ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
v.20, n.7, p.672-677, 2016
Campina Grande, PB, UAEA/UFCG – http://www.agriambi.com.br

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v20n7p672-677

Drying kinetics of atemoya pulp

Plúvia O. Galdino[1], Rossana M. F. de Figueirêdo[1], Alexandre J. de M. Queiroz[1] & Pablícia O. Galdino[2]

[1] Universidade Federal de Campina Grande/Centro de Tecnologia e Recursos Naturais/Unidade Acadêmica de Engenharia Agrícola. Campina Grande, PB. E-mail: pluviagaldino@hotmail.com (Corresponding author); rossana@deag.ufcg.edu.br; alex@deag.ufcg.edu.br
[2] Universidade Estadual da Paraíba/Centro de Ciências e Tecnologia/Departamento de Química. Campina Grande, PB. E-mail: publiciaog@hotmail.com

---

Key words:
Annona cherimoya Mill. x *Annona squamosa* L.
dehydration
modeling

ABSTRACT

This study was conducted in order to obtain drying curves of whole atemoya pulp through the foam-mat drying method. The suspension was prepared with whole atemoya pulp mixed with 2% of Emustab® and 2% of Super Liga Neutra® with mixing time of 20 min, and dried in a forced-air oven at different temperatures (60; 70 and 80 °C) and thicknesses of the foam layer (0.5, 1.0 and 1.5 cm). The drying rate curves were plotted against the water content ratio and the semi-theoretical models of Henderson & Pabis, Page and Midilli were used. All tested models showed coefficient of determination (R^2) above 0.993, and the Midilli model showed the best fit for all conditions. Drying curves were affected by temperature and layer thickness.

Palavras-chave:
Annona cherimola Mill. x *Annona squamosa* L.
desidratação
modelagem

Cinética de secagem de polpa de atemoia

RESUMO

Este trabalho foi desenvolvido com o objetivo de se obter curvas de secagem a partir de uma suspensão da polpa integral de atemoia através do método de secagem em camada de espuma (*foam mat drying*). A suspensão foi elaborada com polpa integral de atemoia e adição de 2% de Emustab® e 2% de Super Liga Neutra® com tempo de batimento de 20 min e desidratada em estufa com circulação de ar forçado em diferentes temperaturas (60; 70 e 80 °C) e espessuras da camada de espuma (0,5; 1,0 e 1,5 cm). As curvas de cinética de secagem foram traçadas quanto à razão de água e aplicados os modelos semiteóricos de Henderson & Pabis, Page e Midilli. Todos os modelos testados apresentaram coeficiente de determinação (R^2) acima de 0,993 enquanto o modelo de Midilli foi o que apresentou os melhores ajustes para todas as condições. As curvas de secagem foram influenciadas pela temperatura e pela espessura da camada.

Ref. 099-2015 – Received 30 Jun, 2015 • Accepted 9 May, 2016 • Published 3 Jun, 2016

INTRODUCTION

Atemoya is a fruit of a plant from the *Annonaceae* family; it is a hybrid resulting from the cross between sugar-apple (*A. squamosa* L.) and cherimoya (*A. cherimola* Mill.) (Medeiros et al., 2009). It has intense metabolic activity and is very perishable due to its high water content. Other unfavorable factors of atemoya are the rapid softening of the pulp and the darkening of its skin, as the main problems that affect its commercialization (Yamashita et al., 2002).

Drying is a commercial process widely used to preserve the quality of agricultural products with the objective of promoting long storage periods without significant losses during the process (Martinazzo et al., 2010). Foam-mat drying is a process that helps to preserve the nutrients of the pulp for prolonged period and immediately after dehydration; in addition, the powder can be reconstituted as juice and/or used as ingredient for the preparation of beverages and food (Kadam et al., 2010)

Although there is a great interest in its comprehension, drying is still one of the least understood operations, due to the complexity of the phenomena involved in the simultaneous transfer of heat, mass and amount of movement in the solid during the process (Kingsly et al., 2007). Researchers study the drying process based on the external conditions of air, relative humidity and temperature. Thus, it requires mathematical models that represent the reduction in water content ratio of the products during the process (Alves, 2010). The use of mathematical models to represent the process is important, because the generated information is utilized in the development of devices and prediction of drying times (Silva et al., 2009).

