

STUDY OF THE DRYING KINETICS AND DESORPTION ISOTHERMS OF EGGPLANT IN CONVECTIVE AIR DRYING

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Abstract

Eggplant is a high-yielding vegetable crop well adapted to hot and wet environments that can provide significant nutritive benefits to human health like vitamins, minerals, phenolics and antioxidants. Therefore, the crop has been used in traditional medicine but due to their perishability it cannot be preserved long even when refrigerated and thus it is necessary to freeze or dry it to extend its shelf-life. The present study aimed to evaluate the effect of air temperature on the drying kinetics and sorption isotherms of eggplant for hot air temperatures ranging from 50 to 80 °C.

Eggplants were obtained from a local market and, after removal of the peel, they were cut into slices with 6 mm thickness. Convective drying with hot air was performed in a drying chamber with an air flow rate of 0.5 m/s and at constant temperatures of 50, 60, 70, and 80 °C, for the different essays performed. The drying operation was undertaken until the final product reached a moisture content of about 10% (wet basis). The experimental data were fit to seven mathematical models commonly used to describe the drying kinetics of food products in terms of the dimensionless moisture ratio. The desorption isotherms were obtained measuring both the moisture content ((halogen moisture analyser) and the water activity (hygrometer, coupled to an isothermal bath) along drying and the experimental values were adjusted using models presented in the literature.

The results showed that the drying process at 80 °C provides a very important energy saving, since it allowed a reduction of about 67% in the drying

time, as compared with the temperature of 50 °C. The statistical indicators obtained by fitting the experimental data to the tested kinetic models allowed concluding that the Page, logarithmic and Wang & Singh models satisfactorily described the drying behaviour of eggplant slices, but the best was the Vega & Lemus model. Furthermore, a nonlinear relation was obtained between the Vega & Lemus k constant and temperature. According to the Brunauer-Emmett-Teller (BET) classification, the moisture sorption isotherms of eggplant fall into category III. For increasing temperature, the amount of adsorbed water decreased for the same water activity, making eggplant less hygroscopic at higher temperatures. Furthermore, the Chen model was confirmed to be accurate in predicting the equilibrium moisture content of the eggplant slices in the temperature range studied.

The shelf-stable dried eggplant should contribute to better exploitation of this crop and foster its use as an ingredient in the development of flours to be used as a functional ingredient in different kinds of meals, like soups, sauces and baked goods.

Key words: Eggplant, Hot-air drying, Drying kinetics, Thin layer model, Sorption isotherm, Vega & Lemus model, Chen model.

1. Introduction

Eggplant is an agronomically and economically important non-tuberous species of the nightshade *Solanaceae* family. The fruit of the eggplant is

botanically classified as a berry, containing numerous edible soft bitter seeds due to nicotinoid alkaloids [1].

Several different eggplant species have been cultivated for centuries in Asia, Africa, Europe, Near East and Mediterranean countries, but the most commonly cultivated one is *Solanum melongena*. This species differs from its wild predecessors mostly in terms of fruit colour (ranging from dark purple to black with some green and white varieties) and shape (larger and more variable) [1, 2].

Eggplant is a high-yielding vegetable crop well adapted to hot and wet environments and thus remains affordable while other vegetable crop prices increase. This crop can provide significant nutritive benefits, like vitamins, minerals, phenolics and antioxidants (anthocyanins, phenolic acids and flavonoids), which are beneficial to human health. It also contains low calories and high moisture contents [1, 3 - 6]. Eggplant has also been used in traditional medicine with therapeutic effects on warts, burns and many inflammatory diseases, such as stomatitis, arthritis and gastritis [4, 7]. However, it is a perishable vegetable that cannot be preserved long even when refrigerated and thus it is necessary to freeze or dry them in order to extend their shelf-life. The short shelf-life of these vegetables can be a major cause of postharvest losses, especially during peak harvesting season and constitutes a heavy drawback for commercial purposes. However, the shelf stable dried eggplant is a valuable ingredient in the production of flour to be used as a functional ingredient in different kinds of meals, like soups, sauces and baked goods (breads, crackers and pasta) [8 - 12].

Drying is one of the most convenient technologies to produce shelf stable food products. From an engineering point of view, drying is a complex process involving simultaneous heat and mass transfer occurring both inside and at the surface of the food. Convective drying, that mainly consists of forcing air through the product to be dried, is the most traditional dehydration method used to preserve foods.

