the description of deep bed drying requires the knowledge of the drying rate in thin layer, and this fact defines the objective of this article, that is to describe the thin-layer drying kinetics of lima bean, using empirical models. To this end, four models were chosen, and the selection obeyed the following criterion: from each selected model, an analytical expression must be obtained to calculate the drying rate as a function of the time.

MATERIALS AND METHODS

Experiments

Lima bean variety "olho de peixe" was purchased in the city of Itabaiana, state of Paraiba, Brazil, and its initial moisture content was 66.0% (wet basis, wb). The product was divided into samples of 110.0 g each, and then packaged in plastic bags.

The plastic bags containing the samples of lima bean were stored in a refrigerator at 4°C for 24 h, in order to homogenize the moisture content of the grains. Three trays, each containing a sample of lima bean with an initial mass of 110.0 g, were placed upon the grid of a convective dryer with vertical air flux. The velocity of the drying air was kept at 1.0 m s^{-1}. After ten minutes, each sample was weighed and placed back on the grid of the convective dryer. The whole procedure was repeated every ten minutes in the beginning of the experiments, and then gradually extended up to 60 min at the final part of the experiments. The average value of the three experimental moisture contents (in dry basis, db) was used to analyse the drying kinetics. With this experimental methodology, drying curves were determined at 40, 50 and 60°C.

The average room temperature during the measurements of the three drying curves was about 26°C, and the mean relative humidity of the air in the laboratory was about (61±1)%. After recording the drying curves, the samples were left in the dryer until their masses remained constant to determine the equilibrium moisture content. Finally, all samples whose drying curves had been determined were placed into a kiln for 24 h, at 105°C, according to AOAC (1990), to determine the dry mass of the lima bean samples.

Empirical models

Various methods that describe deep bed drying divide the domain into many thin layers. In this way, an empirical equation (and several others), is used to describe the process in each layer. In this case, expressions involving the drying rate as a function of the time are required, and an empirical equation can be used with this finality (Aregba et al., 2006; Dantas et al., 2011). Thus, to describe the thin layer drying kinetics of lima bean using empirical equations, the following assumptions were established: (1) The number of fitting parameters of the empirical equations should be only one or two; (2) An analytical expression for the drying rate as a function of the time should be obtained from the empirical equation.

In order to determine moisture content in dry basis, the following equation was used.

$$X = \frac{m(t) - m_d}{m_d} \,. \quad (1)$$

In Equation (1), X is the average moisture content in dry basis (db), $m(t)$ is the sample mass of the lima bean, $m(t) - m_d$ is the mass of water inside the product, t is the time, and m_d is the dry mass of the product.

According to the assumption number 1, the moisture content X at a time t should be given by Equation (2):

$$X = X_{eq} + (X_i - X_{eq}) f(t,a,b) \,, \quad (2)$$

where $f(t,a,b)$ is a function with up to two fitting parameters, X_{eq} is the equilibrium moisture content and X_i is the initial moisture content. Equation (2) can be modified to express dimensionless moisture content at a time t in the following way:

$$X^* = f(t,a,b) \quad (3)$$

In which

$$X^* = \frac{X - X_{eq}}{X_i - X_{eq}} \,, \quad (4)$$

And X^* is frequently called dimensionless moisture content. Empirical equations that satisfy the established assumptions and that will be used herein are given in Table 1. The table presents a recent reference where such empirical equation was used, and also the correspondent expression for the drying rate as a function of the time.

Empirical models were fitted to the experimental datasets using LAB Fit Curve Fitting Software (www.labfit.net). On the other hand, the obtained results were evaluated through the statistical indicators chi-square and determination coefficient (Bevington and Robinson, 1992; Taylor, 1997). In addition to these indicators, the average error as well as the error distribution was used in order to evaluate the results.

