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Analysis of Drying Kinetics of Eggplant through Thin Layer Models and Evaluation of Texture and Colour Properties

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Abstract Eggplant is a food with unique characteristics. However, due to its high moisture content it is very perishable. Thus, to increase its shelf life it can be applied the drying process. This work aimed at studying the effects of drying on eggplant, namely on the physical properties of colour and texture, as well as the analysis of drying kinetics by thin layer models. The drying was carried out using a convection chamber with a temperature of 80ºC and an air velocity of 0.5 m/s. The texture profile analysis was done with a texturometer equipped with a 75 mm probe and the colour measurement was performed with a calorimeter in the CIELab coordinates. For both texture and colour, all analysis were done in triplicate, before and after drying.

The results showed that there were clear differences in colour, with the difference being higher in the case of the dried sample (ΔE = 25.95) when compared to the fresh sample analysed 10 minutes after the cut (ΔE = 9.69).Regarding the texture, drying caused alterations in the eggplant structure, with an increase in elasticity and chewiness and a decrease in hardness, resilience and cohesiveness. As for the kinetics, the sample took 2.5 hours to reach a moisture content of approximately 10%. Four thin layer models were tested, being the Wang & Singh model the one that proved to be the most suitable to fit the experimental data, with a correlation coefficient equal to 0.9902.

Keywords colour, texture, thin layer, drying constant, kinetic model

1. Introduction

Eggplant (*Solanum melongena* L.) belongs to the Solanaceae family and is a widely consumed food throughout the world, varying in colour, size and shape [1, 2]. It is characterized by having a bitter taste and fibrous and elastic pulp, being very indicated for the prevention and treatment of diabetes, as it improves glucose tolerance and contributes to the reduction of LDL cholesterol levels [3]. However, it has a high moisture content, and can present up to 94% of water, which is reflected in its high perishability. To increase its shelf life, and thus reduce losses, the drying process can be applied. Some advantages of using drying include longer shelf life, increased product added value and ease of transport [2, 4].

Drying is an ancestral practice and one of the most used methods for food preservation [5, 6]. This method aims to remove most of the water from a food by evaporation or sublimation [7]and is a complex operation involving both heat and mass transfer phenomena during the removal of moisture. This complexity in the process is owing to the changes caused in the volume, besides the transfer of heat and mass[8]. Drying causes changes in taste, colour and texture that results in unique elastic properties [9]. Thus, a thorough knowledge of the factors that may be responsible for the decrease of product quality during the drying process is of great importance, because the quality of the dried product will depend on the extent of the changes that occur in the physical-chemical properties of the fresh product, such as chemical composition, mechanical properties, volume or porosity [8, 10].

Thin-layer drying consists in the practice of drying a product sample in a single layer of particles or slices. In order to be able to analyse the drying processes, mathematical models are used. In the case of thin-layer drying, there are currently three types of mathematical models: theoretical models, which only study the internal resistance to moisture transfer between product and air, semi-theoretical models and experimental models that only take into account the external resistance [11, 12].

There are numerous thin-layer drying models of the semi-theoretical and empirical types. Henderson and Pabis, Page and Modified Page models are examples of semi-theoretical models. The model of Wang and Singh and the model of Thompson are two examples of empirical models [13, 14].

The objective of this work was to evaluate the changes in colour and texture properties that occur in eggplant during the convective drying process, as well as to analyse the drying kinetics by means of this-layer models.

Experimental

Drying experiments

The fruit used in this study was eggplant (*Solanum melongena* L.), having been dried in slices with a uniform thickness of approximately 5 mm. For this purpose an automatic cutter was used and afterwards the eggplant slices were placed on trays. The drying was carried out in a WT Binder chamber, with air circulation, at a constant temperature of 80 °C and with an air velocity of 0.5 m/s.