Thus, this study aimed to dehydrate a suspension of atemoya through the foam-mat drying, for different values of layer thickness (0.5, 1.0 and 1.5 cm) and temperatures (60, 70 and 80 °C), and study the adjustment of drying mathematical models to the experimental data.

MATERIAL AND METHODS

The raw material consisted of whole atemoya pulp, from the municipality of Petrolina, PE, and Emustab® and Super Liga Neutra®, both obtained from the market, in the municipality of Campina Grande-PB, Brazil.

Initially, Emustab® and Super Liga Neutra®, both at the concentration of 2%, were added to the whole atemoya pulp. This mixture was taken to a planetary mixer for homogenization for 20 min, in order to form a stable suspension to be dehydrated in layer for the evaluation of its drying kinetics.

The suspension was spread on stainless-steel trays forming a foam layer with different thicknesses (0.5, 1.0 and 1.5 cm), measured with a caliper. Then, they were placed in a forced-air oven at temperatures of 60, 70 and 80 °C, defined by preliminary tests. The drying kinetics curves of the suspension were obtained by weighing the trays until constant mass, in regular intervals. Water content ratios (Eq. 1) were calculated based on the experimental data.

$$RX = \frac{X - X_0}{X_0 - X_e} \tag{1}$$

where:

RX - water content ratio, dimensionless;
X - water content, dry basis;
Xe - equilibrium water content, dry basis; and,
Xo - initial water content, dry basis.

The semi-theoretical models of Henderson & Pabis (Eq. 2), Page (Eq. 3) and Midilli (Eq. 4) were applied for the determination of the drying curves.

- Henderson & Pabis

$$RX = a \cdot \exp\left(-kt\right) \tag{2}$$

where:

RX - water content ratio, dimensionless;
a - dimensionless constant of the equation;
k - constant of the equation, L h^{-1}; and,
t - time, min.

- Page

$$RX = \exp\left(-kt^n\right) \tag{3}$$

where:

RX - water content ratio, dimensionless;
k - constant of the equation, L h^{-1};
n - constant of the equation; and,
t - time, min.

- Midilli

$$RX = a \cdot \exp\left(-kt^n\right) + bt \tag{4}$$

where:

RX - water content ratio, dimensionless;
a - constant of the equation, dimensionless;
k - constant of the equation, L h^{-1};
b - constant of the equation, dimensionless;
n - constant of the equation; and,
t - time, min.

The model that best adjusted to the experimental data was evaluated through the parameters coefficient of determination (R^2) and mean quadratic deviation (Eq. 5).

$$MQD = \frac{\sqrt{\sum\left(RX_{pred} - RX_{exp}\right)^2}}{n} \tag{5}$$

where:

MQD - mean quadratic deviation;
RX_{pred} - water content ratio predicted by the model;
RX_{exp} - experimental water content ratio; and,
n - number of observations.

RESULTS AND DISCUSSION

Figure 1 shows the kinetics of foam-mat drying for thicknesses of 0.5, 1.0 and 1.5 cm, at temperatures of 60, 70 and 80 °C, in the dimensionless form of the water content

