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Drying kinetics models for guava slices dried with a rustic solar dehydrator

Modelos de cinética de secado para rebanadas de guayaba secadas con un deshidratador solar rústico

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Abstract

The objective of this study was to calibrate and evaluate 11 thin-layer models and determine the drying time of guava slices using a natural convection mixed-type rustic dehydrator. The models were fitted by the method of nonlinear least squares using two-set of experimental data. The Rank procedure, which includes the RMSE, MAE, and E statistics, was used to select the model with the best fit in the calibration. To determine the drying time, the first derivative of the Hii model with Rank's best fit was used in the calibration stage with both data sets. The drying time was defined when the rate was less than -0.1%. The drying time was 19.4 h and 21.9 h, when 1.27 kg and 2.01 kg of guava slices (5 mm thickness), respectively, were placed into the dehydrator under autumn-winter climatic conditions in Zacatecas, Mexico. The Hii model had the best fit in both experiments in the calibration and evaluation stage of the model.

***Psidium guajava* L., Nonlinear, Calibrate, Evaluation, Derivative**

Resumen

El objetivo de este estudio fue calibrar y evaluar 11 modelos de capa fina y determinar el tiempo de secado de rebanadas de guayaba utilizando un deshidratador rústico tipo mixto de convección natural. Los modelos fueron estimados por el método de mínimos cuadrados no lineales usando dos grupos de datos experimentales. El procedimiento Rank, que incluye los estadígrafos RMSE, MAE y E, fue usado para seleccionar el modelo con mejor ajuste en la calibración. Para determinar el tiempo de secado se utilizó la primera derivada del modelo Hii con mejor ajuste de Rank en la etapa de calibración con ambos conjuntos de datos. El tiempo de secado se definió cuando la tasa fue menor al -0.1%. El tiempo de secado fue de 19.4 h y 21.9 h, cuando se colocaron en el deshidratador, 1.27 kg y 2.01 kg de rodajas de guayaba (5 mm de espesor), respectivamente, en condiciones climáticas de otoño-invierno en Zacatecas, México. El modelo de Hii tuvo el mejor ajuste en ambos experimentos en la etapa de calibración y evaluación del modelo.

***Psidium guajava* L., No lineal, Calibración, Evaluación, Derivada**

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Introduction

Guava (*Psidium guajava* L.) is a native fruit from the American tropics. Mexico is the fourth largest producer in the world (Pérez-Gutiérrez et al., 2008). The most important producing areas are located in the states of Aguascalientes and Zacatecas, particularly in the region known as "Calvillo-Cañones" (Padilla et al., 2007; Padilla et al., 2014). Fruit has great productive and economic potential due to its wide adaptability (Fischer & Melgarejo, 2021), nutritional value and medicinal properties (Pérez-Gutiérrez et al., 2008), concentrations of vitamins, mainly C. (Rajan & Hudedamani, 2019). However, short shelf life remains a problem due to its high moisture content (> 81%), making it a highly perishable fruit susceptible to rapid deterioration (Rokib et al., 2021). Also, guava fruits are very susceptible to chilling damage and disease causing browning (oxidation), which limits their storage under refrigeration (Mata and Rodriguez, 2000).

This highlights the importance of using techniques to increase the shelf life of this fruit, such as dehydration and drying to reduce water activity (Cabrera et al., 2016). Drying is an ancient fresh produce preservation technique that consists of removing water under ambient conditions of solar and wind radiation (De Michelis & Ohaco, 2012). In contrast, dehydration of fresh produce considers the removal of water from the product through artificial heat (e.g., pre-heated air or surfaces) (De Michelis & Ohaco, 2012).

The former technique has a negative effect on the color, texture and quality of the product due to the exposure of the product to sunlight. Consequently, mechanical techniques for dehydration (e.g., hot air, freeze-drying, etc.) have emerged using solar energy to avoid direct exposure of the product to sunlight (Ali et al., 2016). Thus, in the context of sustainable energy use, mixed natural or forced convection solar dehydrators have been designed to capture and utilise solar energy (Jamradloedluk & Wiriyaumpaiwong, 2007). These dehydrators, for the removal of water from the product, consider temperature, relative humidity and wind speed rather than air velocity as the most important variables (Bravo, 2022)

On the other hand, the drying time and the final moisture content of the product are of great importance to have a quality product, as well as to make this process more efficient. Mathematical equations of drying kinetics have been used to design, optimise and control the dehydration process (Belghith et al., 2011). Thin layer models are used to represent, estimate and predict the moisture ratio of fruit and vegetable products. In guava, these models have been used in the production of guava foams at temperatures of 75, 80 and 85 °C in natural convection dehydrators (Maciel et al., 2007).