Evaluation of moisture content

The moisture content of the eggplant samples was determined periodically using a HG53 Halogen Moisture Analyzer, Mettler Toledo scale, operated at speed 5 (on a scale between 1 = very fast to 5 = very slow) and at 120 °C. For the assessment of the mean values, six repetitions were made at the beginning and also at each time point along drying.

Measurement of colour

A colorimeter (Chroma Meter - CR-400, Konica Minolta) was used to determine the colour, which measured the Cartesian coordinates L * a * b * in the CIELab colour space. The dimension L* represents the brightness on a scale from 0 (black) to 100 (white) and the dimensions a* and b* are chromaticity coordinates, with a* ranging from green (-a) to red (+a) and b* ranging from blue (-b) to yellow (+b) [15-16].

The surface colours of eggplant slices were first evaluated immediately after cutting and approximately 10 minutes after cutting. After drying, the colour analysis was also performed, and all measurements were made six times.

To make an overall assessment of the change in colour due to exposure to air or drying, the colour difference was calculated (ΔE) using Equation (1) [17], where the chromatic coordinates with the index 0 correspond to the reference values, which in this case refer to the values obtained shortly after the cutting operation, i.e., before oxidation could occur:

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (1)$$

The colour difference can be classified in: unrecognizable differences ($0.0 \leq \Delta E \leq 2.0$), differences possibly identified by an experienced observer ($2.0 < \Delta E \leq 3.5$) and evident colour differences ($\Delta E \geq 3.5$). The highest the value of ΔE, the greater the colour difference in relation to the reference sample [18].

Determination of textural properties

The texture analysis was performed using a texturometer (model TAXT Plus from Stable Micro Systems) in order to obtain the texture profiles (TPA), as exemplified in Figure 1. The texture profile analysis comprised two cycles of compression, spaced by a 5-second interval, using a flat probe of 75 mm diameter. The load cell used was 30 kg and the test and post-test rates were both 0.5 mm/s.

Six TPAs were obtained for the fresh and also for the dried eggplant samples. The textural parameters hardness, springiness, cohesiveness, resilience and chewiness were calculated through Equations (2) to (6) taking into account Figure 1 [15]:

$$Hardness\ (N) = F1 \tag{2}$$

$$Springiness\ (\%) = \frac{\mathrm{T2}}{\mathrm{T1}} x\ 100 \tag{3}$$

$$Cohesiveness\ (dimensionless) = \frac{\mathrm{A2}}{\mathrm{A1}} \tag{4}$$

$$Resilience\ (\%) = \frac{\mathrm{A5}}{\mathrm{A4}}\ x100 \tag{5}$$

$$Chewiness\ (N) = F1\ x\ \frac{\mathrm{T2}}{\mathrm{T1}} x\ \frac{\mathrm{A2}}{\mathrm{A1}} \tag{6}$$

