Drying kinetics of potato pulp waste

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Abstract

Potato pulp waste (PPW) drying was investigated under different experimental conditions (temperatures from 50 to 70 °C and air flow from 0.06 to 0.092 $m^3\ m^{-2}\ s^{-1}$) as a possible way to recover the waste generated by potato chip industries and to select the best-fit model to the experimental results of PPW drying. As a criterion to evaluate the fitting of mathematical models, a method based on the sum of the scores assigned to the four evaluated statistical parameters was used: regression coefficient (R^2), relative mean error P (%), root mean square error (RMSE), and reduced chi-square (χ^2). The results revealed that temperature and air velocity are important parameters to reduce PPW drying time. The models Midilli and Diffusion had the lowest sum values, i.e., with the best fit to the drying data, satisfactorily representing the drying kinetics of PPW.

Keywords: *Solanum tuberosum* L.; recovery of by-products; processing; mathematical model.

1 Introduction

Potato (*Solanum tuberosum* L.) is a tuberous crop of great importance in the world economy and feeding. It is characterized as the fourth agricultural product most grown crop worldwide, and in Brazil it is among the ten most consumed and the most economically relevant vegetable (Pinelli et al., 2006). It is widely consumed fresh, and its industrialization is on the rise, especially the production of starch and chips (Agrianual, 2011). However, an apparent problem of this type of industrialization is the production of highly polluting waste, which represents not only loss of raw materials, but also additional expenses in the treatment for future disposal in the environment.

If appropriate technologies were used, agro-industrial waste could be converted into commercial products or raw materials for secondary processes (Pelizer et al., 2007). Aiming at reducing raw vegetable costs of in industrial processes, studies have been carried out for the transformation of residues into by-products thus adding value to the system as a whole (Laufenberg et al., 2003; Soares Júnior et al., 2009, 2011; Sena et al., 2012; Dias et al., 2014).

In the industrial processing of potato chips, waste production mainly occurs after operations such as raw material peeling, slicing, and washing. Potato pulp waste (PPW) is one type of waste generated and is composed of water, cell residues, intact starch molecules, and small pieces of bark (Fernandes et al., 2008). The possible use of PPW as an ingredient in the production of another food product can bring benefits, making it a product with added value, which is able to be used in other supply chains. In addition to the economic benefits, positive environmental factors may result from this measure.

The strategy for using this waste from potato industrialization would be to convert it into a modified dry form that could be stored as flour and be suitable for various applications, which would make it suitable as an ingredient in the industry in other product lines, such as the fried snacks and extruded or baked products. The drying operation is a method by which free water is extracted from the food, which directly contributes to stability, both microbiologically and in terms of deteriorative enzymatic reactions such as browning and rancidity. By decreasing the water content, these reactions are decelerated, if not avoided, ensuring longer shelf life to the product (Costa, 2007).

The mathematical modeling of a dynamic system can be defined as a set of equations that can predict the accuracy of the process. Mathematical models can be quite different depending on the system considered and the particular circumstances of each function, and some models can be more appropriate than others (Ogatha, 2003). There are a few studies on the mathematical modeling drying kinetics of potato slices (Aghbashlo et al., 2009), but none on the PPW although there are some on byproducts of other tuberous plants, such as peels (Vilhalva et al., 2012) and fibrous mass of cassava (Castiglioni et al., 2013).

The present study aimed to understand the kinetics of the drying process of PPW under various experimental conditions through mathematical modeling of drying kinetics of potato pulp waste and to select the model that best fits the experimental results of PPW drying considering the sum of the scores assigned to the four evaluated statistical parameters.

