KINETIC AND MATHEMATICAL MODELING IN PUMPKIN FOAM-MAT DRYING

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ABSTRACT:

The aim of this research was to adjust mathematical models to the pumpkin foam drying process at different drying temperatures, noting the sensitivity of the parameter temperature. A dose of 8% w/w Emustab® were added to the pulp and the mixture was subjected to stirring. The formed foam was placed in the trays and subjected to drying at temperatures of 40, 50, 60, 70 and 80 °C. The average times to reach the water content equilibrium for 40, 50, 60, 70 and 80 °C were 1830, 930, 360, 270 and 150 min, respectively. The Midilli models, the Modified Midilli and the Logarithm fit to the experimental data of pumpkin pulp foam drying. Regardless of pumpkin foam-mat drying temperature, in relation to the sensitivity of the temperature parameter, it was noted that the Logarithm model is the most sensitive to the increase in the drying temperature compared with the other models. Within the same temperature, this model was observed to behave as the most sensitive, and the Henderson and Pabis model as the least sensitive.

KEYWORDS: mathematical modeling, pumpkin powder, water loss.

CINÉTICA E MODELAGEM MATEMÁTICA NA SECAGEM EM LEITO DE ESPUMA DE ABÓBORA

RESUMO:

Objetivou-se, com essa pesquisa, ajustar modelos matemáticos ao processo de secagem de espuma de abóbora, em diferentes temperaturas de secagem, observando a sensibilidade do parâmetro temperatura. Adicionou-se à polpa 8% m/m de Emustab®, sendo esta mistura submetida à agitação. A espuma formada foi colocada em bandejas e submetidas à secagem nas temperaturas de 40, 50, 60, 70 e 80 °C. O tempo médio para que se atingisse o teor de água de equilíbrio para 40, 50, 60, 70 e 80 °C foram de 1830, 930, 360, 270 e 150 min, respectivamente. Os modelos de Midilli, Midilli Modificado e Logarítmo se ajustaram satisfatoriamente aos dados experimentais da secagem da espuma de polpa da abóbora. Independentemente da temperatura de secagem de polpa de abóbora em leito de espuma, em relação a sensibilidade do parâmetro temperatura, observou-se que o modelo de Logarítmico é o mais sensível ao aumento da temperatura de secagem comparado aos demais modelos. Nesse sentido, observa-se que dentro de uma mesma temperatura esse modelo, também, comportou-se como o mais sensível, e o modelo de Henderson e Pabis comportou-se como o de menor sensibilidade.

PALAVRAS-CHAVE: modelos matemáticos, pó de abóbora, perda de água.

INTRODUCTION

Despite the high nutritional value of pumpkin, its consumption is not higher because of the difficulty in peeling and the large size of the fruit, which makes transportation and storage difficult (Alves et al., 2010). The use of vegetable

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by-products is of great importance due to its functional, technological and nutritional properties and cost savings for industries.

Among the technologies with potential for use in pumpkin post-harvest, the use of fruit pulp products based on dehydrated powder can become an economically viable alternative, since this process greatly reduces packaging costs, transport, storage and conservation.

According to Silva et al. (2008), the foam-mat drying is one of the techniques used for obtaining food products in powder, distinguished by being a method through which liquid or semi-liquid foods are transformed into stable foams, through vigorous stirring and the addition of foaming agents to then be dehydrated (Costa et al., 2011).

For the correct choice of temperature and drying time of agricultural products, the first step is the study of drying kinetics (Avhad and Marchetti, 2016). In addition, through mathematical modeling it is possible to simulate and size a drying system (Baptestini et al., 2015). The study of drying kinetics and mathematical modeling of agricultural products has been reported by several authors (Corrêa Filho et al., 2015; Costa et al., 2016; Méndez-Lagunas et al., 2017; Azeez et al., 2017).

Therefore, this study aimed to determine the drying curves in pumpkin foam-mat at different temperatures, by adjusting the mathematical drying models to experimental data obtained in the drying, determining the best adjusted model, and thus analyzing the sensitivity of the parameter temperature during drying for the models.

MATERIAL AND METHODS

Fruits used in the experiment were hybrid Japanese pumpkins (*Cucurbita moschata* Duch). For pulping, a centrifuge was used.

Before the drying process, 8% w/w of Emustab® were added to the pulp and the mixture was subjected to stirring in a mixer for 15 minutes to obtain the foam. After stirring, formed foam was placed in the trays forming a thin layer of about 7.0 mm thick. The drying process was carried out in laboratory scale dryer with air circulation, in which the temperature, speed and average relative humidity of the inlet air were 40, 50, 60, 70 and 80 °C, 5.6 m s^{-1} and 60% respectively. The choice of these temperatures was based on preliminary experiments and previous work on foam-mat drying.

