Description of Seedless Grape Drying and Determination of Drying Rate

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Abstract

This article compares some empirical models, with one or two parameters, used to describe seedless grape drying at low temperature. Chosen models have, as a common characteristic, an analytical expression for the derivative of dimensionless moisture content with respect to time. Comparison of the results for the simulations of drying kinetics indicates that, despite Page and Silva et alli models well represent the process, the best model is Peleg. For this model, the statistical indicators of the simulation can be considered excellent (the determination coefficient is $R^2 = 0.99944$ and the chi-square is $\chi^2 = 1.2335 \times 10^{-3}$).

Keywords: Drying rate, Process time, Mathematical model, Raisins, Drying kinetics.

1. Introduction

Grapes are fruits among the most perishable foods, compared with other agricultural products. They are very susceptible to microbial decay and moisture loss. To prolong the consuming time of grapes, the drying mechanism is usually applied. This process results in a food very appreciated in several parts of the world: raisins. To increase the drying rate, a pretreatment is usually accomplished. According to Silva et al. (2012a), several pretreatment techniques involving the use of chemical additives are described in the literature (Pangavhane et al., 1999; Doymaz and Pala, 2002; Doymaz, 2006; Esmaiili et al., 2007). However, several authors observe that the demand for natural foods is increasing in many parts of the world. Thus, alternatives to chemical additives are used as pretreatment for the production of raisins, such as abrasion (Di Matteo et al., 2000) and dipping in hot water (Esmaiili et al., 2007; Ramos et al., 2010). For example, Esmaiili et al. (2007) studied drying of seedless grapes submitted to two types of pretreatments, as is described in the following. The grapes were dipped in an alkaline emulsion of ethyl oleate (EO) and also in hot water (HW) before drying. According to the authors, the EO solution was prepared at room temperature by adding 2% ethyl oleate to a 5% solution of potassium carbonate. For HW, tap water was heated to approximately 95 °C. Dipping times in EO and HW were 60 and 15 s, respectively.

To describe thin-layer drying of an agricultural product, two main groups of models are frequently found in the literature. The first group corresponds to the diffusion models (Karim and Hawlader, 2005; Da Silva et al., 2012a, 2012b and 2012c; Mabellini et al., 2013) and second one corresponds to the empirical models (Turhan et al., 2002; Diamante et al., 2010; Kaleta and Gornicki, 2010; Sahoo et al., 2012; Silva et al., 2012b; Malekjani 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. According to Silva et al. (2013), in some methods of simulation, the deep bed is divided into several thin layers, and a set of equations is required to describe the drying process in each layer. Two of these equations are necessary to express the drying rate as a function of the time, and also the drying time as a function of the moisture content. Normally, an empirical model is used with this finality (Aregba et al., 2006; Dantas et al., 2011). In this context, the importance of

empirical equations in drying simulations is emphasized.

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

2. Material and methods

2.1 Experimental Data of Seedless Grape Drying

Experimental data obtained by Esmaiili et al. (2007) for the drying of seedless sultana grapes (*Vitis vinifera* L.) with hot air are explored in the present paper. In order to increase the skin's permeability to moisture, a pretreatment was applied. The grapes were dipped for 15 s in hot water at 95 ℃. The temperature of the drying air was 50 ℃, its relative humidity was 10%, and its velocity was kept at 1.5 m s^{-1}. The initial moisture content, X_i, was 3.25 (db), and the equilibrium moisture content, X_{eq}, was 0.17 (db).

The dimensionless moisture content data, X^*, were digitized by using xyExtract Digitizer (http://zeus.df.ufcg.edu.br/labfit/index_xyExtract.htm) and they are presented through Fig. 1.
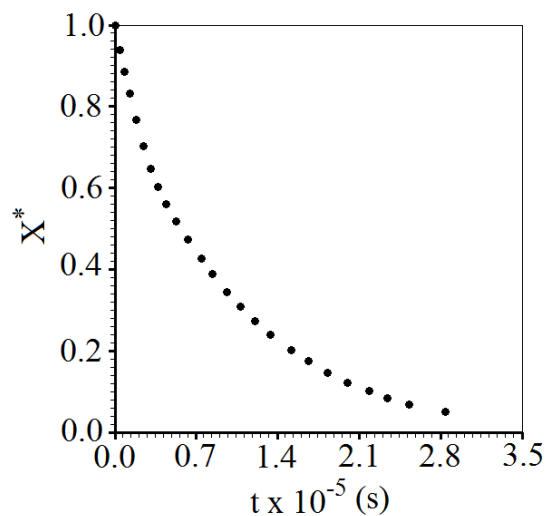

Figure 1. Experimental dataset of seedless grape drying.