2 Materials and methods

2.1 Sample collection and PPW drying

The liquid residues derived from washing cv *Atlantic* potatoes preparing for the production of chips and shoestring in the Cicopal Ltda Company (Senador Canedo-GO) were

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collected between January and February 2011 in high-density polyethylene containers (HDPE). The PPW samples were homogenized and submitted to sedimentation for 15 min. The supernatant was removed and the sediment portion was dried to reach the moisture content (wb) of 12 g 100 g^{-1}. The chemical compositions of the PPW (db) were determined according to official methods of AOAC International (Association of Official Analytical Chemists, 2006). The analyses were performed in triplicate in samples submitted to drying at temperature of 60 °C and air flow of 0.076 $m^3\ m^{-2}\ s^{-1}$.

Drying was performed using a forced air circulation oven with an axial flow fan, an electric heater with voltage variator, and flow control valves. the inner chamber of the oven measured 1.18 m of height, 0.70 m of width, and 0.65 m of depth and included a support for five trays (0.50×0.50 m). In order to study the drying process, rotational central composite design was used (Table 1). The temperature of the internal drying air was determined using a thermostat at 50, 52.9, 60, 67.1, and 70 °C. The temperature levels were established to cover the range below and above potato starch gelatinization temperature (78-82 °C) (Blahovec et al., 2012).

The trays had hollow bottom to allow air flow, and the wind speed was measured using an anemometer (Icel, model NA-3070) placed at the only air flow exit at the top of the drying equipment. This cylindrical opening (anemometer) was 3.31 10^{-3} m^2. The air speed values were multiplied by the opening area to obtain the volumetric air flow ($m^3\ s^{-1}$), which were divided by the tray area (0.25 m^2) (Equation 1), to obtain the following air flow values: 0.06, 0.064, 0.076, 0.088, and 0.092$m^3\ m^{-2}\ s^{-1}$, respectively.

$$AF = \frac{V_{AIR} \times A_{NA}}{TA} \quad (1)$$

where: *AF*: Air flow ($m^3\ m^{-2}\ s^{-1}$); V_{AIR}: air speed (m s^{-1}); A_{Na}: anemometer opening area (m^2), and *TA* tray area (m^2).

The initial moisture of PPW before drying was 54.2 g 100 g^{-1}, determined on wet basis (wb). Drying was stopped when the material moisture content (wb) was less than 12 g 100 g^{-1}.

Weighing of trays, initially containing 1 kg of sedimented PPW in dry basis (d.b.) were performed every 5 min the first 60 min of process and then every 10 min for 130 min and thereafter every 20 min. The dried material was stored in threaded polypropylene (PP) containers, sealed with polyvinyl chloride film (PVC), and stored at −18 °C.

2.2 Mathematical modeling of the drying kinetics

Seven mathematical models widely used in literature for drying experiments with food material were studied: Lewis, Page, Henderson and Pabis, Wang and Singh, Midilli, Diffusion Approach, and Logarithmic (Martinazzo et al., 2007). The mathematical models used in the drying kinetics of PPW are respectively represented in Equations 2-8.

$$Y = \exp(-kt) \quad (2)$$

$$Y = \exp(-kt^e) \quad (3)$$

$$Y = a \times \exp(-kt) \quad (4)$$

$$Y = 1 + at + bt^2 \quad (5)$$

$$Y = a \times \exp(-kt^e) + bt \quad (6)$$

$$Y = a \times \exp(-kt) + (1-a) \times \exp(-kbt) \quad (7)$$

$$Y = a \times \exp(-kt) + c \quad (8)$$

in which: *Y* = dimensionless moisture, *k* = kinetic constant (min^{-1}), *t* = time (min), *a, b, c*: experimental constants (dimensionless), *e*: exponent.

The dimensionless moisture value was calculated by Equation 9. However, this equation was simplified because the relative humidity of the drying air was continually modified, making it impossible to reach moisture equilibrium [X_{BS} *(eq)*], which led to the use of Equation 10 (Bozkir, 2006).

$$Y(t) = \frac{X_{BS}(t) - X_{BS}(eq)}{X_{BS}(0) - X_{BS}(eq)} \quad (9)$$

$$Y(t) = \frac{X_{BS}(t)}{X_{BS}(0)} \quad (10)$$

in which: *Y* = dimensionless moisture at time t, $X_{BS}(t)$ = moisture at time t (db), X_{BS} *(0)* = initial moisture content (db), X_{BS} *(eq)* = equilibrium moisture content (db).