The experiment was designed in a completely randomized design (CRD) with 4 replications and 5 treatments (temperatures). To adjust the mathematical models, linear and non-linear regression analysis was performed, using the Gauss Newton method and the software Statistica 5.0®. For sensitivity analysis, data were submitted to analysis of variance. Averages were compared using the Tukey test at 5% probability.

Drying models frequently used to describe the drying phenomenon were adjusted to the experimental data from pumpkin foam drying (Table 1).

Table 1. Mathematical models used to pumpkin foam drying modeling.

Model name	Model equation	
Henderson and Pabis	MR = a exp (-k t)	(1)
Logarithm	MR = a exp (-k t) + b	(2)
Midilli	MR = a exp (-k tn) + b t	(3)
Page	MR = exp (-k tn)	(4)
Modified Midilli	MR = exp (-k tn) + (b t)	(5)

they are:

t: drying time (min);

k: drying constant (min^{-1}); and,

a, b, n: coefficients of the models (dimensionless).

The moisture ratio (MR) was determined according to Eq. 6.

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (6)$$

They are:

Mt - water content at time t ($kg_a\ kg_{ms}^{-1}$);

Mo - initial water content, ($kg_a\ kg_{ms}^{-1}$); and,

Me - equilibrium moisture content ($kg_a\ kgm_s^{-1}$).

The experimental drying data were submitted to regression analysis and model selection was based on the coefficient of determination, of the average relative error and the estimated average error.

The mean relative deviation (MRD) and the standard error of estimation (SEE) were calculated according to Eqs 7 and 8:

$$MRD = \frac{100}{n}\sum_{i=1}^{n}\frac{|M_i - MR_i|}{M_i} \quad (7)$$

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(M_i - MR_i)^2}{GLR}} \quad (8)$$

they are:
Mi - observed value;
MRi -estimated value;
N -number of observed data; and,
GLR -degrees of freedom of the residue

After determining the moisture ratio, the data were used for the sensitivity analysis. One way to perform the model sensitivity analysis, varying each input parameter individually, while the others are held constant, was presented by McCuen and Willar (1986); these authors used the Relative Sensitivity Index (IS), shown below:

$$IS = \frac{\frac{R_1 - R_2}{R_{12}}}{\frac{I_1 - I_2}{I_{12}}} \quad (9)$$

The element sare:

IS - the model sensitivity index to the input parameter;

R_1 - the result obtained from the model for the smallest input value;

R_2 - the result obtained from the model for the biggest input value;

R_{12} - the average of the results obtained with the smallest and the biggest input value;

I_1 - the smallest input value;

I_2 - the biggest input value, and,

I_{12} - the average of the input values.

According to McCuen and Willard (1986), the IS value is the normalized change generated in the model output to a normalized change in inputting data, which allows comparison of the sensitivity to different magnitudes of input parameters representing a function of input parameters for a nonlinear response. The larger (in magnitude) the indexes obtained, the more sensitive the model will be to the parameter, since the values near zero indicate that the model does not show sensitivity to the parameter.

RESULTS AND DISCUSSION

Figure 1 shows the drying curves in pumpkin foam-mat drying in temperatures of 40, 50, 60, 70 and 80 °C. The analysis of these curves shows that the increase in temperature favors the reduction of the drying time. Prolonged drying can adversely affect product quality (Marfil et al., 2008), and is expensive. Thus, the results obtained in this study can provide a subsidy to make the best use of the binomial (temperature and drying time) feasible, making the drying process technically and economically viable.

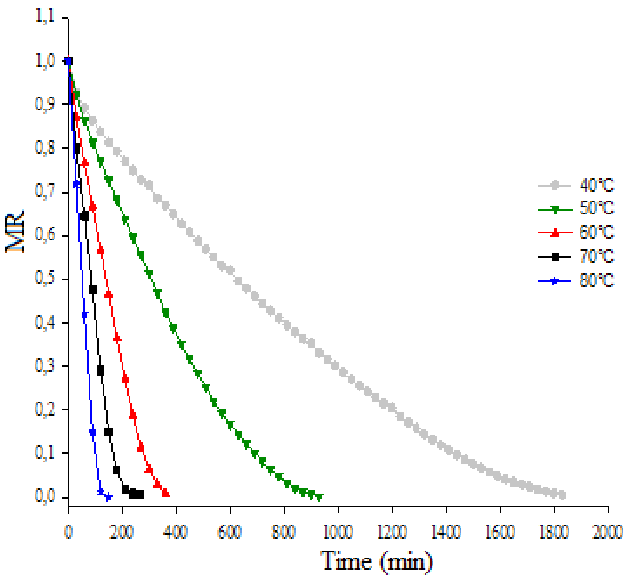

Figure 1. Drying curves of pumpkin pulp foam-mat at different temperatures (40, 50, 60, 70 and 80 °C)