Drying kinetics have also been evaluated in mature and immature guava with Fick models as a function of temperature (Reynoso, 2018). Both reports concluded that the higher the temperature, the faster the drying rate increases. Also, thin film models have been used in the estimation of drying kinetics of guava with different ripening stages using solar dehydrators (Lins et al., 2021). On the other hand, mechanical and solar drying of guava slices with different thicknesses and at different temperatures have been evaluated. In these studies, a relationship of drying time inversely proportional to temperature and slice thickness was established (Rokib et al., 2021).

Mugi, & Chandramohan, (2022) evaluated the thermal and kinetic properties of dried guava with forced convection, natural convection and sunlight drying solar dryers. These authors found that the drying time was 14, 18 and 24 h for each dryer, respectively. Apaza & Ureta (2022) evaluated the physicochemical characteristics and quality of 'Golden MD2' pineapple and determined that with 14 hours of drying the best physicochemical and sensory characteristics were maintained. The drying time is very useful to make the dehydrators more efficient and, thus, improve the quality of the dehydrated fruit. Therefore, the objective of the study was to calibrate and evaluate 11 thin film models and to determine the drying time of guava using a rustic mixed natural convection dryer under autumn-winter climatic conditions in Zacatecas, Mexico.

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Materials and methods

Experimental site

The experiment was conducted from October to November 2022 at the agro-industrial pilot food between pilot and plant of the Zacatecas Experimental Field (CEZAC; 22º 54' N, 102º 39' W) with an altitude of 2 197 masl, mean annual temperature of 14.6 ºC, mean annual rainfall of 416 mm and mean annual evaporation of 1609 mm. The average annual wind speed and solar irradiation were 4 m/s and 520 W/m^2, respectively

Description of the rustic solar dehydrator

The drying experiments of the guava slices were carried out in a rustic solar dehydrator with a wooden frame, mixed natural convection. The dehydrator has a bed-type heat collector (2.0 m x 1.05 m x 0.24 m) and drying chimney (1.24 m x 1.05 m x 0.33 m). The chimney is provided with four 24-wire-per-inch wire mesh trays with 30 x 93 cm wooden frames. The dehydrator has a 720-gauge clear polyethylene cover on all sides with UV treatment. The bed is suspended from the floor with the aid of 17.5 and 22 cm wooden supports with a slope of 2.25%. The lower part of the litter has a 39.9 x 15 cm mesh window with a wooden frame for air intake at room temperature with hot air exhaust at the top of the chimney through a 14.6 x 93 cm mesh window (Figure 1).

Figure 1 Mixed type rustic solar dehydrator

Drying kinetics

Two drying experiments were conducted with two initial guava weight values. Experiment one (EXPI) was conducted from 24-26 October 2022 with an initial total fresh product mass of 2.01 kg (≈ 500 g per tray) and experiment two (EXPII) was conducted from 02-05 November 2022 with a fresh mass of 1.27 kg (≈ 300 g guava per tray). Both experiments used fresh guava from production in the Cañones region, which was washed and disinfected prior to experimentation. The fruit was sliced to a thickness of 5 mm and placed in the four trays of the dehydration chamber (Figure 2).

Figure 2 Guava drying chamber and drying trays

Measurements were performed over three days with discontinuous measurements, i.e. only during the day, from 9:00 to 18:00 h until reaching constant mass (≈ 24 h sun). Measurements started at 10:00 am and 11:00 am for EXPI and EXPII, respectively. At 18:00 h the inlets and outlets were covered with polyethylene to prevent moisture ingress during the night and were removed at 9:00 h. Mass measurements of each tray were made every 60 min with the aid of a digital balance accurate to ± 0.01 g until a constant mass was reached.

Mathematical modelling

The moisture content (%) of guava on a wet basis (Mwb) was determined with equation (1):

$$M_{wb} = \left(\frac{W_o - W_d}{W_o}\right) * 100 \quad (1)$$

where W_o is the mass of the wet sample (kg) and W_d is the dry mass.