The modelling of the drying processes allows their understanding and the establishment of appropriate operating conditions. Many mathematical models have been proposed to describe drying process, from diffusion to thin-layer models, being these categorized into theoretical, semi-theoretical, and empirical [13, 14].

The water is one of the most important components in foods that importantly impacts quality and conservation. The free water can be responsible for degradation of the food through chemical or enzymatic reactions, as well as microbial growth. Hence, the water

activity (a_w), which is related to this free water available, is a most important property of foods [15].

Foods are characterized by different sorption isotherms depending on temperature. These represent the interdependence of the equilibrium moisture content of the food with the relative humidity of the surrounding atmosphere. Sorption isotherms are, therefore, useful for food processing operations such as drying, packaging and storage [16 - 19].

Many different models can be found in the literature, over 200 different models, to describe the sorption behaviour of foods, being over 200 different models represented by semi-empirical equations that comprise a variable number of parameters [15]. The isotherm models can be grouped into various categories: kinetic models based on an absorbed mono-layer of water (BET model), kinetic models based on a multi-layer and condensed film (GAB model), semi-empirical (Halsey model) and purely empirical models (e.g. Oswin and Smith models). The moisture sorption isotherms are unique for every material and for each temperature and must be evaluated experimentally [19, 20]. The GAB model, in particular, presents a great versatility, being widely applied to the study of isotherms in food and allows to determine certain effects of temperature on the isotherms by means of Arrhenius type equations [15, 21].

The information on convective drying kinetics of eggplant is quite limited [2, 8, 9, 22 - 28] and, consequently, it is essential the identification of a suitable drying model to describe the most traditional dehydration method (convective drying) used to preserve foods.

The objective of this research work was to study the drying kinetics and sorption isotherms for the convective drying of eggplant, for different drying temperatures varying from 50 to 80 °C. The experimental data obtained was then fitted to different models found in the literature to describe the drying kinetics and the sorption isotherms.

2. Materials and Methods

Eggplants were obtained from a local market and, after removal of the peel, they were cut into slices with 6 mm thickness (Figure 1).



Figure 1. Sliced eggplant before drying

Convective drying with hot air was performed in a drying chamber WTB Binder with an air flow rate of 0.5 m/s. The chamber was operated at constant temperatures of 50, 60, 70 and 80 °C, for the different essays performed. Drying operation was undertaken until the final product reached a moisture content of about 10% (wet basis). Table 1 presents the drying conditions used in each essay.

Table 1. Experimental conditions of the different drying temperatures tested

Temperature (°C)	50	60	70	80
Drying time (h:min)	6:00	4:30	3:15	2:00
Initial moisture (% wet basis)	91.4	91.4	91.4	90.3
Final moisture (% wet basis)	7.5	6.8	6.9	11.7

Desorption isotherms were obtained measuring both the moisture content and the water activity along drying. For that, random samples were collected at 15 minutes' intervals to analyse. Moisture content was determined using a halogen moisture analyser, model hg53, from Mettler Toledo. The operation conditions on the halogen moisture analyser can vary in terms of temperature and evaporation rate (scale from 1 = very fast to 5 = very slow). In the present case the operation parameters were set at 120 °C and rate 3 (medium).

The values of water activity were obtained through measurement of the relative humidity (RH) of the atmosphere produced by the sample in a closed compartment. For this was used a hygrometer (Hygroskop BT-RS1, from Rotronic), coupled to an isothermal bath, with temperature set at constant values equal to that of the corresponding drying essay. The sample was placed inside the chamber in the hygrometer and then the measurement of the relative humidity started. It takes some time for the equilibrium to be reached between the sample and the atmosphere in the small compartment of the equipment, but after some minutes the reading stabilized and the value of RH was registered. The values of RH were given in

percentage, so the values of water activity were then calculated by dividing the RH by 100, to obtain the values on the range from 0 to 1.

2.1 Mathematical modelling

2.1.1 Describing drying kinetics through thin layer models

Thin layer models are equations that describe the drying curves for many agricultural and food products. These equations relate the changes in moisture content that happen during drying with particular parameters, such as the drying constant and the lag factor, be in account for combined effects of transport phenomena of different nature happening simultaneously during drying [29]. Typically, these models relate the dimensionless moisture ratio (MR) with time. MR depends on the moisture content at any moment, W_t , the equilibrium moisture content, W_e , and the initial moisture content, W_0 , all expressed on dry basis, according to the following equation:

$$MR = \frac{W_t - W_e}{W_0 - W_e} \quad (1)$$

The semi-theoretical models Page, Modified Page, Henderson and Pabis, Logarithmic, Diffusion approach, Wang and Singh, and Vega-Lemus were commonly used to correlate the experimental data obtained for drying curves in foods [30 - 32].