In line with this observation are the studies by Melo et al. (2013), which searchthe mandacaru pulp foam-mat drying at different temperatures. The behavior has also been elucidated by Thuwapanichayanan et al. (2008) for the banana pulp foam-mat drying method, verifying that as the drying temperature increased, there was a reduction in processing time. Other studies involving the drying of agricultural products showed the same behavior: garlic (Madamba et al., 1996), eggplant (Ertekin and Yaldiz, 2004) and okra (Doymaz, 2005). This phenomenon is explained by the increased drying rate (Akpinar et al., 2003). The increased heat transfer potential between the air and the product layer (Ferreira et al., 2012) causes a loss of mass of the product due to the drying air.

The average time to reach water content equilibrium for 40, 50, 60, 70 and 80 °C were 1830, 930, 360, 270 and 150 min, respectively. Doymaz (2007), in studying the drying kinetics of pumpkin slices through forced air convection, observed that the time required to reach the equilibrium moisture at 50, 55 and 60 °C were 750, 390 and 270 min, respectively. This reduced time found by these authors to achieve the equilibrium water content is possibly due to the fact that the authors used a reduced amount of pumpkin pulp (150 g).

It is possible to show that drying occurred in two stages. In the first, there was a rapid reduction in water content; in the second, the reduction of the water content continued, however, in a slower way, thus characterizing a decreasing drying rate. A predominant physical mechanism along the drying process is suggested; there is a moisture diffusion process (Silva et al, 2009; Doymaz, 2007). In the final drying stage, the moisture migration rate from the inner to the upper surface is reduced (Rajkumar et al., 2007). This result, of a decreasing drying rate, is found in Akpinar et al. (2003) for pumpkin, Gogus and Maskan (1999) for okra, and Kaymak-Ertekin (2002) for capsicum.

Table 2 presents the summary of adjustments and statistical parameters of the Henderson and Pabis, Logarithm, Midilli, Page and Modified Midilli models adjusted to the experimental pumpkin foam drying data, the coefficients of determination (R^2), mean relative deviation (MRD), and the standard error of estimation (SE). Values below 10% for relative mean error (P) indicate good suitability for practical purposes (Mohapatra and Rao, 2005). The smaller the value of the standard error of the estimate (SE) the better the quality of the model's adjustment in relation to the observed data (Baptestini et al., 2015).

As a criterion for selecting the model that best represents the pumpkin pulp drying process, we used the coefficient of determination (R^2) and the average mean relative deviation (MRD) (Ertekin and Yaldiz, 2004), in which the lower the value of MRD is, the better the representation of the model employed becomes. The Midilli models, followed by the equations of Modified Midilli and the Logarithm, represented the experimental data of pumpkin foam drying in a satisfactory manner. Therefore, these models are the most adequate to describe the phenomenon of drying pumpkin pulp in foam bed, and consequently, can subsidize the design of industrial dryers.

The results presented in this study corroborate Lima et al. (2007), who evaluated various mathematical equations for drying kinetics of *facheiro* pulp (*Cereus squamosus*) and concluded that the Midilli equation showed a better R^2 and MRD. Similar performance was observed by Meisami--Asl et al. (2009), who studied the different mathematical models of thin layer drying kinetics of apple slices at temperatures from 40 to 80 °C, and concluded that the Midilli model best represented the drying experimental data. The results presented in this study corroborate Baptestini et al. (2015), who usedmathematical modeling of drying of soursop foam and concluded that it adjusted well to the experimental data of soursop foam drying.

The mean values of sensitivity were affected ($P < 0.05$) by the different temperatures for all the models. It was found, in general, for all temperatures, that the Logarithm model presented the highest mean values of sensitivity. In contrast, the Henderson and Pabis model, in general, presented the lowest mean values of sensitivity for all the evaluated temperatures.

Through the analysis of Table 3, it can be seen that the Logarithm model is the most sensitive to increased drying temperature compared to other models. Within the same temperature, with the exception of 40 °C, this model also behaves as the most sensitive. In contrast, the Henderson and Pabis model behaved as the least sensitive. However, we noted that the variation in sensitivity between models is very small ranging from 0.8537 to 1.0845 (27.03%) at 40 °C; 0.8936 to 1.0988 (22.96%) at 50 °C; 0.9073 to 1.1890 (31.05%) at 60 °C; 1.0168 to 1.2533 (23.26%) at 70 °C; and from 1.0312 to 1.4169 (37.4%) at 80 °C. It was found that there was a larger variation in sensitivity among the models at the temperature of 80 ° C.