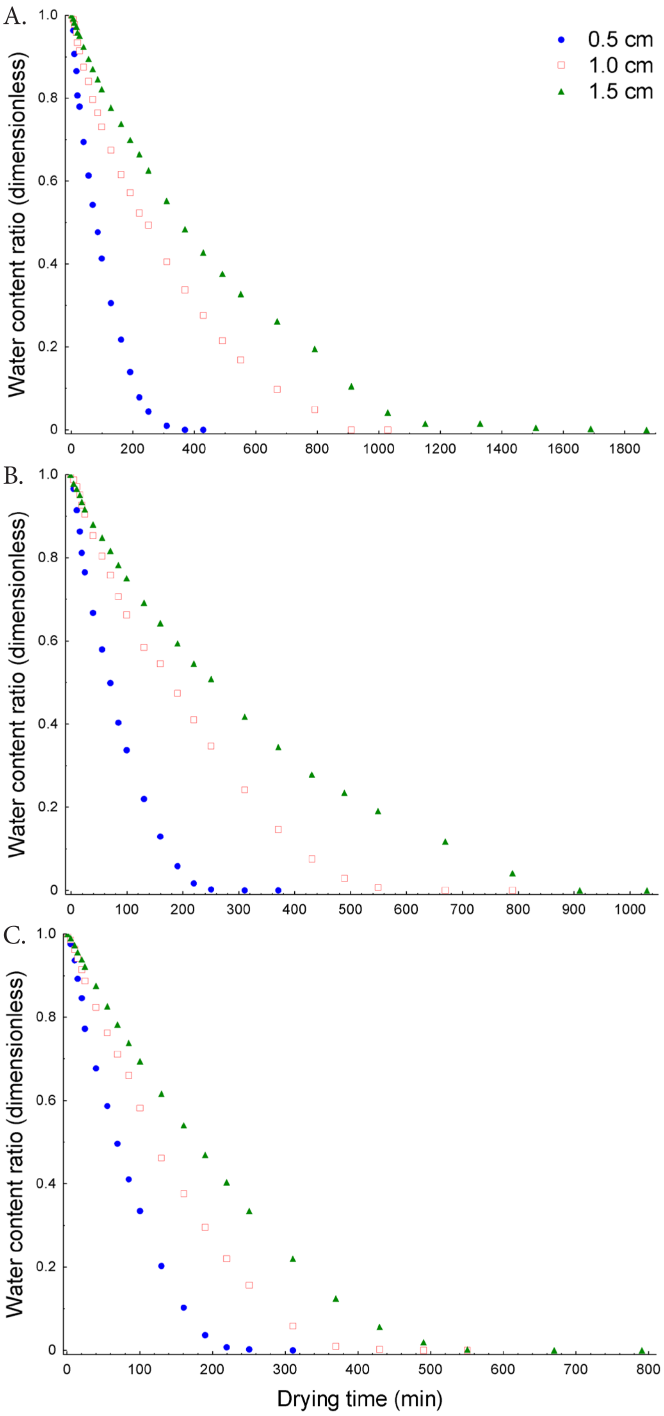

Figure 1. Drying curves of atemoya foam at temperatures of 60 (A), 70 (B) and 80 (C) °C and foam layer thicknesses of 0.5, 1.0 and 1.5 cm

(water content ratio) as a function of the drying time; the foams showed initial water content of 72.13% (d.b.).

The drying process of all samples was faster for smaller thicknesses (0.5 cm) at the three studied temperatures (60, 70 and 80 °C), and the drying times were equal to 420, 380 and 310 min, with final water contents of 13.23, 8.96 and 7.37% (w.b.), respectively. For the thickness of 1.0 cm, at the three temperatures, the drying times were equal to 1,000, 800 and 550 min, with final water contents of 12.48, 7.21 and 5.82% (w.b.), while for the thickness of 1.5 cm the drying times were 1,850, 1,100 and 850 min with final water contents of 12.26, 5.55 and 4.25% (w.b.), at the temperatures of 60, 70 and 80 °C, respectively.

All drying curves were influenced by the thickness of the layer. This behavior was also observed by Raharitsifa & Ratti (2010), who applied lyophilization on apple juice foam prepared with 3% of egg albumin in different thicknesses (1, 4 and 6 cm) and observed that thickness has a significant impact on foam drying, i.e., the smaller the thickness, the shorter is the drying time.

During the drying process, besides the influence of foam layer thickness, there was the interference of drying air temperature, since the temperature of 80 ºC led to the shortest drying times for the thicknesses of 0.5, 1.0 and 1.5 cm, which were equal to 310, 550 and 850 min, respectively. At the temperature of 70 ºC, the drying times were equal to 380, 800 and 1,100 min, for the three thicknesses, while at 60 ºC the drying times were 420, 1,000 and 1,850 min.

The influence of temperature increment on the drying time is expected and reported by Krasaekoopt & Bhatia (2012), who also observed reduction in the drying time with the increase in temperature, when drying yogurt through foam-mat drying. These differences in drying times occur mainly because of the different temperatures applied and the characteristics of each product. Melo et al. (2013) observed the influence of drying temperature and foam layer thickness in foam-mat drying of cactus (*Cereus jamacaru*) fruit, and the drying occurred in a shorter time at the highest temperature for the smallest thickness.