RESULTS AND DISCUSSION

In this paper, the moisture contents determined through the experiments were written in the dimensionless form, according to Equation (4). Performing nonlinear regressions, the obtained results are presented through Table 2. The statistical indicators listed in Table 2 are as good as those obtained by Da Silva et al. (2009). In their work, these authors described lima beans drying through a diffusion model with constant effective diffusivity. On the other hand, the statistical indicators obtained here

Table 1. Empirical models to describe drying kinetics of lima bean.

Number - Name	Empirical model	Reference	Drying rate
1 - Lewis	$X^* = e^{-at}$	Kaleta and Górnicki (2010)	$dX^* / dt = -a e^{-at}$
2 - Wang and Singh	$X^* = 1 + at + bt^2$	Kaleta and Górnicki (2010)	$dX^* / dt = a + 2bt$
3 - Page	$X^* = e^{-at^b}$	Diamante et al. (2010)	$dX^* / dt = -abt^{b-1} e^{-at^b}$
4 - Silva et al.	$X^* = e^{-at-b\sqrt{t}}$	Silva et al. (2012b)	$dX^* / dt = -(a + bt^{-1/2} / 2)e^{-at-b\sqrt{t}}$

Table 2. Results for the drying kinetics of lima bean described by empirical models.

T (°C)	Number	a	b	R^2	$\chi^2 \times 10^3$
40	1	8.552×10^{-3}	-	0.9926	53.679
	2	-5.698×10^{-3}	7.977×10^{-6}	0.9357	279.447
	3	2.647×10^{-2}	0.7633	0.9985	2.874
	4	4.728×10^{-3}	4.031×10^{-2}	0.9961	7.432
50	1	1.247×10^{-2}	-	0.9962	27.726
	2	-8.271×10^{-3}	1.680×10^{-5}	0.9543	196.693
	3	2.663×10^{-2}	0.8223	0.9992	1.786
	4	8.368×10^{-3}	3.295×10^{-2}	0.9977	4.951
60	1	1.729×10^{-2}	-	0.9951	26.063
	2	-1.041×10^{-2}	2.574×10^{-5}	0.9368	221.935
	3	3.857×10^{-2}	0.8003	0.9993	1.241
	4	1.087×10^{-2}	4.554×10^{-2}	0.9978	3.848

make it possible to conclude that the worse model to describe drying of lima bean is Wang and Singh. Lewis model is reasonable but the best ones are given by the number 3 (Page) and 4 (Silva et al.), for all temperatures of the drying air. Similar results were obtained by Silva et al. (2012b) describing water transport into chickpea through empirical models. In their research, the authors recommended the use of Page and Silva et al. models to describe the drying and soaking processes of the grains. With relationship to the Page equation, among several works that have used this equation, EL-Mesery and Mwithiga (2012) also recommended such model to describe drying of onion slices in two types of hot-air convective dryers. For the air at 40°C, the drying kinetics represented by the models is given in Figure 1.

A visual inspection in Figure 1 reveals the complete inadequacy of the Wang and Singh model to the experimental dataset: between the instants 300 and 400 min the dimensionless moisture content assumes negative values, and this fact has no significance from the physical viewpoint.

The drying kinetics at 50°C is represented by the four models as shown in Figure 2. Finally, the drying kinetics at 60°C is shown in Figure 3. Figures 1 to 3 enable visually to observe that models 3 and 4 really well, describing the drying kinetics of lima bean at all studied temperatures. On the other hand, in order to observe the coherence between the models 3 and 4, the drying rates referring to the two models are shown in Figure 4, for all temperatures, from t = 2 min up to the final instant of the process.

Figure 4 shows that for all the temperatures, the drying rates are decreasing during the whole process. Furthermore, Figure 4 also shows that it is difficult to distinguish the curves resulting of the models 3 and 4, and this fact means that really these models well describe the drying process of lima bean. To evaluate the goodness-of-agreement between the drying rates, the 45 values of dX^*/dt used to draw each graph of Figure 4 were compared and the correlation coefficients, for the three temperatures, were greater than R = 0.9970.