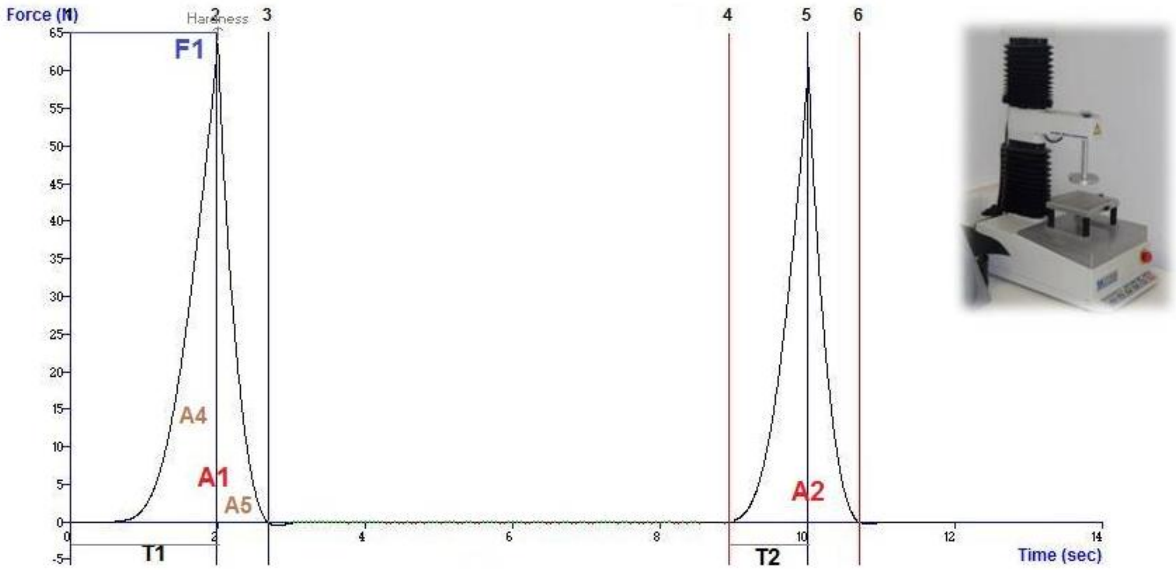

Figure 1: Texture profile of a fresh eggplant sample

Modelling of Drying Kinetics

The thin layer models are mathematical expressions that allow to determine the drying kinetics from the experimental data [19]. These models relate the variations of the average moisture content of the food product during drying, i.e., along time, with some parameters, such as the drying constant, k [s^{-1}] or the lag factor, k_0 [dimensionless], and these parameters explain the combined effects of various transfer phenomena occurring during drying[17, 20]

There are several thin layer kinetic models which express themselves in terms of the moisture ratio (MR[1]), being MR defined according to equation (7) [17]:

$$MR = \frac{\mathrm{W - We}}{\mathrm{W0 - We}} \tag{7}$$

Where W, W_0 and We are, respectively, the moisture contents at the generic instant t, at the initial moment and at equilibrium, all expressed in kg of water per kg of dry matter.

The experimental data (MR, t) were adjusted to four kinetic models described in the literature through Equations (8) to (11) [17, 21, 22].

$$Page: MR = \exp(-\ kt^{n}) \tag{8}$$

$$Modified\ Page: MR\ =\ \exp[-\ (k\ \mathrm{t})^{n}] \tag{9}$$

$$Vega - Lemus: MR = (a + k\ t)^{2} \tag{10}$$

$$Wang\ \&\ Singh: MR = 1 + a\,t + b\,t^2 \tag{11}$$

Statistical analysis

To evaluate the model that best fits the experimental data was used the coefficient of determination (R^2), and also on different statistical test parameters, as described by Equations (12) to (17):

Mean absolute error: $$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|V_{\exp,i} - V_{pred,i}\right| \tag{12}$$

Root mean square error: $$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_{\exp,i} - V_{pred,i}\right)^2} \tag{13}$$

Standard error: $$SE = \frac{\sqrt{\sum_{i=1}^{N}\left(V_{\exp,i} - V_{pred,i}\right)^2}}{N-1} \tag{14}$$

Sum of square errors: $$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(V_{\exp,i} - V_{pred,i}\right)^2 \tag{15}$$

Chi square: $$CS = \frac{1}{N - n_p}\sum_{i=1}^{N}\left(V_{\exp,i} - V_{pred,i}\right)^2 \tag{16}$$

Relative percent deviation: $$RPD = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|V_{\exp,i} - V_{pred,i}\right|}{V_{\exp,i}} \tag{17}$$

Where N is the number of experimental observations and n_p is the number of parameters. Also, $V_{exp,i}$ and $V_{pred,i}$ are, respectively, the experimental and predicted values for the dependent variable, which is MR in the present case, for each observation i. The highest the value of R^2, approaching 1, the better is the fit, while lower values of CS and RMSE, tending to zero, are indicative of predictions more adequate to the experimental data. These last indicators (RMSE and CS) compare the differences between the experimental and predicted values of MR, whereas the RPD compares the absolute differences between them. Values of RPD under 10% are indicative of a good fit [23].