For all studied temperatures and thicknesses, there was greater loss of water at the beginning of the process, with subsequent decrease in the rate of migration of water from the inside to the surface. As a result, lower drying rates were observed in the final drying stage. Melo et al. (2013), studying the drying kinetics of cactus (*Cereus jamacaru*) fruit pulp, observed that the water ratio reduced rapidly in the beginning of the process and slowly as the drying time increased, for the studied temperatures.

Table 1 shows the coefficients of the models of Page, Henderson & Pabis and Midilli for the drying temperatures of 60, 70 and 80 °C and foam layer thicknesses of 0.5, 1.0 and 1.5 cm, as well as the coefficients of determination (R^2) and the mean quadratic deviations (MQD). For the three thicknesses, all models can be used to represent the foam-mat drying of atemoya pulp, because they showed coefficients of determination (R^2) higher than 0.99 and mean quadratic deviations below 0.05.

For the thickness of 0.5 cm, among the tested models, Midilli showed the best fit to the experimental data, with the highest coefficients of determination and the lowest mean quadratic deviations. Furtado et al. (2010) studied the drying kinetics of 'ceriguela' (*Spondias purpurea*) pulp, at temperatures of 60, 70 and 80 ºC, and observed that the Midilli model was satisfactory. According to Azzouz et al. (2002), the parameter *n* in the Page model depends on the drying air speed and initial water content of the product and *k* depends on temperature and initial water content. The obtained *k* values decreased with the increase in drying temperature, while the parameter *n* increased as temperature increased.

Table 1. Parameters, coefficients of determination (R^2) and mean quadratic deviations (MQD) of the models adjusted to the drying curves of atemoya foam with 2% of Emustab®, 2% of Liga Neutra® and mixing time of 20 min, for foam layer thicknesses of 0.5, 1.0 and 1.5 cm at different temperatures

Thickness (cm)	Model	Temp. (ºC)	Parameter				R^2	MQD
			A	K	N	B		
0.5	Page	60		0.0065	1.0792	-	0.9980	0.0386
		70		0.0053	1.1674	-	0.9983	0.0290
		80		0.0034	1.2630	-	0.9983	0.0251
	Henderson & Pabis	60	1.0073	0.0096	-	-	0.9974	0.0278
		70	1.0309	0.0116	-	-	0.9964	0.0352
		80	1.0577	0.0125	-	-	0.9943	0.0416
	Midilli	60	0.9819	0.0062	1.0746	-0.00008	0.9988	0.0017
		70	0.9842	0.0049	1.1713	-0.00008	0.9989	0.0024
		80	0.9935	0.0038	1.2303	-0.00012	0.9989	0.0020
1.0	Page	60	0.0024	1.0407	-	-	0.9983	0.0266
		70	0.0016	1.1815	-	-	0.9973	0.0381
		80	0.0013	1.3015	-	-	0.9989	0.0293
	Henderson & Pabis	60	1.0020	0.0030	-	-	0.9981	0.0212
		70	1.0266	0.0046	-	-	0.9948	0.0386
		80	1.0505	0.0066	-	-	0.9940	0.0446
	Midilli	60	1.0017	0.0038	0.9429	-0.00009	0.9996	0.0007
		70	0.9853	0.0016	1.1652	-0.00006	0.9983	0.0017
		80	0.9868	0.0012	1.3070	-0.00004	0.9994	0.0049
1.5	Page	60	0.0012	1.0802	-	-	0.9975	0.0880
		70	0.0019	1.0679	-	-	0.9981	0.0364
		80	0.0009	1.2865	-	-	0.9982	0.0404
	Henderson & Pabis	60	1.0135	0.0021	-	-	0.9971	0.0360
		70	1.0017	0.0029	-	-	0.9975	0.0249
		80	1.0443	0.0046	-	-	0.9931	0.0460
	Midilli	60	0.9861	0.0009	1.1164	-0.00002	0.9989	0.0018
		70	0.9890	0.0025	0.9997	-0.00008	0.9997	0.0007
		80	0.9871	0.0009	1.2802	-0.00005	0.9989	0.0022

Giraldo-Zuniga et al. (2010) studied the drying kinetics of sliced cupuaçu (*Theobroma grandiflora*) pulp, at temperatures of 50, 60 and 70 ºC, and observed variation in the parameters *k* and *n* in relation to the studied temperatures in the model of Page. Alexandre et al. (2009) studied the drying of sliced pineapple (*Ananas comosus* L.), cv. 'Pérola', at temperatures of 50, 60, 70 and 80 ºC, and obtained $R^2 > 0.97$ for the model of Page.