As suggested by Da Silva and Silva (2012), complementing the statistical analyses already performed other

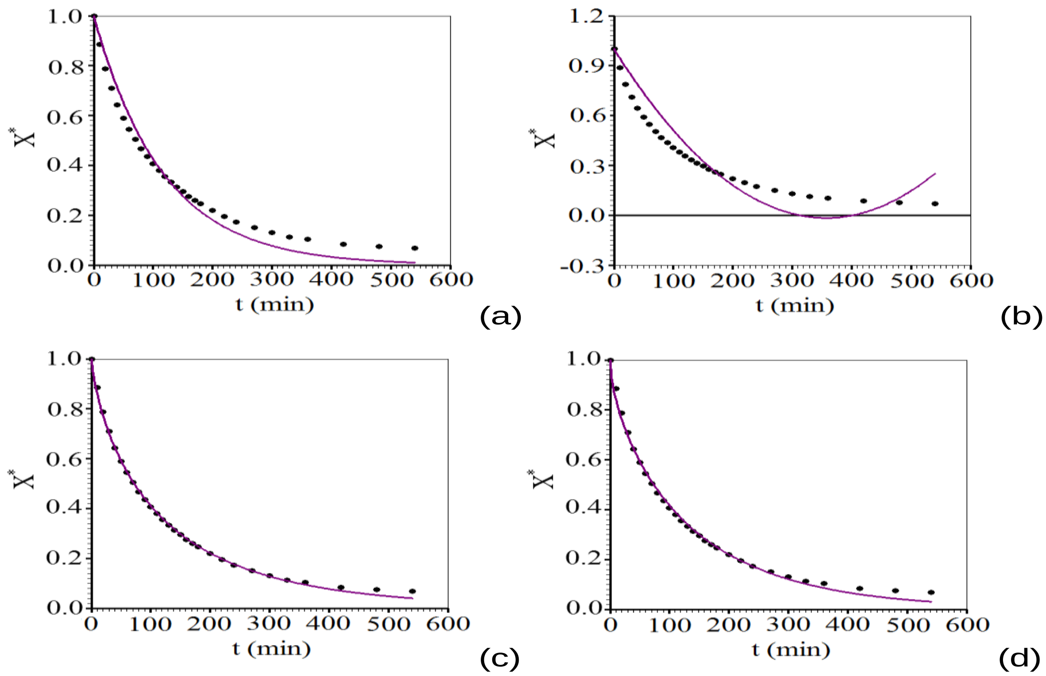

Figure 1. Drying kinetics at 40°C simulated by the model: (a) Lewis; (b) Wang and Singh; (c) Page; (d) Silva et al.