Results and Discussion

Colour characteristics

Figure 2 shows the colour coordinates L* a* b* obtained for samples of fresh eggplant (immediately after cutting and 10 min after cutting) and dried. The sample analysed 10 min after cutting was darker than the fresh sample evaluated immediately after the cut, and furthermore, the drying operation turned the sample even darker (L * lower). The results are in agreement with the expected, since after the cut occur enzymatic reactions and non-enzymatic darkening that influence the colour of the eggplant [24]. Regarding the parameter a*, before drying the green colour prevailed, but after drying the colour changed to red (a* positive). The b* coordinate always had positive values, with an increase in the value of the fresh sample (immediately after the cut) for the dried sample. This means that both, before and after drying, yellow rather than blue predominated and this colour became more intense upon drying. The colour changes from the fresh samples to the dried ones are due to the browning reactions that occur during the drying process [22]. The results obtained for the parameters a* and L* are coincident with those of other studies [2, 6]. The colour difference (ΔE), calculated by Equation (1), was equal to 25.95 in the case of the dried sample and 9.69 in the case of the fresh sample analysed 10 minutes after the cut. According to the classification suggested by Valdivia-López and Tecante [25] these values correspond to clear colour differences in both cases, this difference being greater in the case of the dried sample.

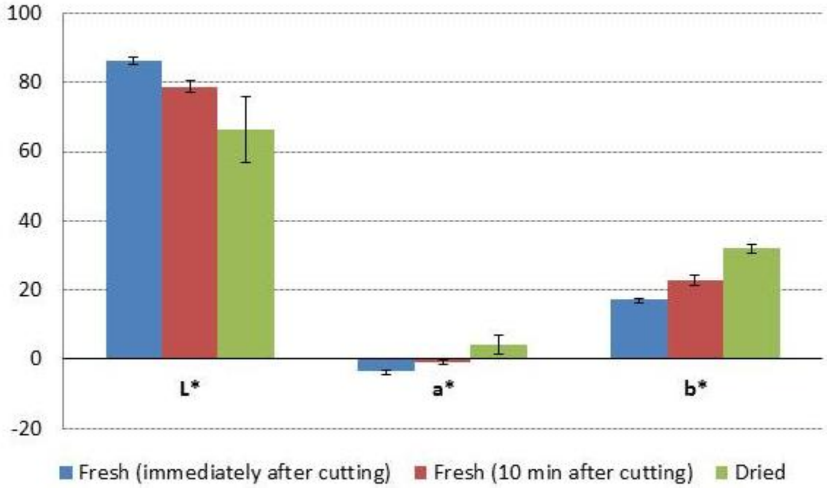

Figure 2: Colour coordinates of fresh and dried eggplant

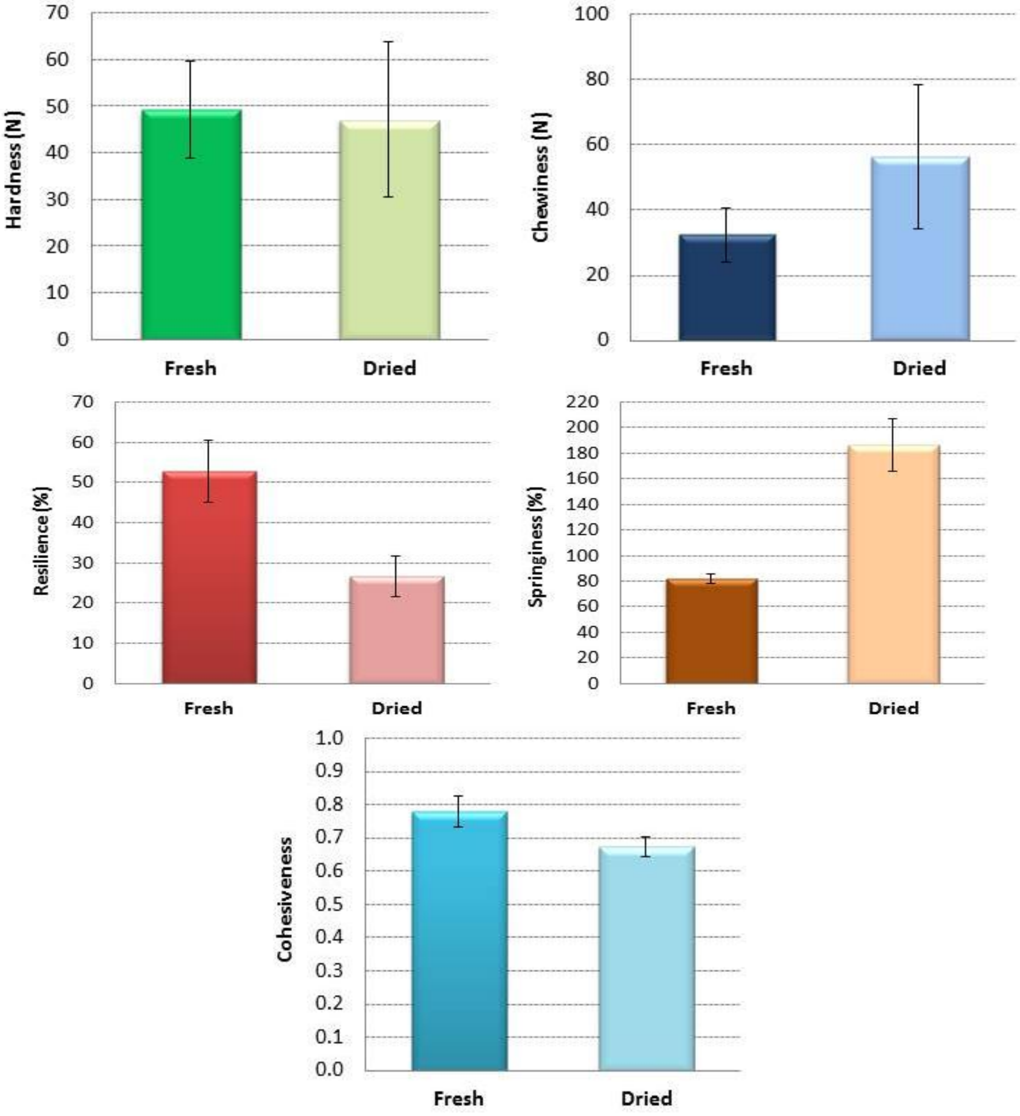

Figure 3: Texture parameters of fresh and dried eggplant

Textural properties

Figure 3 shows the results obtained for the textural parameters evaluated before and after drying. The hardness corresponds to the force that is required to deform a product, that is, the force that is necessary to compress a food between the molars and the teeth, in the case of solids, or between the tongue and the palate, in the case of semi-solid foods [15, 26]. Chewiness is defined as the force necessary to disintegrate a solid food to the point of being swallowed [27]. After the data analysis, it was verified that the drying operation reduced hardness but increased chewiness. In the case of hardness, similar results were observed in other studies for the drying of apples and pumpkin [17, 28].

The cohesiveness is related to the strength of the inner bonds that make a food remain cohesive [29]. The resilience represents the ability of a product to return to its initial position, being measured at the withdrawal of the first penetration, before the start of the waiting period. In this way, it can be interpreted as an instantaneous elasticity [29]. As can be seen in Figure 3, drying resulted in a decrease of these two parameters. According to Cruz et al. [17], the reduction of cohesiveness during drying may be due to the loss of integrity that occurs during this process as a consequence of the loss of moisture.