2.2.2 Modelling of the sorption isotherms

From the models listed in Table 2, the GAB model is one of the most widely used and therefore was used as reference. This model includes three parameters with physical meaning [34], namely, a_w is the water activity, W_e is the equilibrium moisture content, W_m is the water content of the monolayer, and C and K are temperature dependent functions.

Table 2. Mathematical models for sorption isotherms [15, 32, 33, and 36]

Dependence on temperature	Model	Equation	Parameters
Implicit	GAB		W_m, C, K
Implicit	Oswin		C, b
Implicit	Smith	$W_e = A + B \ln(1 - a_w)$	A, B
Implicit	Chen	$a_w = \exp(-A \exp(-B W_e))$	A, B
	Model	Equation	Parameters
Explicit	Chung & Pfof		A, B
Explicit	Halsey	$a_w = \exp\left(-\frac{A}{RT} \exp(-B W_e)\right)$	A, W_m, b
Explicit	Henderson	$a_w = \exp\left(-\frac{A}{RT} \frac{1}{(W_e / W_m)^b}\right)$	C, b

2.2.3 Statistics

The results were analysed using software Sigma Plot V 11.0 and some statistical indicators were used to further complement the analysis and evaluate the adequateness of the model fittings to experimental data [15, 37, and 38]. These statistical indicators include the regression coefficient, R , and also the MAE, EMSE, SE, SSE and RPD, according to the following equations:

$$\text{Mean absolute error: } MAE = \frac{1}{N} \sum_{i=1}^N |V_{exp,i} - V_{pred,i}| \quad (2)$$

$$\text{Root mean square error: } RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_{exp,i} - V_{pred,i})^2} \quad (3)$$

$$\text{Standard error: } \mathcal{E} = \frac{\sqrt{\sum_{i=1}^N (V_{exp,i} - V_{pred,i})^2}}{N-1} \quad (4)$$

$$\text{Sum of square errors: } SSE = \frac{1}{N} \sum_{i=1}^N (V_{exp,i} - V_{pred,i})^2 \quad (5)$$

$$\text{Relative percent deviation: } RPD = \frac{100}{N} \sum_{i=1}^N \frac{|V_{exp,i} - V_{pred,i}|}{V_{exp,i}} \quad (6)$$

In the these equations N is the number of observations, and $V_{exp,i}$ and $V_{pred,i}$ are the experimental and predicted values, respectively. RMSE compares the differences between the experimental and predicted values, and when the value approaches zero it means that the prediction is close to the real value. The relative percentage error compares the absolute differences between the experimental and predicted values, and for RPD under 10% the fit is considered good. RMSE provides information on the short-term performance of the correlations by allowing a term by term comparison of the actual deviation between the calculated value and the measured value [15, 31].

3. Results and Discussion

3.1 Experimental drying curves

Figure 2 shows the variations of the dry basis moisture content of the eggplant samples during drying performed at different temperatures: 50, 60, 70 and 80 °C. The initial moisture content of eggplant was 10.63 kg water/kg dry solids, corresponding to 91.40% (wet basis). according to the drying curves, the moisture content decreased linearly with time for the initial drying period, while for higher drying times the decrease in moisture content was slower, following the characteristic falling rate period.

To achieve equilibrium, the drying process took 360 min. and 120 min., at temperatures of 50 °C and 80 °C,

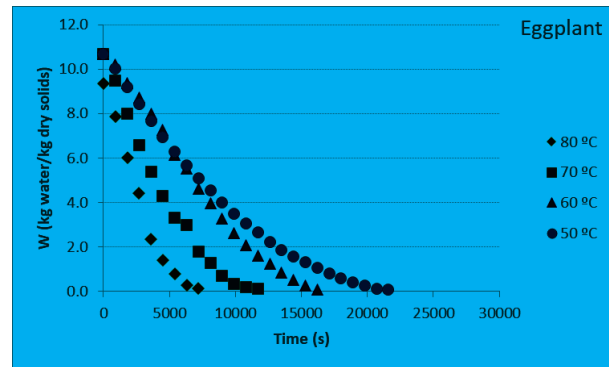


Figure 2. Variations of the dry basis moisture content for eggplant along drying

respectively. According to Gözde Bayraktaroglu Urun *et al.*, [2], the time to dry eggplant slices up to 10% of moisture and with the same thickness (6 mm) was 540 min. and 240 min., respectively, to hot air convective drying at 50 °C and 60 °C. Besides, the drying time of peeled slices with a thickness of 6 mm reduces from 225 min. to 135 min. when air drying temperature increases from 50 to 70 °C [39].