Table 2. Parameters of the models used for the representation of experimental data and their respective coefficients of determination (R2), mean relative deviation (MRD), mean relative error (P) and the estimated average error (SE)

Models	T (°C)	Parameters[1]				R^2	MRD	P	SE
		K	a	n	b				
Henderson and Pabis	40	$1.3345\ 10^{-3}$	1.0326	-	-	0.9848	0.0969	104.76	0.0491
	50	$2.8713\ 10^{-3}$	1.0728	-	-	0.9836	0.0490	156.73	0.0498
	60	$6.7385\ 10^{-3}$	1.0966	-	-	0.9793	0.0640	181.24	0.0667
	70	$1.1543\ 10^{-2}$	1.1052	-	-	0.9819	0.0629	217.91	0.2684
	80	$1.8280\ 10^{-2}$	1.0898	-	-	0.9749	0.0774	2351.19	0.0856
Logarithm	40	$6.1506\ 10^{-4}$	1.4351	-	-0.4832	0.9995	0.0092	19.92	0.0093
	50	$1.5636\ 10^{-3}$	1.3436	-	-0.3438	0.9992	0.0122	46.56	0.0125
	60	$2.9916\ 10^{-3}$	1.5753	-	-0.5572	0.9979	0.0203	71.07	0.0216
	70	$7.8188\ 10^{-3}$	1.2461	-	-0.1895	0.9931	0.0389	144.80	0.2773
	80	$9.4026\ 10^{-3}$	1.4526	-	-0.4168	0.9938	0.0286	1783.16	0.0452
Midilli	40	$6.7626\ 10^{-4}$	0.9498	1.0301	-1.20 10-4	0.9994	0.0097	21.09	0.0099
	50	$5.2958\ 10^{-4}$	0.9618	1.2280	-1.18 10-4	0.9995	0.0094	27.61	0.0098
	60	$6.9891\ 10^{-4}$	0.9687	1.3703	-3.07 10-4	0.9989	0.0148	39.95	0.0161
	70	$5.6859\ 10^{-4}$	0.9636	1.6011	-6.96 10-5	0.9984	0.0186	57.91	0.4166
	80	$1.1792\ 10^{-3}$	0.9731	1,5978	-3.55 10-4	0.9980	0.4084	718.68	0.0277
Page	40	$2.7849\ 10^{-4}$	-	1.2263	-	0.9911	0.0007	68.98	0.0376
	50	$3.6406\ 10^{-4}$	-	1.3293	-	0.9957	0.0277	81.09	0.0282
	60	$4.7335\ 10^{-4}$	-	1.4927	-	0.9953	0.0308	73.54	0.0321
	70	$7.9555\ 10^{-4}$	-	1.5462	-	0.9975	0.0234	49.42	0.3051
	80	$1.1044\ 10^{-3}$	-	1.6443	-	0.9962	0.0303	550.41	0.0335
Modified Midilli	40	$0.0025 10^{-3}$	-	0.8260	-1.70 10-4	0.9991	0.0121	28.02	0.0122
	50	$0.0012 10^{-3}$	-	1.0907	-1.59 10-4	0.9992	0.0120	37.56	0.0123
	60	$0.0014 10^{-3}$	-	1.2390	-3.97 10-4	0.9986	0.0165	36.87	0.0184
	70	$0.0010 10^{-3}$	-	1.4768	-1.01 10-4	0.9980	0.0210	63.86	0.3082
	80	$0.0019 10^{-3}$	-	1.4934	-4.35 10-4	0.9977	0.0236	818.64	0.0609

[1] Determination in quadruplicate for each temperature

Table 3. Sensitivity Index (SI) of Henderson and Pabis, Page, logarithm, Midilli and Modified Midilli models to the temperature parameter

Models	SI - Sensitivity Index				
	Temperatures (°C)				
	40	50	60	70	80
Henderson and Pabis	0.8537d	0.8936c	0.9073d	1.0168d	1.0312d
Page	0.9009c	0.9520b	1.0037c	1.0950c	1.1819c
Logarithm	1.0647b	1.0988a	1.1890a	1.2533a	1.4169a
Midilli	1.0681b	1.0724a	1.1386b	1.1410b	1.2935b
Modified Midilli	1.0845a	1.0857a	1.1507b	1.1523b	1.3031b

* Means followed with the same letter, in the column, at different temperatures, do not differ according to Tukey's test at 5% significance level.

CONCLUSION

1. Increasing temperature favors the reduction of drying time.

2. The Midilli model followed by the Modified Midilli equation and the Logarithmic model represented the experimental data of pumpkin pulp foam drying satisfactorily.

3. The Logarithmic model is more sensitive to increased drying temperature either within a same temperature as well as between different temperatures, while the Pabis and Henderson model has an opposite behavior, as the least sensitive.

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