2.2 Mathematical Models

According to Silva et al. (2013), in many occasions empirical models are seen as a method that only serves to describe the thin-layer drying kinetics of an agricultural product. However, the authors also observed that there are several methods to describe deep bed drying, and one is by dividing the domain into many thin layers. In this case, an empirical equation, together with several other equations, is used to describe the process in each layer. In this case, expressions involving the drying rate as a function of the time, and the drying time as a function of the moisture content are required, and an empirical equation can be used with this finality (Aregba et al., 2006; Dantas et al., 2011). In addition, to describe the heat penetration in a body during the water removal using hot air, an expression involving the drying rate is required (Karim and

Hawlader, 2005; Mariani et al., 2008), and normally an empirical model is used to determine this rate. In this context, in order to describe the drying kinetics of seedless grapes using empirical equations, the following assumptions were established:

1) The number of parameters of each model should be only one or two;

2) A mathematical expression for the drying rate as a function of the time should be obtained from each model;

3) A mathematical expression for the drying time as a function of the moisture content must be obtained from each model.

From the first assumption, the moisture content X at time t should be given by an expression of the type:

$$X = X_{eq} + (X_i - X_{eq})f(t,a,b) \qquad (1)$$

in which $f(t,a,b)$ is a function with one or two parameters (a and/or b), and this function must satisfy all the established assumptions. On the other hand, Eq. (1) can be modified to express dimensionless moisture content at time t, as follows:

$$X^* = f(t,a,b) \qquad (2)$$

where

$$X^* = \frac{X - X_{eq}}{X_i - X_{eq}} \qquad (3)$$

The selected models are given in Table 1.

Table 1. Empirical models to describe drying kinetics.

Model	Name	Empirical expression	Reference
1	Lewis	$X^* = e^{-at}$	Kaleta and Gornicki (2010)
2	Henderson and Pabis	$X^* = a\,e^{-bt}$	Diamante et al. (2010)
3	Wang and Singh	$X^* = 1 + at + bt^2$	Kaleta and Gornicki (2010)
4	Peleg	$X^* = 1 - t/(a + bt)$	Mercali et al. (2010)
5	Page	$X^* = e^{-at^b}$	Diamante et al. (2010)
6	Silva et alii	$X^* = e^{-at - b\sqrt{t}}$	Silva et al. (2012b)

From Table 1, the mathematical expressions for the drying rate as a function of the time are expressed as is shown in Table 2.

Table 2. Drying rate and drying time expressions obtained through the empirical models.

Model	Drying rate	Drying time
1	$dX^*/dt = -a\,e^{-at}$	$t = -\ln X^* / a$
2	$dX^*/dt = -ab\,e^{-bt}$	$t = -\ln(X^*/a)/b$
3	$dX^*/dt = a + 2bt$	$t = \left(-a \pm \sqrt{a^2 - 4b(1-X^*)}\right)/(2b)$
4	$dX^*/dt = -a/(a+bt)^2$	$t = a(1-X^*)/(1-b+bX^*)$
5	$dX^*/dt = -abt^{b-1}\,e^{-at^b}$	$t = \left(-\ln X^*/a\right)^{1/b}$
6	$dX^*/dt = -(a + bt^{-1/2}/2)e^{-at-b\sqrt{t}}$	$t = \left[\left(-b \pm \sqrt{b^2 - 4a\ln X^*}\right)/(2a)\right]^2$

This table also shows the expressions to determine the drying time for given dimensionless moisture content. Models were fitted to the experimental dataset, using nonlinear regression through LAB Fit Curve Fitting Software (Da Silva et al., 2004), and the results were evaluated through the statistical indicators chi-square and determination coefficient (Taylor, 1997).

3. Results and Discussion

It is worth mention that similar studies with other fruits have been investigated and published in the literature using empirical models (Ganesapillai et al., 2008; Diamante et al., 2010; Kaleta and Gornicki, 2010; Kumar et al., 2010; Mercali et al., 2010; Tunde-Akintunde and Ogunlakin, 2011). However, the main focus of these studies is only to describe the thin-layer drying kinetics. In the present article, attention is given to the determination of the drying rate, enabling the use of the obtained results to study the heat penetration and/or deep bed drying.

The obtained results for selected models are presented in Table 3.

Table 3. Results for the drying kinetics described by empirical models.

Model	a	b	χ^2	R^2
1	1.157×10^{-5}	-	1.8898×10^{-2}	0.99651
2	0.95315	1.0821×10^{-5}	9.7518×10^{-3}	0.99564
3	-8.7232×10^{-6}	2.0262×10^{-11}	9.4024×10^{-2}	0.97713
4	6.6096×10^{4}	0.81605	1.2335×10^{-3}	0.99944
5	5.4682×10^{-5}	0.86327	1.9501×10^{-3}	0.99910
6	8.7465×10^{-6}	7.8429×10^{-4}	2.5226×10^{-3}	0.99884

An inspection of the statistical indicators provided by Table 3 makes it possible to conclude that worse model is 3 (Wang and Singh). Models 1 (Lewis), 2 (Henderson and Pabis) and 6 (Silva et alli) are reasonable, but best ones were model 4 (Peleg), with a determination coefficient of 0.99944 and chi square of 1.2335 x 10^{-3}; and model 5 (Page), with a determination coefficient of 0.99910 and chi square of 1.9501 x 10^{-3}.