Regarding the springiness, dried eggplants showed higher elasticity when compared to fresh eggplants, which means that the dried eggplant had a greater capacity, after deformation, to recover its initial condition when the applied force was withdrawn. Similar results were obtained in the Cruz et al. [17] for the drying of apples.

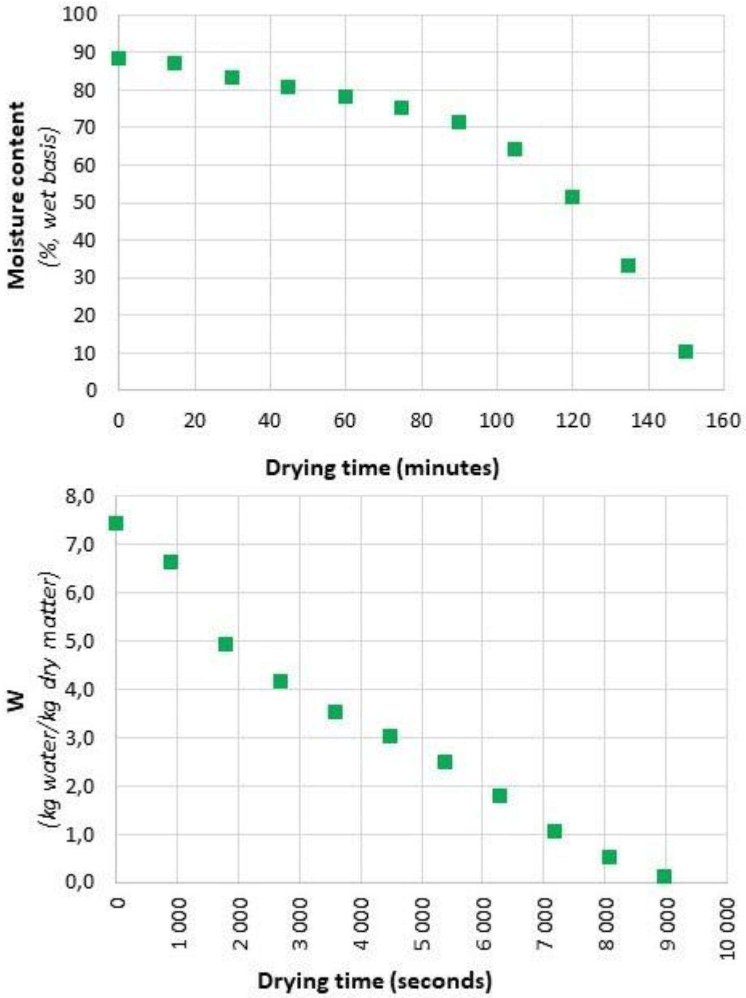

Figure 4: Variation of moisture along drying in wet basis and dry basis

Drying kinetics

Figure 4 shows the evolution of the moisture content (wet basis and dry basis) of the eggplant throughout the drying process. It is found that the eggplant took 2.5 hours to reach a moisture content of about 10%. The curve of W versus time indicates that there was a first period of approximately constant drying rate (until t=1800 s) followed by a period of falling rate (after t = 1800 s). This is a general behaviour observed for the drying of many agricultural products [30].