Statistical analysis of the experimental drying data was performed by non-linear regression using the Statistica 7.0 software (Stasoft, Tulsa, USA). The criterion for choosing the best adjustments was based on the determination of the regression coefficient (R^2) (Oliveira et al., 2012) and the value of the other three criteria: relative mean error (P (%)), root mean square error (RMSE), and reduced chi-square (χ^2), according to

Table 1. Experimental design for drying the potato pulp waste as a function of the drying variables in coded values and actual values.

Experiment	Temperature (x1)		Air flow (x2)	
	Coded	Actual (°C)	Coded	Actual (m^3 kg.s^{-1})
1	−1	52.9	−1	0.016
2	+1	67.1	−1	0.016
3	−1	52.9	+1	0.022
4	+1	67.1	+1	0.022
5	−1.41	50	0	0.019
6	1.41	70	0	0.019
7	0	60	−1.41	0.015
8	0	60	1.41	0.023
9	0	60	0	0.019
10	0	60	0	0.019
11	0	60	0	0.019
12	0	60	0	0.019

Equations 11, 12 and 13, which took into account the responses obtained experimentally and the values predicted by the model.

$$P(\%) = \frac{100}{N} \sum_{i=1}^{N} \frac{\left| Y_{pre,i} - Y_{\exp,i} \right|}{Y_{\exp,i}} \quad (11)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Y_{pre,i} - Y_{\exp,i} \right)^2 \right]^{1/2} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(Y_{\exp,i} - Y_{pre,i} \right)^2}{N - v} \quad (13)$$

in which: χ^2 = reduced chi-square, RMSE = root mean square error, P = relative mean error, $Y_{\exp\ i}$ = dimensionless moisture experimentally observed; $Y_{pre\ i}$ = dimensionless moisture predicted by the model, N = number of experimental points, and v = number of coefficients and constants.

It is known that a good-fitting model should achieve high linear regression coefficient values (R^2), close to 1.0, and lower P (%), RMSE, and χ^2 values, close to zero. This mathematical method was developed to assess, concomitantly, the four statistical factors used [P (%), χ^2, RMSE and R^2] to ensure selecting the best- fitting model. Accordingly, for each statistical factor, a list was made in crescent order, in which they were stratified according to the Sturges' Frequency Distribution (Machado et al., 2010), where each distribution class received a score (ranging from 1 to 8), and the lower the score, the better the adjustment of the model for that statistical factor in that experiment. The number of class stratifications and the amplitude of each were obtained by Equations 14 and 15.

$$N = 1 + 3{,}3 \times \log(n) \quad (14)$$

$$amp = \frac{AMP}{k} \quad (15)$$

in which: N = number of classes; n = number of observations for each statistical factor; amp = amplitude of the class; and AMP = amplitude of sample data observed for each statistical factor.

Next, the scores a sum of scores of each experiment for each statistical factor in each model were summed in order to obtain a single value per model. This number was used to compare the models; the model with the lowest value would be the most appropriate, taking into account the four statistical factors simultaneously. The data of each of the 12 drying experiments were also treated by ANOVA to determine the significance of the linear, quadratic, and interaction effects of temperature and air flow on PPW drying.

3 Results and discussions

3.1 Drying kinetics of potato pulp waste

The importance of temperature (x_1) in the drying process of PPW, experiments 2 and 4, both at temperature of 67.1 °C, showed drying time far shorter than those of experiments 1 and 3, 52.9 °C (Figure 1a). Several other authors have identified temperature as the factor that most affects the drying kinetics of food products, such as drying cashews (Gouveia et al., 2002), sliced potato, and apple (García et al., 2008), and isoflavone during soybean drying (Niamnuy et al., 2012). These results also showed that variable air flow (x_2) did not show the same level of significance (Table 2).