Equation (2) was used to calculate the humidity ratio (HR) (Prakash & Kumar, 2017).

$$RH = \frac{M_t}{M_i} \quad (2)$$

Where M_t is the moisture content at any time (kg water-kg dry matter^{-1}) and Mi is the moisture content at the initial time (kg water-kg dry matter^{-1}) and Mi is the moisture content at the initial time (kg water-kg dry matter^{-1}).

Calibration and evaluation

The thin-layer models were programmed in Matlab using the non-linear least squares procedure that is programmed in the lsqnonlin function of the Matlab Optimisation tool for non-linear regressions. The theoretical coefficients of the 11 thin-layer models shown in Table 1 (Arepally et al., 2017). EXPI data were used in the calibration stage.

Name	Model
1) Newton	$RH = \exp(-kt)$
2) Page	$RH = \exp(-kt^{n})$
3) Henderson and Pabis	$RH = a\exp(-kt^{n})$
4) Logarithmic	$RH = a\exp(-kt) + c$
5) Two-term	$RH = a\exp(-k_0t) + b\exp(-k_1t)$
6) Two-term exponential	$RH = a\exp(-k_0t) + (1-a)\exp(-k_1at)$
7) Diffusion approximation	$RH = a\exp(-kt) + (1-a)\exp(-kbt)$
8) Modified Henderson and Pabis	$RH = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
9) Verma	$RH = a\exp(-kt) + (1-a)\exp(-gt)$
10) Midilli and Kucuk	$RH = a\exp(-kt^{n}) + bt$
11) Hii	$RH = a\exp(-kt^{n}) + b\exp(-gt^{n}$

Table 1 Thin film models for moisture ratio calculation

To determine the performance of the models, the following statistics were estimated: 1) the mean absolute error (MAE; Eq. 3), 2) the root mean square error (RMSE; Eq. 4) and 3) the efficiency proposed by Nash and Sutcliffe (E; Eq. 5).

$$MAE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n} \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (4)$$

$$E = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (5)$$

where y_i represents the observed value of RH, (y_i)ˆthe estimated value of RH, ¯y is the average of the observed values of RH and n the number of observations.

First stage: the models were calibrated with the EXPI data and evaluated with the EXPII data.

Second stage: calibrated with EXPII and evaluated with EXPI data.

To select the best fitting thin layer model in the calibration, the Rank criterion (Eq. 6) was used which considers the RMSE, MAE and E-statistics as follows:

$$Rank = (E) - [(RMSE * 0.5) + (MAE * 0.5)] \quad (6)$$

The Rank value closer to one indicates that the model has a better fit; while a value equal to one means a perfect fit.

Drying time

To determine the drying time, the derivative with respect to the time of the different proposed models that showed the best Rank of fit in the calibration stage was determined. The drying time was defined when the rate was less than -0.1% with the following function:

$$\frac{\partial MR}{\partial t} = -0.001 \quad (7)$$

where $\frac{\partial MR}{\partial t}$ is the first derivative of the HR model

Results and discussion

Table 2 shows the estimated coefficients that minimised the squared error with the Matlab non-linear least squares method with 24 data for EXPI and EXPII.

	Coefficients EXPI	Coefficients EXPII
1	K = 0.093;	K = 0.119;
2	K = 0.14; n = 0.828;	K = 0.354; n = 0.512;
3	K = 0.168; n = 0.775; a = 1.055;	K = 0.38; n = 0.495; a = 1.037;
4	K = 0.155; a = 0.878; c = 0.174;	K = 0.294; a = 0.785; c = 0.229;
5	K = 0; K_1 = 0.155; a = 0.174; b = 0.878;	K = 0; K_1 = 0.294; a = 0.229; b = 0.785;
6	K = 0; K_1 = 0.872; a = 0.162;	K = 0; K_1 = 1.268; a = 0.228;
7	K = 0.141; a = 0.838; b = 0;	K = 0.289; a = 0.772; b = 0;
8	K=0; a=0.174; b=0; c=0.878; g=0.238; h=0.155;	K = 0; a = 0.228; b = 0.786; c = 0; g = 0.296; h = 0.085;
9	K = 0.084; a = 70.585; g = 0.084;	K = 0.118; a = 70.766; g = 0.118;
10	K = 0.052; n = 1.353; a = 0.975; b = 0.008;	K = 0.253; n = 0.853; a = 1.014; b = 0.01;
11	K = 0.071; n = 1.418; a = 0.769; b = 0.217; g = 0;	K = 0.258; n = 1.11; a = 0.754; b = 0.245; g = 0.002;