In the model of Henderson & Pabis, the values of the parameter *k* increased with the increment in temperature. This behavior can be observed with the parameter *a* and this fact occurred because the drying curves were very close to each other.

The values of *k* and *n* for the Midilli model decreased and increased with the increment in temperature, respectively. Madureira et al. (2011), adjusting the drying data of the formulation of cactus pear (*Opuntia fícus-indica* Mill.) pulp mixed with 25% of modified starch, highlight that *n* values increased as temperature increased.

For the thickness of 1.0 cm, in the three models, the parameter *k* decreased with the increase in temperature for the models of Page and Midilli, while the opposite occurred for the model of Henderson & Pabis. For the parameter *n*, there was an increase with the increment in temperature. Perez et al. (2013) observed that the model of Page adjusted well to the experimental data of drying of 'cupuaçu' (*Theobroma grandiflorum*) pulp for the studied treatments, showing coefficient of determination (R^2) higher than 0.99 and mean percent errors lower than 8.5%; thus, it can be used in the prediction of cupuaçu pulp drying kinetics. Among the tested models, Midilli showed the best adjustments, which is confirmed by the coefficients of determination (R^2) above 0.99 and mean quadratic deviations below 0.05.

For the thickness of 1.5 cm, in the three models used, the parameters *k* and *n* did not show a defined behavior as temperature increased in the models of Page and Midilli, and the parameter *k* increased with the increment in temperature in the model of Henderson & Pabis. Santos et al. (2010) analyzed the drying kinetics of starfruit (*Averrhoa carambola* L.) at the temperatures of 50, 60 and 70 ºC and observed that the model of Page showed the best fit for the experimental data, with the highest R^2 and the lowest relative mean error. Among the tested models, Midilli showed the best fits, with $R^2 > 0.98$, and the lowest MQD, all below 0.09.

Figure 2 shows the drying kinetics curves for atemoya pulp foam at different temperatures and foam layer thicknesses of 0.5, 1.0 and 1.5 cm, fitted to the Midilli model.

As shown in Figure 2A, the experimental data are close to the curves established by the model and the drying temperature influences the kinetics, indicating the tendency that the higher the temperature, the shorter the drying time. There are small differences between the curves of 70 and 80 ºC, with greater distance from the curve of 60 ºC.

According to Figure 2B and 2C, the experimental data are close to the curves predicted by the model and the loss of water is more intense in the beginning of the drying. There was influence of temperature on the drying curves, which indicates that the higher the temperature, the faster is the drying. Sousa et al. (2011) also obtained excellent accuracy using the Midilli model