Experiments 2 and 4, although conducted at the same temperature, had different air flow values, and those of experiments 4 and 3 were equal to or greater than 1 and 2. However, even with a difference in the air flow values, the curves were nearly coincident, and the drying time of experiment 4 was only 10 min. Similar behavior was observed in experiments 1 and 3, in which, despite the small difference observed in

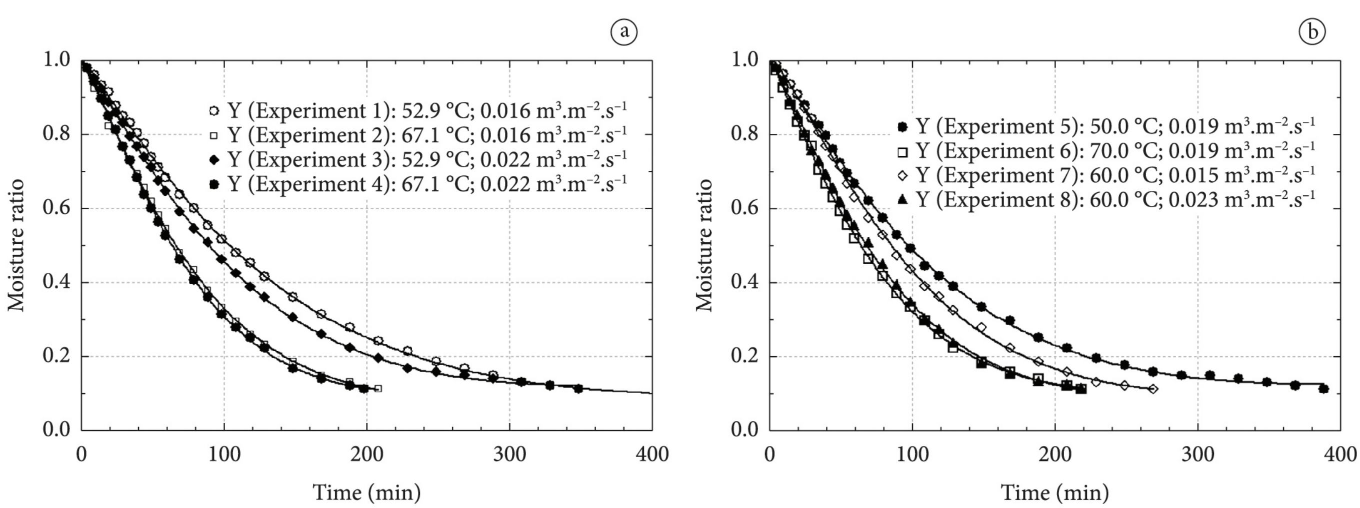

Figure 1. Moisture ratio versus time for experiments 1 to 4 (factorial points) (a) and 5 to 8 (axial points) (b) for the kinetic modeling of drying PPW. Solid lines represent the adjustment of the data predicted by the Midilli model.

Table 2. Analysis of variance (ANOVA) of the model adjusted to the depedent variable drying time versus temperature (°C) (x_1) and the flow of the drying air (m^3 $Kg.s^{-1}$) (x_2).

Factor	Sum of squares	Degrees of freedom	Mean square	F value tabulated	level of significance (p)
x_1 linear	33861.75	1	33861.75	279.7739	0.000000*
x_1 quadrátic	7709.82	1	7709.82	63.7004	0.000044*
x_2 linear	1026.84	1	1026.84	8.4840	0.019507*
Residual error	968.26	8	121.03		
Total error	43566.67	11			

*Significant factors in the adjusted model ($p \leq 0.05$).

Table 3. Regression coefficient (R^2) and mean relative error [P(%)] values.