Table 2 Calibration coefficients estimated by models in each experiment

The results of the first stage, where the models were calibrated with the EXPI data and evaluated with EXPII data, it was observed that the model that showed the best performance, according to the Rank in the calibration stage, was the eleven model (Hii) with values of 0.1, 0.1 and 1 of RMSE, MAE and E, respectively. The models with the lowest fit were Newton (model 1) and Verma (model 9) both with similar values of 0.06, 0.05 and 0.95 of RMSE, MAE and E, respectively. In the evaluation stage, the Two exponential terms (model 5 and 6) and Diffusion approximation (model 7) were the models that showed the best fit, both with similar values of 0.09, 0.07 and 0.79 for RMSE, MAE and E, respectively. The Midilli and Kucuk model (model 10) showed the lowest fit. However, the average Rank (Table 3), the models with the best fit were Two exponential terms (model 6) and Diffusion approximation (model 7); while the lowest fit was Newton (model 1) with an overall Rank value (average of calibration and evaluation) of 0.68. Mugi & Chandramohan (2022) point out that Page's model best represents the guava drying curve using natural and forced convection solar dehydrators. Lins et al. (2021) argue that the Page and Henderson-Pabis models produce a better fit to the guava drying curve in tropical climates in Brazil. In contrast, the Midilli and Kucuk model had a better fit to experimental data obtained by solar dehydrator in Brazil (Maciel et al., 2017).

	Rank Calibration (EXP01)	**Rank Evaluation (EPX02)**	**Rank global**
1	0.89	0.47	0.68
2	0.92	0.63	0.77
3	0.92	0.63	0.77
4	0.96	0.69	0.82
5	0.96	0.69	0.82
6	0.95	0.70	0.83
7	0.95	0.70	0.83
8	0.96	0.69	0.82
9	0.89	0.46	0.68
10	0.94	0.45	0.70
11	0.98	0.66	0.82

Table 3 First stage performance measures

It was observed that the Hii model minimised the distance between observed and estimated values compared to other models (Figure 3).

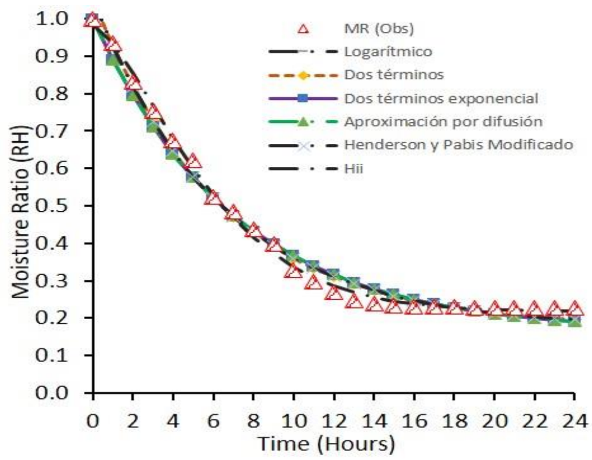

Figure 3 Models with the best fit in the calibration stage with information from the EXPI

In the second stage, where the models were calibrated with the EXPII information and evaluated with the EXPI data, it was observed that the model with the best performance, according to the Rank in the calibration stage, was the Hii model with RMSE and MAE values > 0.001 and E of 0.999. In the evaluation stage, the model with the lowest fit was Page and Verma's model. However, when generating the overall Rank, Page's model had a lower fit (Table 4). Thus, the Hii model performed better in both the calibration and evaluation stages (Figure 4).

	Rank Calibration (EXPII)	Rank Evaluation (EXPI)	Rank global
1	0.58	0.78	0.68
2	0.89	0.73	0.81
3	0.90	0.73	0.81
4	0.99	0.74	0.87
5	0.99	0.74	0.87
6	0.99	0.74	0.87
7	0.99	0.74	0.87
8	0.99	0.74	0.87
9	0.58	0.78	0.68
10	0.98	0.75	0.86
11	1.00	0.74	0.87

Table 4 Performance measures in the second stage of the study

In the calibration stage with the EXII experimental data all models showed a good fit by following the trend with the observed data (Figure 4), except for Verma's model, which produced values of 0.11, 0.10 and 0.69 for RMSE, MAE and E, respectively.