As expected, the air temperature affects drying kinetic curves, decreasing the drying time of the samples. Similar effect of temperature on the drying time was reported by other authors for eggplant [2, 9, 22, 25, 27, 39, and 40]. The drying rate was higher with increase in the temperature from 50 °C to 80 °C, so that drying time at 80 °C was reduced in about 67%, as compared with 50 °C. The drying rate was maximum at higher temperatures and then decreased according with the decrease in moisture content. This is because the migration of water from the inner sample to the surface and the evaporation rate at the surface diminish along drying, as the moisture available for elimination decreases. According to Guiné *et al.*, [26], the values of diffusivity and mass transfer coefficient to convective drying eggplant rise with increasing operating temperature, from 50 °C to 80 °C. Furthermore, the activation energy for moisture diffusion (E_d) was 35.3 kJ/mol, while the activation energy for convective mass transfer (E_c) was 48.5 kJ/mol.

3.2 Sorption isotherm curves

Sorption isotherms are useful to predict shelf life and to optimize processing operations such as drying, conditioning, mixing, packaging, and storage, because they allow identification of the requirements to obtain a stable product. The initial value of water activity (a_w) for the eggplant samples was 0.97, indicating that the product had high free water content. Figure 3 shows the variation of the equilibrium moisture content as a function of a_w corresponding to the desorption isotherms at the different temperatures studied: 50, 60, 70 and 80 °C. According to the classification of Brunauer *et al.*, [41], the sorption curves obtained

for eggplant are of type III, which is one of the most often seen for food systems. Moreira *et al.*, [42], also identified the same type of isotherm for eggplant at 50 °C and 65 °C.

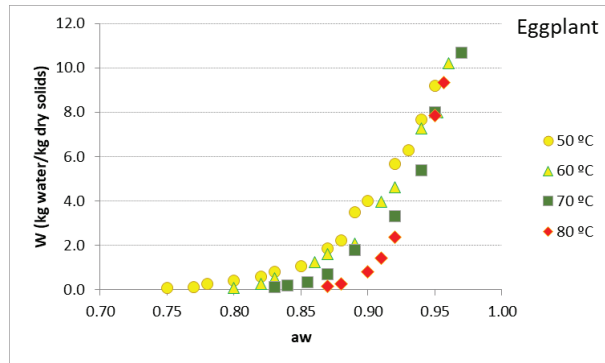


Figure 3. Desorption isotherms of eggplant at temperatures 50, 60, 70 and 80 °C

At a given temperature, the equilibrium moisture content was higher for higher water activity. The results from Figure 3 revealed two different regions in the isotherm curves: 1) for lower values of a_w in the multilayer sorption region, the relation between the moisture content and a_w was linear, while at higher values of a_w the water content increased sharply with a_w going to capillarity, in the capillary condensation region. The effect of temperature on the sorption isotherm is essential to help predict drying operations and final product quality, both after drying and also during storage. The equilibrium moisture content showed an increase in moisture content as the temperature decreased for a constant value of water activity. This trend is explained by the state of excitation of the molecules in the food matrix, since at higher temperatures the water molecules are in a more intense state of excitation. This results in liberation of the sorption sites and the links become less stable, thus diminishing the equilibrium moisture content. In this case, the food becomes less hygroscopic at higher temperatures as a result of physical and/or chemical changes in the product induced by temperature [43].

The curves showed negligible intersection with the increase in temperature, indicating that the sorption isotherm shift due to temperature was mostly attributed to changes in water binding, dissociation of water and/or increase of solute solubility in water [44].

3.3 Mathematical modelling of drying kinetics

Moisture content data were expressed in terms of the dimensionless moisture ratio (MR) and fitted to the mathematical models Page, Modified Page, Henderson and Pabis, Logarithmic, Diffusion approach, Wang and Singh, and Vega-Lemus.

Goodness of the fit for each model was evaluated based on the statistical indicators as defined by equations (2) to (6). The details about statistical parameters of the tested models are provided as Supplementary Material.