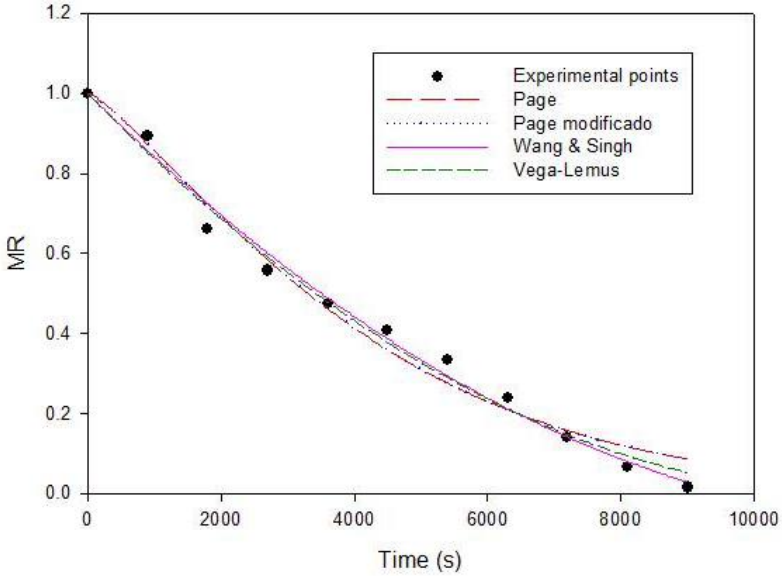

Figure 5: Fitting with the tested kinetic models

Table 1: Results obtained for each model tested

Page		**Modified Page**	
Parameters		**Parameters**	
k (± sd [1])	2.5784e-5 (±2.3085e-5)	k (± sd [1])	2.2669e-4 (± 9.0773e-6)
n (± sd [1])	1.2590 (± 0.1061)	n (± sd [1])	1.2589 (± 0.1060)
Statistics		***Statistics***	
R^2	*0.9814*	R^2	*0.9810*
MAE	*0.0357*	*MAE*	*0.0360*
RMSE	*0.0420*	*RMSE*	*0.0418*
SE	*0.0139*	*SE*	*0.0137*
SSE	*0.0018*	*SSE*	*0.0017*
CS	*0.0022*	*CS*	*0.0020*
RPD	*24.90*	*RPD*	*22.85*
Vega-Lemus		**Wang & Singh**	
Parameters		**Parameters**	
k (± sd [1])	-8.5622e-5 (± 3.5819e-6)	a (± sd [1])	-1.6510e-4 (± 7.6991e-6)
a (± sd [1])	0.9997 (± 0.0122)	b (± sd [1])	6.3540e-9 (± 1.0546e-9)
Statistics		***Statistics***	
R^2	*0.9891*	R^2	*0.9902*
MAE	*0.0276*	*MAE*	*0.0244*
RMSE	*0.0322*	*RMSE*	*0.0306*
SE	*0.0107*	*SE*	*0.0101*
SSE	*0.0010*	*SSE*	*0.0009*
CS	*0.0013*	*CS*	*0.0011*
RPD	*10.57*	*RPD*	*4.38*

[1] sd = standard deviation.

Figure 5 shows the adjustment of the experimental points obtained for the moisture ratio (MR) according to the four thin layer models tested. Table 1 presents the results obtained for each model, by using the software Sigma Plot (version 11), and also includes the calculated statistical parameters according to equations (12) to (17). Taking into account the results obtained, it is verified that all the adjustments were acceptable, because in all cases the correlation coefficients (R^2) were close to 1. However, the model that best fits the experimental data was Wang & Singh, with a correlation coefficient of 0.9902. Furthermore, it is the model with the lowest RPD (under 10%) and also lowest values for al other statistical parameters (MAE, RMSE, SE, SSE and CS).

These results are in agreement with those obtained in the work by Doymaz [21], where it was also found that the Wang & Singh model was suitable to describe the drying kinetics of aubergine slices. However, because it is a purely empirical model, it does not allow to estimate some parameters of interest, such as the drying constant, which is important for the knowledge of the process.

Conclusion

The results obtained in this work showed that there were marked differences in the colour of the eggplant samples analysed 10 minutes after the cut, as well as in the dried eggplant, when compared to the fresh eggplant analysed immediately after the cutting operation. Drying also altered the different texture parameters, on the one hand resulting in a decrease in hardness, cohesiveness and resilience and, on the other hand, in an increase in chewiness and springiness.

The kinetic data were well adjusted to the four thin-layer models tested, but the Wang & Singh's purely empirical model gave the best fit.

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