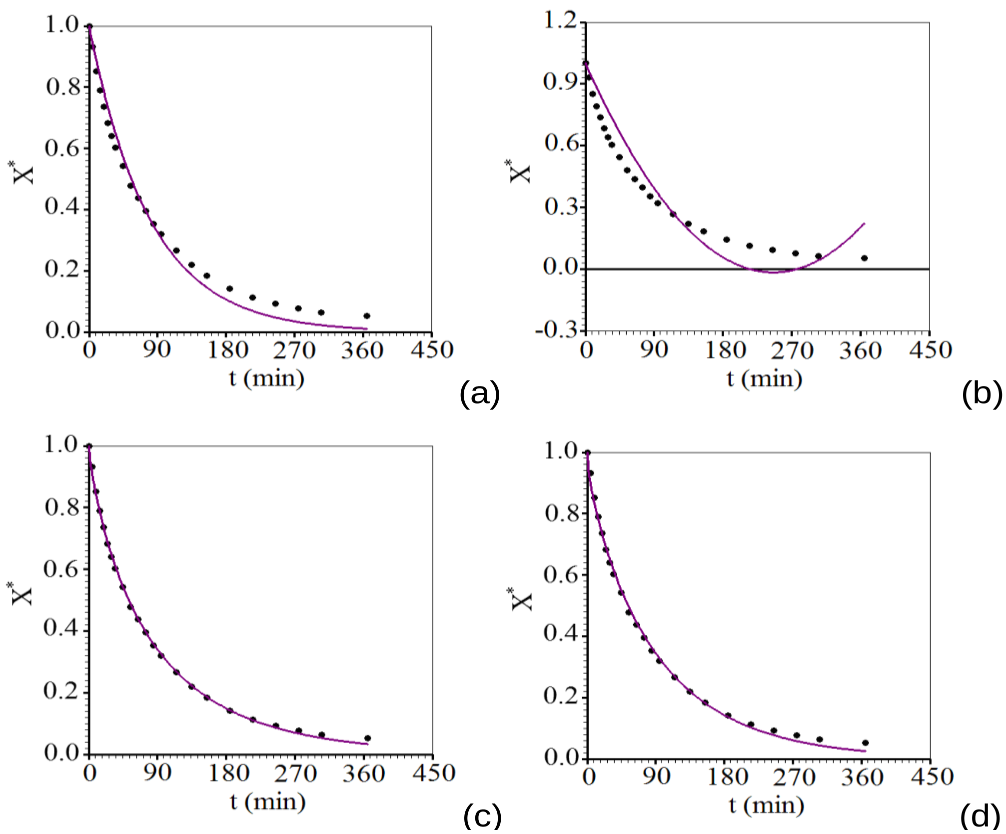

Figure 2. Drying kinetics at 50°C simulated by the model: (a) Lewis; (b) Wang and Singh; (c) Page; (d) Silva et al.

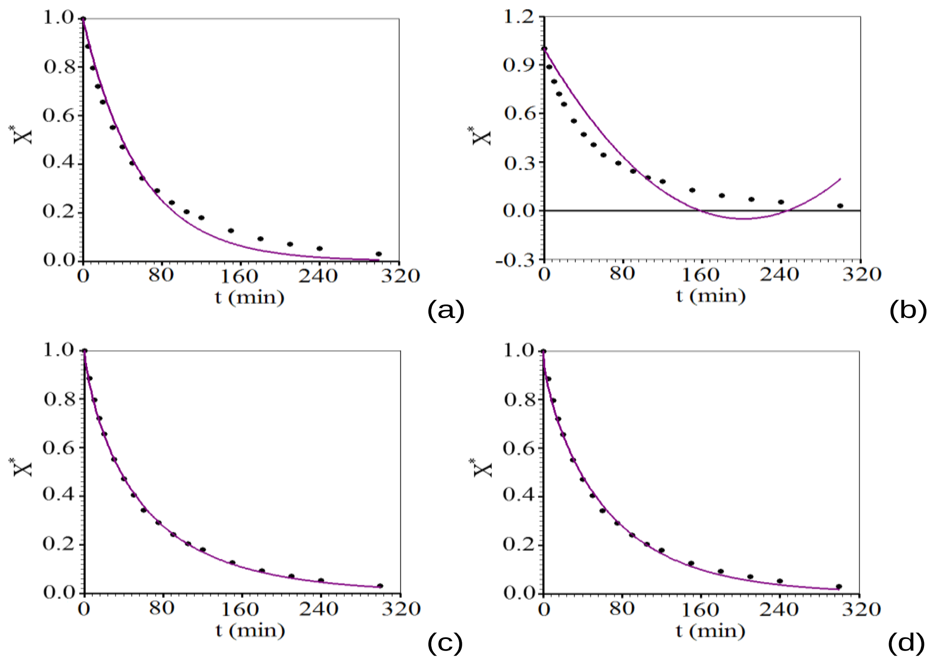

Figure 3. Drying kinetics at 60°C simulated by the model: (a) Lewis; (b) Wang and Singh; (c) Page; (d) Silva et al.