Statistical Factor	Experiment	Models						
		Lewis	Page	Henderson & Pabis	Wang & Singh	Midilli	Diffusion Approch	Logarithmic
R^2 (%)	1	99.6230	99.8180	99.8600	99,8180	99.9670	99.9330	99.8630
	2	99.2350	99.8400	99.8480	99,8480	99.9400	99.8920	99.7090
	3	99.4830	99.5390	99.6320	99.6520	99.9830	99.6720	99.7720
	4	98.9660	99.7890	99.6160	99.7020	99.9800	99.9420	99.6570
	5	99.3380	99.3550	99.4700	99.3860	99.9540	99.5030	99.7540
	6	99.5790	99.7340	99.7720	99.7670	99.9600	99.8440	99.7890
	7	98.7890	99.7230	99.5830	99.5650	99.9540	99.9330	99.6200
	8	99.3780	99.7940	99.7320	99.8880	99.9360	99.8650	99.7400
	9	97.7680	99.4930	98.8000	99.2240	99.8980	99.6370	99.9450
	10	98.6410	99.7190	99.4750	99.5930	99.9520	99.8830	99.5340
	11	98.1900	99.7090	99.6970	99.7110	99.8650	99.8620	99.7060
	12	98.1340	99.7830	99.6880	99.7730	99.9720	99.9720	99.7050
	Parcial sum of scores	51	16	23	24	12	15	17
P (%)	1	3.1830	3.4967	2.3566	3.9677	1.0220	2.3179	1.9515
	2	5.2625	3.1846	3.4045	2.2312	1.0351	2.3062	3.7995
	3	6.5831	7.0672	6.4315	6.4315	1.1541	6.3015	3.8186
	4	6.0897	3.9600	3.4558	2.6406	0.8549	2.2021	3.9887
	5	7.6268	7.9477	7.1476	7.9612	1.6354	7.6616	3.6765
	6	4.3719	4.6070	3.8405	4.1221	1.1390	3.6402	3.0905
	7	6.5476	4.3883	3.4818	2.9610	1.1632	2.1290	3.7605
	8	5.3694	4.1091	3.9103	1.8144	1.7777	3.4606	4.1722
	9	10.8461	7.5588	8.0959	6.3060	2.0703	6.1473	8.9967
	10	7.3748	4.5975	4.5935	3.0036	1.5661	2.8879	4.8541
	11	5.5149	4.1960	3.8306	2.6905	2.3215	3.2072	3.9287
	12	5.7078	3.9419	3.5399	2.2421	1.0304	2.6092	3.9602
	Parcial sum of scores	56	44	43	35	13	36	38

the curves during the process (experiment 3 curve was more inclined), showed no difference in terms of the final drying time.

The experiment 5 and 6 curves (Figure 1b) showed the importance of temperature in the process. These experiments showed the same air flow, differing only in terms of temperature values. As a result of the difference of 20 °C between the experiments, the difference between the drying time of the experiment with the highest temperature (70 °C) and that with the lowest temperature (50 °C) was 170 min.

Analyzing the experiment 6 and 8 curves, it was observed that there was a reasonable balance between the variables temperature and air flow since both experiments showed the same drying time; experiment 6 showing higher temperature but lower air flow compared to those of experiment 8. Experiments 7 and 8 showed a small influence of the air flow on PPW drying, as they were conducted at the same temperature (60 °C), but experiment 8 had a shorter drying time (50 min shorter). Similar behavior was observed in the study of Nicoleti et al. (2011), who dried pineapple slices and observed that a large increase in the drying air velocity resulted in increased water diffusivity, reducing the drying time. However, for a small variation in the air flow value, virtually there was no difference in water diffusivity or the process time. Bozkir (2006) also found that the air velocity was important to decrease the temperature and drying time of apricots.

Table 4. Reduced chi-square (χ^2) and root mean square error (RMSE) values.