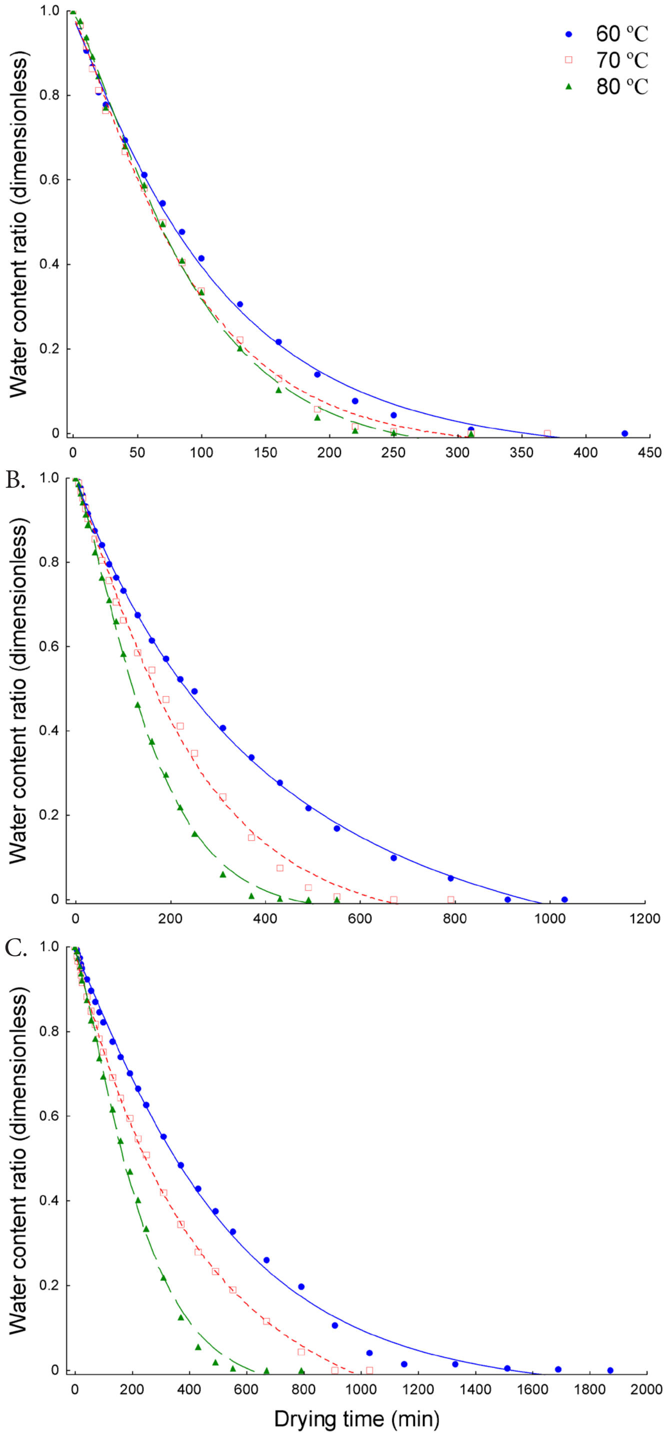

Figure 2. Drying curves in atemoya foam layer for layer thicknesses of 0.5 (A), 1.0 (B) and 1.5 (C) cm, at different drying temperatures, adjusted to the Midilli model

in the prediction of drying data in a thin layer of oiti (*Opuntia fícus-indica* Mill.) pulp at the temperatures of 50, 60 and 70 ºC.

CONCLUSIONS

1. The drying curves were influenced by temperature and layer thickness, with gradual reduction in the drying times under the effect of higher drying air temperatures and smaller layer thicknesses.

2. The Midilli model showed the best adjustment for all studied conditions.

LITERATURE CITED

Alexandre, H. V.; Gomes, J. P.; Barros Neto, A. L.; Silva, F. L. H. da; Almeida, F. de A. C. Cinética de secagem de abacaxi c.v. pérola em fatias. Revista Brasileira de Produtos Agroindustriais, v.11, p.123-128, 2009. http://dx.doi.org/10.15871/1517-8595/rbpa.v11n2p123-128

Alves, S. B. Estudo experimental da cinética de secagem do abacate (*Persea America* Mill.). João Pessoa: Universidade Federal da Paraíba, 2010. 1102p. Dissertação Mestrado

Azzouz, S.; Guisan, A.; Jomaa, W.; Belghith, A. Moisture diffusivity and drying kinetic equation of convective drying of grapes. Journal of Food Engineering, v.55, p.323-330, 2002. http://dx.doi.org/10.1016/S0260-8774(02)00109-7

Furtado, G. F.; Silva, F. S.; Porto, A. G.; Santos, P. Secagem de polpa de ceriguela pelo método de camada de espuma. Revista Brasileira de Produtos Agroindustriais, v.12, p.9-14, 2010. http://dx.doi.org/10.15871/1517-8595/rbpa.v12n1p9-14

Giraldo-Zuniga, A. D.; Arévalo-Pinedo, A.; Silva, A. F.; Silva, P. F.; Valdes-Serra, J. C.; Pavlak, M. C. M. Datos experimentales de la cinética del secado y del modelo matemático para pulpa de cupuaçu (*Theobroma grandiflorum*) en rodajas. Ciência e Tecnologia de Alimentos, v.30, p.179-182, 2010. http://dx.doi.org/10.1590/S0101-20612010000100027