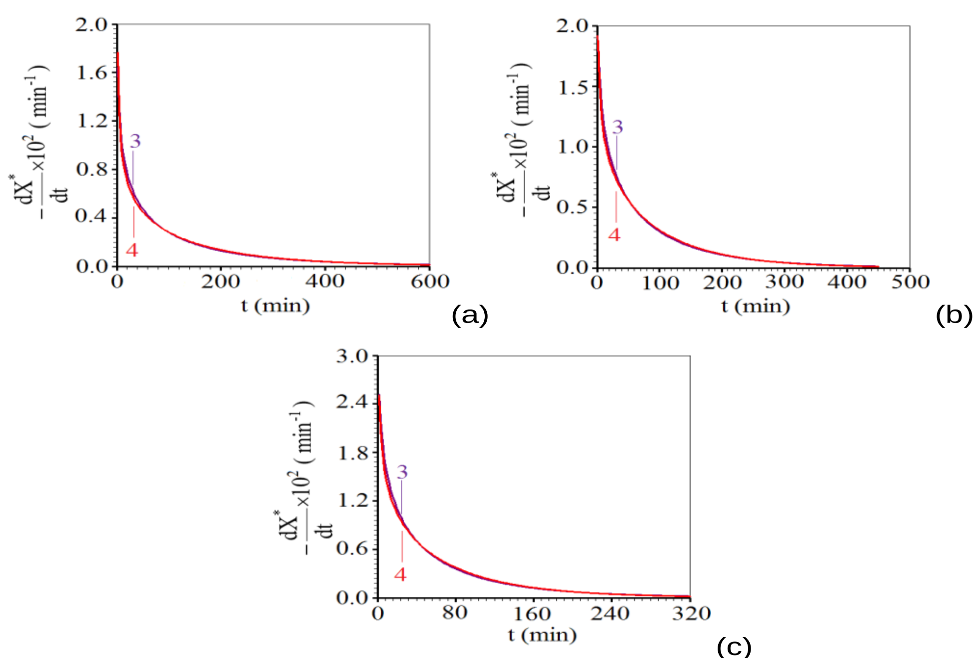

Figure 4. Drying rates calculated using the expressions obtained by the models 3 and 4 at temperature T =: (a) 40°C; (b) 50°C; (c) 60°C.

statistical tests should be used in order to answer if the simulated curves really represent the drying kinetics. Thus, the error of each experimental point as function of the dimensionless moisture content was plotted as it is shown in Figure 5 which also shows average error.

An inspection of Figure 5 showed that although the error distribution can not be considered completely random for the two best models, the average error is