In all cases, the values of R were higher than 0.9778 (the minimum observed), indicating a satisfactory fit. Models Page, Logarithmic, Wang and Singh, and Vega and Lemus produced very good statistical indicators. The values of R, MAE, RMSE, SE, SSE and RPD for these models ranged, from 0.995 to 0.999, 0.0031454 to 0.035603, 0.0042498 to 0.033144, 0.00088538 to 0.014454, 0.000018061 to 0.00083555 and 2.5269 to 47.8580. These models were identified in the literature as the most suitable ones in describing the drying behaviour of eggplant slices at different temperatures [9, 22, and 40]. The best model was Vega and Lemus, showing the highest values of R and lowest values of RPD, on average, and for that reasons was chosen to describe the thin layer drying of eggplant in the range of temperatures tested, from 50 to 80 °C. Table 3 comprises the model parameters (k and a) and the corresponding statistical coefficients obtained to Vega and Lemus model. Doymaz, [9], tested two models (Henderson and Pabis and Page) to describe the cabinet drying characteristics of eggplant slices with thicknesses of 0.5 and 1 cm in the range of 50 - 80 °C and found that the Page model was found to be the

Table 3. Vega and Lemus parameter estimation and values of statistical coefficients for the drying of eggplant at 50, 60, 70 and 80 °C

Estimation		Temperature			
		50 °C	60 °C	70 °C	80 °C
Parameters	k	-4.3133e-5	-5.3289e-5	-8.1501e-5	-1.3338e-4
	a	1.0029	1.0343	1.0076	1.0208
Statistics	R	0.9999	0.9966	0.9992	0.9965
	MAE	3.6139e-3	2.1978e-2	1.0082e-2	2.5403e-2
	RMSE	4.2498e-3	2.7171e-2	1.3215e-2	2.8906e-2
	SE	8.8538e-4	6.5797e-3	3.8035e-3	1.0840e-2
	SSE	1.8061e-5	7.3825e-4	1.7463e-4	8.3555e-4
	RPD	3.3591	31.3943	10.8697	16.8909

Legend: MAE - Mean absolute error; RMSE - Root mean square error; SE - Standard error; SSE - Sum of square errors; d RPD - Relative percent deviation.

most suitable to describe the process. Adiletta *et al.*, [8], refer that the logarithmic model is the most suitable one for describing the hot-air drying of eggplant for the temperature of 50 °C and the Page model for 60 °C.

Figure 4 highlights the excellent agreement between the experimental data and the values predicted by the model Vega and Lemus, confirming this model as adequate to describe the drying behaviour of eggplant.

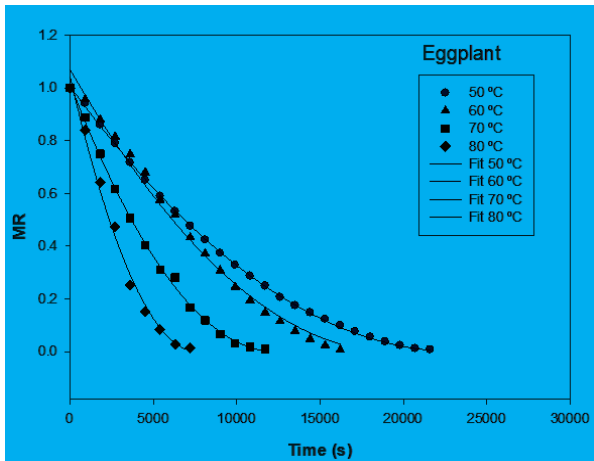


Figure 4. Fitting of the kinetic data for different temperatures to Vega and Lemus model

Constant a (dimensionless) in the Vega and Lemus model does not depend on temperature as the results in Table 4 indicate always values very much close to 1 for the four temperatures. For this temperature range, the percentage of variation in this constant was only 3%. On the contrary, the constant k (s^{-1}) depends on temperature in the studied range of values. In order to account for the effect of temperature, constant k (s^{-1}) was expressed in terms of temperature, T ($^{\circ}C$), and a corrected Vega and Lemus constant was obtained, as indicated in Equation (7).