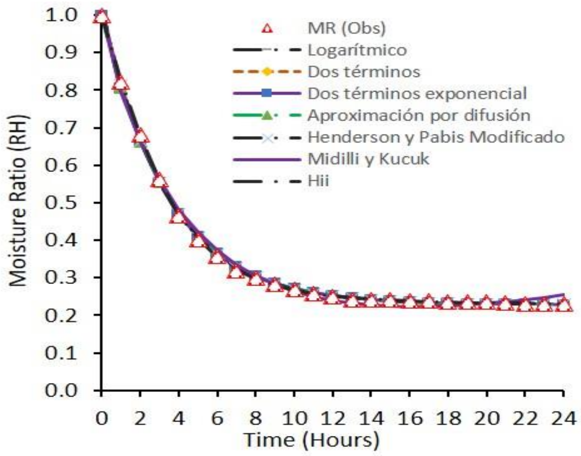

Figure 4 Models with best fit at the calibration stage with EXPII data

The Hii model had the best fit in both calibration stages, comparing the K and n coefficients. The parameter "K" represents the drying constant and the parameter "n" refers to the internal resistance to drying (Pérez et al., 2013). The highest value of K = 0.258 was obtained when calibrated with EXPII data when using 1.27 kg of guava slices, i.e. a faster drop in drying was observed. The value of n = 1.418 was higher when calibrated with the EXPI data, this experiment was conducted with a fresh mass of 2.01 kg of guava slices. This suggests that the higher the weight of the sample, the higher the resistance to drying.

Drying time

When solving the first derivative of the 11 models at a drying rate of 0.1% equation (7) most do not converge to a feasible time. The Hii model was the model that showed the best overall fit at both calibration stages and feasible drying time.

The Hii model was used to determine the drying time.

Hii model with optimal coefficients with observed EXPI data.

$$RH = 0.769\ exp(-0.071t^{1.418}) + 0.217\ epx(-0t^{1.418}) \quad (8)$$

Deriving:

$$\frac{\partial RH}{\partial t} = -\frac{38710691\ \exp\frac{-(-71\ t^{0.418})}{1000}\ t^{0.418}}{500\ 000\ 000} \quad (9)$$

equal to the permissible drying rate:

$$-0.001 = \frac{38710691\ \exp\frac{-(-71\ t^{0.418})}{1000}\ t^{0.418}}{500\ 000\ 000} \quad (10)$$

solving for time ($t = t_1$)

$$t_1 \approx 21.9\ horas \quad (11)$$

Hii model with optimal coefficients with observed EXPII data.

$$RH = 0.754\ exp(-0.258t^{1.11}) + 0.245\ epx(-0.002t^{1.11}) \quad (12)$$

deriving;

$$\frac{\partial RH}{\partial t} = -\left[\frac{111\ \exp\frac{-(-129\ t^{1.11})}{500}}{500\ 000\ 000}\right] * \left[\frac{1\left(97266 + 245\ \exp\frac{-(-129\ t^{1.11})}{125}\right)t^{1.11}}{500\ 000\ 000}\right] \quad (13)$$

equaling the permissible drying rate;

$$-0.001 = -\left[\frac{111\ \exp\frac{-(-129\ t^{1.11})}{500}}{500\ 000\ 000}\right] * \left[\frac{1\left(97266 + 245\ \exp\frac{-(-129\ t^{1.11})}{125}\right)t^{1.11}}{500\ 000\ 000}\right] \quad (14)$$

and resolving to estimate the time ($t = t_2$)

$$t_2 \approx 19.4\ hours \quad (15)$$

The drying time results were congruent with the values of the coefficients K and n, where 2.01 kg of initial fresh mass was used, the drying time was 21.9 hours; while where an initial fresh mass of 1.27 kg of product was used, the drying time was 19.4 hours.

Conclusions

The Hii model had a better fit in both experiments. However, the inclusion of other climatic variables (e.g., wind speed, vapour pressure deficit, etc.) in the model would be important for the estimation of moisture loss and drying time when using natural convection solar dehydrators.

The maximum drying time was ≈ 22 h in autumn-winter in this semi-arid region. However, optimisation of the load (fresh mass) of fresh produce that this type of dehydrator can process at different times of the year is required.

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