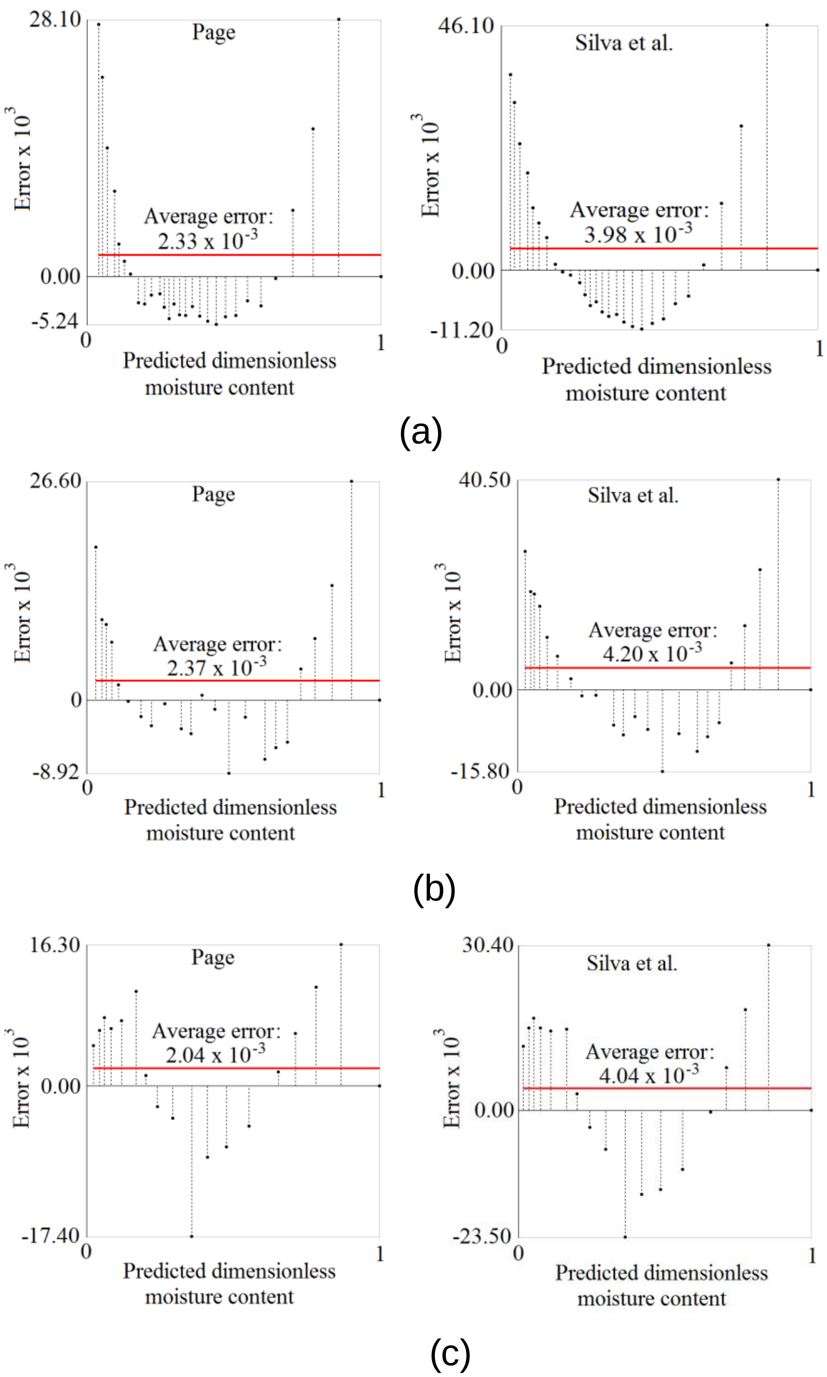

Figure 5. Error distribution and average error at T: (a) 40°C; (b) 50°C; (c) 60°C.

very close to zero for both Page and Silva et al. models, for all temperatures of the drying air. Obviously, the value zero for the average error is the expected value if the fit is perfect.

As a final comment, the drying rates determined in this article are important from the industrial viewpoint because it is precise and accurate information, which can be used in the description of deep bed drying processes that is the first step of a safe storage.

Conclusion

In this study, it is possible to conclude that thin-layer drying of lima bean took place exclusively in the falling rate period. Four empirical equations were investigated to describe the drying kinetics. Among these equations, the worst result was obtained using Wang and Singh model. Such model should be discarded to describe drying kinetics of lima bean. On the other hand, Lewis model reasonably describes the processes. According to the statistical indicators, Page and Silva et al. models well describe the thin layer drying kinetics of lima bean at all investigated temperatures. These two models led to the writing of analytical expressions for the drying rate, and these expressions produce statistical indicators that can be considered equivalent. However, if only one model should be used to describe the drying of lima bean, all the statistical indicators presented in this article suggest the use of the Page model.

During the drying experiments, it was possible to observe that none of the three temperatures have caused damage of any nature for the grains. In this sense, the three temperatures can be used to dry lima bean. However, as it was shown in this article, for a given instant *t* the drying rate at 60°C is higher than the drying rates at 40 and 50°C. Thus, if only one temperature should be recommended to dry lima bean, the recommended one is 60°C, which reasonably reduced the time of processing.

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