$$k = -0.00030 + 1.0570 \times 10^{-5} T - 1.0431 \times 10^{-7} T^2 \quad (7)$$

$(R = 0.9998)$

3.4 Mathematical modelling of sorption isotherms

The detailed results of the fitting with the models presented in Table 3 to the experimental sets of equilibrium moisture content as a function of a_w for the different temperatures studied (50, 60, 70 and 80 °C) are presented in the Supplementary Material. The goodness of fit for all sorption models was evaluated through statistical indicators like R, MAE, EMSE, SE, SSE and RPD. Globally, the statistical indicators show that the implicit temperature dependent models gave less robust fittings, with exception of the Chen model. In those models, the values of R ranged between 0.9371 and 0.9901 with RPD up to 218.56, at the studied temperatures. The results of the statistical indicators for the explicit temperature dependent models show that they can be considered as acceptable to predicting the equilibrium moisture content of eggplant. Overall, the Chen and Chung and Pfost models are the best ones to fit the sorption isotherm of eggplant, converging to a similar solution. The goodness of fit can be evaluated by the high values of regression coefficient and low values of RPD (under 2). Figure 5 shows the sorption equilibrium moisture isotherms of eggplant as well as the results of regression performed with the Chen model for different temperatures, while Table 4 comprises the model parameters and the corresponding statistical coefficients.

The Chen model highlights a very close agreement between the experimental points and the predicted curves.

Figure 5 reveals that the moisture content decreased, at a given water activity, when temperature increased.

Table 4. Parameter estimation and statistics for fitting the desorption data with different models

Model	Estimation		Temperature			
			50 °C	60 °C	70 °C	80 °C
Chen (ITD) ¹	Parameters	A	0.2444	0.2030	0.1725	0.1257
		B	0.2134	0.1881	0.1853	0.1262
	Statistics	R	0.9670	0.9849	0.9833	0.9601
		MAE	1.3938e-2	7.6250e-3	7.9111e-3	7.9333e-3
		RMSE	1.6911e-2	9.5887e-3	8.7352e-3	8.4880e-3
		SE	4.5097e-3	3.0196e-3	3.2757e-3	3.7429e-3
		SSE	2.8600e-4	9.1943e-5	7.6304e-5	7.2046e-5
		RPD	1.6582	0.8679	0.8917	0.8774
		RMSE	1.8800e-2	2.1656e-2	1.3808e-2	7.1151e-3
		SE	5.0132e-3	6.8200e-3	5.1779e-3	3.1374e-3
		SSE	3.5342e-4	4.6900e-4	1.9065e-4	5.0624e-5
RPD	1.9271	2.1500	1.2736	0.7210		

Legend: ¹ITD = implicit temperature dependence, ²ETD = explicit temperature dependence, MAE - Mean absolute error; RMSE - Root mean square error; SE - Standard error; SSE - Sum of square errors; RPD - Relative percent deviation.

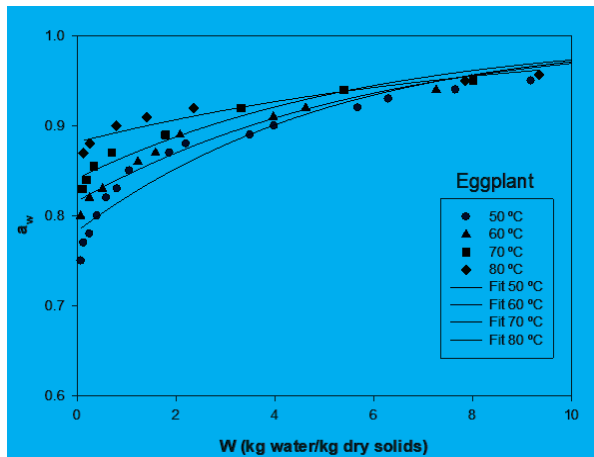


Figure 5. Fitting of the desorption isotherms with model Chen for different temperatures

A similar behaviour was reported by Moreira *et al.*, [45], in experimental sorption isotherms of thin slabs (1.5 mm, approximately) of peeled eggplant without seeds at different temperatures (20, 35, 50 and 65 °C). However, was used the Halsey model to reproduce the experimental sorption data for eggplant fruit.

4. Conclusions

- According the results from the present study, drying of eggplant with hot air at 80 °C is much faster, with a reduction of 67% in the drying time, when compared with the drying at 50 °C. From the statistical fitting measures it was concluded that the kinetic models Page, Logarithmic and Wang and Singh could describe the drying behaviour of eggplant with some accuracy, but the best model was Vega and Lemus. Additionally, it was possible to obtain a liner relation between the Vega and Lemus k constant and temperature.

- The results also indicated that, according to the BET classification, the moisture sorption isotherms of eggplant fall into category III. For increasing temperature, the amount of adsorbed water decreases for the same water activity, making eggplant less hygroscopic at higher temperatures. Finally, it was possible to conclude that the Chen model was able to provide very good prediction results for the sorption isotherms of eggplant in the temperature range studied.

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