The simulation of the drying kinetics using model 4 and the parameters given in Table 3 can be observed in Fig. 2.
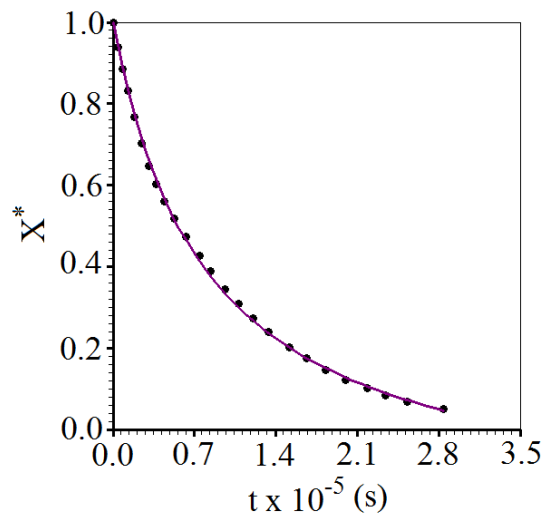
Figure 2. Description of the drying kinetics through model 4 (Peleg).

To observe the coherence between models 4 and 5 during the whole process, Fig. 3 shows the drying kinetics simulations using models 4 and 5, and it is possible to observe in this figure the compatibility between two models, with a little disagreement just at the final part of drying. Even so, Fig. 3 shows that it is difficult to distinguish between the curves generated from models 4 and 5, which means that the models can be considered equivalent.
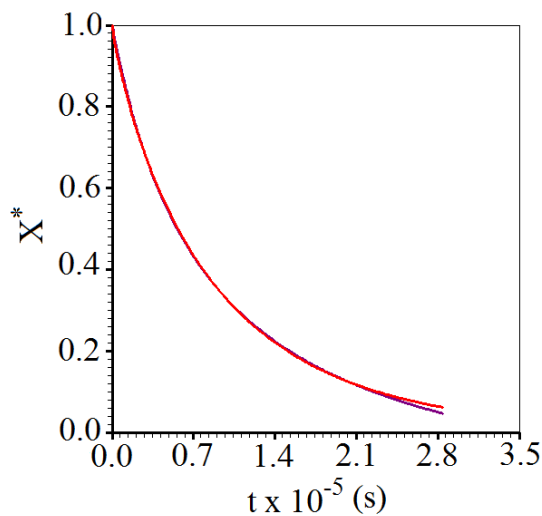

Figure 3. Drying kinetics simulations using models 4 (Peleg) and 5 (Page).

The drying rate referring to model 4 as a function of the time is shown in Fig. 4.
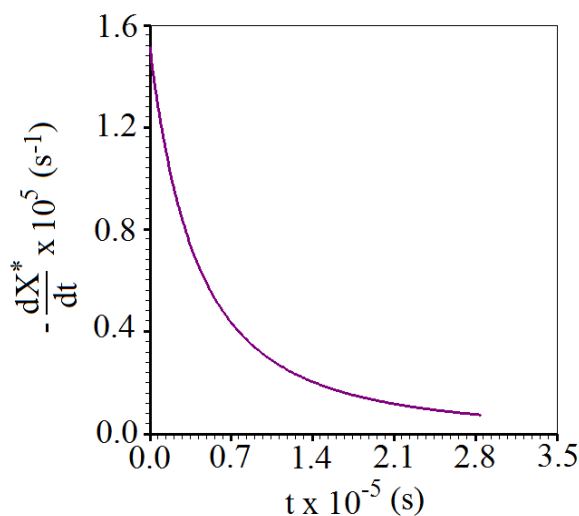
Figure 4. Drying rate calculated using the expression obtained through the model 4.

This figure shows that the drying rate decreases during the whole process, and this behavior also occurs with several other agricultural products (Roberts et al., 2008; Diamante et al., 2010; Kaleta and Gornicki, 2010; Kumar et al., 2010; Mercali et al., 2010; Silva et al., 2012b).

4. Conclusion

The experimental dataset makes it possible to conclude that thin-layer drying of seedless grapes took place exclusively in the falling rate period. Among empirical models investigated in this study, the worst result was obtained with Wang and Singh. On the other hand, Lewis, Henderson and Pabis and also Silva et alli are reasonably models to describe the process. According to the statistical indicators, Peleg and Page models well describe the thin-layer drying kinetics of seedless grapes at low temperature. In addition, these two models enable to write mathematical expressions for the drying rate and the process time, and these expressions produce results that can be considered equivalent.

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