Kadam, D. M.; Wilson, r. A.; Kaur, S. Determination of biochemical properties of foam-mat dried mango powder. Journal of Food Science and Technology, v. 45, p.1626-1632, 2010. http://dx.doi.org/10.1111/j.1365-2621.2010.02308.x

Kingsly, R. P.; Goyal, R. K.; Manikantan, M. R.; Ilyas, S. M. Effects of pretreatments and drying air temperature on drying behaviour of peach slice. International Journal of Food Science & Technology, v.42, p.65-69, 2007. http://dx.doi.org/10.1111/j.1365-2621.2006.01210.x

Krasaekoopt, W.; Bhatia, S. Production of yogurt powder using foam-mat drying. AU Journal of Technology, v.15, p.166-171, 2012.

Madureira, I. A.; Figueirêdo, R. M. F. de; Queiroz, A. J. de M.; Silva Filho, E. D. Cinética de secagem da polpa do figo-da-índia. Revista Brasileira de Produtos Agroindustriais, v.13, p.345-354, 2011. http://dx.doi.org/10.15871/1517-8595/rbpa.v13n4p345-354

Martinazzo, A. P.; Melo, E. C.; Corrêa, P. C.; Santos R. H. S. Modelagem matemática e parâmetros qualitativos da secagem de folhas de capim-limão (*Cymbopogon citratus* (DC.) Stapf). Revista Brasileira de Plantas Medicinais, v.12, p.488-498, 2010. http://dx.doi.org/10.1590/S1516-05722010000400013

Medeiros, P. V. Q.; Mendonça, V.; Maracajá, P. B.; Aroucha, E. M. M.; Pereira, R. G. Physical-chemical characterization of atemóia fruit in different maturation stages. Revista Caatinga, v.22, p.87-90, 2009.

Melo, K. S.; Figueirêdo, R. M. F. de; Queiroz, A. J. de M.; Fernandes, T. K. S.; Bezerra, M. C. T. Secagem em camada de espuma da polpa do fruto do mandacaru: experimentação e ajustes de modelos matemáticos. Revista Caatinga, v.26, p.9-17, 2013.

Perez, L. G.; Oliveira, F. M. N.; Andrade, J. S.; Moreira Filho, M. Cinética de secagem da polpa cupuaçu (*Theobroma grandiflorum*) pré desidratada por imersão- impregnação. Revista Ciência Agronômica, v.44, p.102-106, 2013. http://dx.doi.org/10.1590/S1806-66902013000100013

Raharitsifa, N.; Ratti, C. Foam-mat freeze-drying of apple juice Part 1: Experimental data and ann simulations. Journal of Food Process Engineering, v.33, p.268-283, 2010. http://dx.doi.org/10.1111/j.1745-4530.2009.00400.x

Santos, C. T.; Bonomo, R, F.; Chaves, M. A.; Fontan, R. C. I.; Bonomo, P. Cinética e modelagem da secagem de carambola (*Averrhoa carambola* L.) em secador de bandeja. Acta Scientiarum Technology, v.32, p.309-313, 2010.

Silva, A. S. A.; Melo, K. S.; Alves, N. M.; Fernandes, T. K. S.; Farias, P. A. Cinética de secagem em camada fina da banana maçã em secador de leito fixo. Revista Brasileira de Produtos Agroindustriais, v.11, p.129-136, 2009. http://dx.doi.org/10.15871/1517-8595/rbpa.v11n2p129-136

Sousa, F. C.; Sousa, E. P.; Silva, L. M. M.; Martins, J. J. A.; Gomes, J. P.; Rocha, A. P. T. Modelagem matemática para descrição da cinética de secagem de polpa de oiti. Revista Educação Agrícola Superior, v.26, p.108-112, 2011.

Yamashita, F.; Miglioranza, L. H. S.; Miranda, L. A.; Souza, C. M. A. Effects of packaging and temperature on postharvest of atemoya. Revista Brasileira de Fruticultura, v.24, p.658-660, 2002. http://dx.doi.org/10.1590/S0100-29452002000300021