Statistical Factor	Experiment	Lewis	Page	Henderson & Pabis	Wang & Singh	Midilli	Diffusion Approch	Logarithmic
		Model						
χ^2	1	3.41E-04	1.70E-04	1.31E-04	2.23E-04	3.28E-05	6.47E-05	1.32E-04
	2	6.35E-04	1.39E-04	2.98E-04	1.32E-04	5.49E-05	9.79E-05	2.65E-04
	3	4.79E-04	4.42E-04	3.53E-04	3.53E-04	1.75E-05	3.26E-04	2.27E-04
	4	9.00E-04	1.95E-04	3.49E-04	2.71E-04	1.96E-05	5.56E-05	3.27E-04
	5	6.29E-04	6.32E-04	4.34E-04	6.02E-04	4.87E-05	5.04E-04	2.49E-04
	6	3.54E-04	2.33E-04	2.00E-04	2.04E-04	3.88E-05	1.43E-04	1.93E-04
	7	1.10E-03	2.61E-04	3.94E-04	4.11E-04	4.75E-05	6.62E-05	3.74E-04
	8	5.32E-04	1.84E-04	2.39E-04	9.97E-05	6.26E-05	1.26E-04	2.42E-04
	9	2.10E-03	4.98E-04	1.18E-03	7.62E-04	1.09E-04	3.72E-04	1.08E-03
	10	1.22E-03	2.63E-04	4.92E-04	3.81E-04	4.97E-05	1.15E-04	4.56E-04
	11	7.11E-04	2.66E-04	2.77E-04	2.64E-04	1.34E-04	1.32E-04	2.81E-04
	12	7.54E-04	1.97E-04	2.83E-04	2.06E-04	2.77E-05	6.96E-05	2.80E-04
	Parcial sum of scores	42	16	23	19	12	15	21
RMSE	1	0.01818	0.01263	0.01108	0.01444	0.00535	0.00764	0.01094
	2	0.02467	0.01128	0.01654	0.01101	0.00693	0.00925	0.01522
	3	0.02152	0.02033	0.01817	0.01817	0.00390	0.01715	0.01431
	4	0.02936	0.01336	0.01790	0.01576	0.00404	0.00698	0.01691
	5	0.02470	0.02437	0.02020	0.02378	0.00654	0.02140	0.01504
	6	0.01843	0.01464	0.01357	0.01372	0.00571	0.01121	0.01304
	7	0.03256	0.01556	0.01910	0.01951	0.00636	0.00767	0.01824
	8	0.02260	0.01302	0.01484	0.00958	0.00725	0.01051	0.01461
	9	0.04491	0.02140	0.03292	0.02647	0.00957	0.01810	0.03087
	10	0.03423	0.01556	0.02128	0.01873	0.00646	0.01006	0.02004
	11	0.02615	0.01566	0.01600	0.01562	0.01067	0.01079	0.01576
	12	0.02690	0.01347	0.01614	0.01377	0.00482	0.00783	0.01569
	Parcial sum of scores	59	34	39	36	14	24	38

Table 5. Upper and lower limits of the classes of the values of each statistical factor applied to dimensionless moisture data found during the modeling of drying kinetics of potato pulp waste.

Class / *Score*	Statistical Factors							
	P (%)[a)]		*RMSE*[b)]		χ^2 [c)]		R^2 [d)]	
	L. L.[e)]	U. L.[f)]	L. L.	U. L.	L. L.	U. L.	L. L.	U. L.
1	0.8549	2.1038	0.00390	0.00902	1.75×10^{-5}	2.78×10^{-4}	99.7061%	99.9830%
2	2.1038	3.3527	0.00902	0.01415	2.78×10^{-4}	5.38×10^{-4}	99.4293%	99.7061%
3	3.3527	4.6016	0.01415	0.01928	5.38×10^{-4}	7.99×10^{-4}	99.1524%	99.4293%
4	4.6016	5.8505	0.01928	0.02440	7.99×10^{-4}	1.06×10^{-3}	98.8755%	99.1524%
5	5.8505	7.0994	0.02440	0.02953	1.06×10^{-3}	1.32×10^{-3}	98.5986%	98.8755%
6	7.0994	8.3483	0.02953	0.03465	1.32×10^{-3}	1.58×10^{-3}	98.3218%	98.5986%
7	8.3483	9.5972	0.03465	0.03978	1.58×10^{-3}	1.84×10^{-3}	98.0449%	98.3218%
8	9.5972	10.8461	0.03978	0.04491	1.84×10^{-3}	2.10×10^{-3}	97.7680%	98.0449%

[a]P(%) = relative mean error, [b]RMSE = root mean square error, [c]χ^2 = reduced chi-square, [d]R^2 = linear regression coefficient; [e]L.L. = lower limit of the class, [f]U.L. = upper limit of the class.

3.2 Drying kinetic modeling

The modeling of drying kinetic of PPW was performed based on the experimental values and statistical results shown in Tables 3 and 4. The R^2 values ranged from 97.76 to 99.98% and show that the Midilli, Diffusion Approximation, and Page models showed values closer to 1.0. However, the regression coefficient (R^2) alone is not a good criterion for selecting nonlinear models (Madamba et al., 1996). Therefore, the reduced chi-square (χ^2), root mean square error (RMSE), and relative mean error [P (%)] values were also considered.

The relative mean error values found, except for that obtained in experiment 9 with the Lewis model, were lower than 10%. P values (%) indicate the deviation of the observed values in relation to the curve estimated by the model (Kashani-

Table 6. Sum of scores obtained for the statistical factors of the theoretical models evaluated.

Statistical Factors	Models						
	Lewis	Page	Henderson & Pabis	Wang & Singh	Midilli	Diffusion Approch	Logarithmic
	Parcial sum the scores						
P (%)[a)]	56	44	43	35	13	36	38
RMSE[b)]	59	34	39	36	14	24	38
χ^{2}[c)]	42	16	23	19	12	15	21
R^{2}[d)]	51	16	23	20	12	15	17
Total Sum of *scores*	208	110	128	110	51	90	114

[a]P(%) = relative mean error, [b]RMSE = root mean square error, [c]χ^2 = reduced chi-square, [d] R^2 = linear regression coefficient.

Nejad et al., 2007). Values below 10% are recommended for model selection (Mohapatra & Rao, 2005). It was found that, in general, almost all models were adquate to the process when this factor was taken into account since the values ranged from 0.8549 to 10.8461, in which the Midilli model showed the lowest absolute values for P (%), while the Lewis model had the highest values for this statistical factor. All models showed very low χ^2 and RMSE values, and the Midilli model, once again had the lowest RMSE values.

In order to evaluate the models simultaneously in all experiments, based on the statistical factor values, the data was stratified according to the Sturges' Rule, thus obtaining classes and the range of values comprised in each class (Table 5). According to the Sturges' formula (Machado et al., 2010), the data were stratified into eight classes, each of which received a score from 1 to 8, and the lower the score, the better the adjustment of the model was (Table 6).

It was found that the Midilli and Diffusion Approach models were those with the lowest sum values, i.e., with the best fit to the drying data, considering the four statistical factors simultaneously. These results are in agreement with those found by Barbosa et al. (2007), who dried lemongrass leaves in thin layer with drying air temperature ranging from 40 to 80 °C and constant air speed. In that study, the Midilli and Page models showed the best adjustment. The Lewis model showed the highest scores in all statistical factors thus resulting in a higher sum, and therefore it was least adequate to the PPW drying process.

4 Conclusions

According to the experimental results, temperature is the factor that most affects the drying kinetics of PPW, leading to a reduction in the dehydration time. The variable air flow also affects the drying time of PPW. The new mathematical method developed in this study, based on scores according to the Sturges' Rule, precisely evaluated four statistical factors [P (%), χ^2, RMSE, and R^2], and thus it can significantly contribute to the selection of the most representative models for the drying process of PPW. Among the drying models studied, it was found that the Midilli and Diffusion Approach models were those with the lowest sum values, i.e., with the best adjustment to the drying kinetic data.

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