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Drying kinetics of 'babassu' mesocarp

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A B S T R A C T

'Babassu' mesocarp flour has been used by the pharmaceutical, human food and animal feed industries. However, there is lack of standardization in the production, as well as absence of information on the management of the product's quality. Thus, the objective of this study was to dry the 'babassu' mesocarp in forced-air oven and solar dryer, adjust different mathematical models to the experimental data, as well as to quantify the levels of proteins and crude fiber of the produced flour. The criteria for the adjustment were the coefficient of determination, magnitude of the mean relative error, standard deviation of estimate and the residual distribution trend. Drying in the shortest time occurred in oven at 60 °C (370 min), leading to water content of 4.62%, while in the solar dryer the final water content was 8.07% in 6 days. The mathematical model Two Terms showed the best fit to the experimental data for oven drying and the Midilli model showed the best fit in solar dryer. There was an increase in protein content with the drying in solar dryer and oven at 40, 50 and 60 °C (1.36, 1.33, 1.15 and 1.37%, respectively) in relation to fresh mesocarp (0.88%). Drying in both oven and solar dryer promoted increase of protein in the flour.

Palavras-chave:
Orbignya phalerata Mart.
modelos matemáticos
proteína

Cinética de secagem do mesocarpo de babaçu

R E S U M O

A farinha do mesocarpo do babaçu tem sido utilizada pelas indústrias farmacêuticas e de alimentação humana e animal. Contudo, há falta de padronização na produção, bem como ausência de informações do manejo sobre a qualidade do produto. Deste modo, objetivou-se, no trabalho, secar o mesocarpo do babaçu em estufa de ventilação forçada de ar e secador solar, ajustar diferentes modelos matemáticos, bem como quantificar os teores de proteínas e fibras brutas da farinha produzida. Foram usados, como critério do ajuste, o coeficiente de determinação, a magnitude do erro médio relativo, o desvio-padrão da estimativa e a tendência de distribuição dos resíduos. A secagem em menor tempo ocorreu em estufa a 60 ºC (370 min) obtendo-se teor de água de 4,62%, enquanto no secador solar foi em 6 dias com teor de água final de 8,07%. O modelo Dois Termos foi o que melhor se ajustou aos dados experimentais para secagem em estufa e o modelo Midilli em secador solar. Houve um aumento do teor de proteína com a secagem em secador solar e estufa a 40, 50 e 60 ºC (1,36; 1,33; 1,15 e 1,37%, respectivamente) em relação ao mesocarpo in natura (0,88%). A secagem em estufa e em secador solar proporcionou incremento de proteína na farinha.

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Introduction

The potentials of 'babassu' palm are innumerous, from energy generation to handicraft. Its fruit has economic potential for technological and industrial purposes, and can produce approximately 64 products (BRASIL, 2009a); for instance, the mesocarp is used in the pharmaceutical (Barros, 2011), animal feed and human food industries (Souza et al., 2011; Rostagno et al., 2011).

'Babassu' flour can be obtained through natural or artificial drying, and its quality depends on various factors including raw material, drying method, techniques of procedure and form of storage (Borges et al., 2009).

In the rural communities of the Amazon, 'babassu' flour is not a valued product due to the lack of standardization in the manufacturing process. In general, flour production is made by family activities in rudimentary molds with quality evaluation through color and taste of the product. Drying is performed on concrete floors using natural ventilation, and the water content is controlled empirically (Mendonça et al., 2015). There is little information in the literature on the drying kinetics or even about the effect of the management of 'babassu' mesocarp on the quality of the produced flour.

Thus, obtaining a drying model that satisfactorily represents the experimental data is of fundamental importance to minimize the alterations promoted by the drying, consequently leading to good quality products (Mendonça et al., 2015).

This study aimed to describe the drying kinetics of 'babassu' mesocarp using a solar dryer and forced-air oven, fit different models to the experimental data and quantify protein and fiber in the produced flours after drying.

Material and Methods

'Babassu' (*Orbignya phalerata* Mart.) fruits were collected in areas surrounding the municipality of Ji-Paraná, Rondônia. After collection, the fruits were washed and maintained in water with hypochlorite at 1% for about 20 min, to sanitize the fruits and homogenize the water content. Then, the epicarp was removed using a stainless-steel knife and the mesocarp was separated from the rest of the fruit using a hammer.

The drying kinetics procedure used mesocarp pieces of approximately 3 cm arranged in monolayer and stored in wire baskets, with four replicates for each tested drying method.

Drying occurred in two forms: (i) drying in forced-air oven at speed of 3.0 m s^{-1} with control of temperatures of 40, 50 and 60 °C and weighings at regular time intervals until reaching equilibrium water content (5, 10, 15, 20, 30 and 60 min); and (ii) drying in the solar dryer described by Mendonça et al. (2015), with weighing every 24 h and daily record of temperature and relative humidity using a digital thermo-hygrometer during the day. The initial and final water contents were determined through the standard method of the oven at 105 ± 3 °C, for 24 h, in four replicates (BRASIL, 2009b).

The drying curves were obtained by the conversion of the data relative to water loss into the dimensionless parameter moisture ratio (RX). The moisture ratio of the 'babassu' mesocarp for the different drying conditions was determined using Eq.1.

$$RX = \frac{X - Xe}{Xi - Xe} \tag{1}$$

where:

RX - moisture ratio, dimensionless;
X - moisture content, g;
Xi - initial moisture content, g; and,
Xe - equilibrium moisture content, g.

The mathematical models were fitted to RX values using nonlinear regression through the Quasi-Newton method (Table 1), with the aid of the program Statistics 7.0® (Statsoft Inc, 2007).

The criteria used to determine the best fit of the models to the experimental data were the coefficient of determination (R^2), magnitude of the mean relative error (P), standard deviation of the estimate (SE) and trend of the residual distribution (random or biased), through the difference between experimental data and data estimated by the models. The mean relative error and standard deviation of the estimate for each one of the models were calculated according to Eqs. 7 and 8, respectively.

$$P = \frac{100}{n} \cdot \sum_{i=1}^{n} \frac{\left|\left(Xexp - Xpred\right)\right|}{Xexp} \tag{7}$$

where:

P - mean percent deviation, (%);
Xexp - values obtained experimentally, g;
Xpred - values predicted by the model, g; and,
n - number of experimental data.

$$SE = \sqrt{\sum_{i=1}^{n} \frac{\left(Xexp - Xpred\right)^2}{DF}} \tag{8}$$

where:

SE - standard deviation of the estimate; and,
DF - degrees of freedom of the model (number of observations minus number of parameters of the model).

Table 1. Mathematical models used to fit the 'babassu' mesocarp drying data

Designation of the models	References	Equation	
Two Terms	(Jittanit, 2011)	$RX = a . \exp(-k . t) + b . \exp(-k . t)$	(2)
Henderson & Pabis	(Henderson & Pabis, 1961)	$RX = a . \exp(-k . t)$	(3)
Modified Henderson & Pabis	(Karathanos, 1999)	$RX = a . \exp(-k . t) + b . \exp(-k_0 . t) + c . \exp(-k_1 . t)$	(4)
Logarithmic	(Costa et al., 2011)	$RX = a . \exp(-k . t) + c$	(5)
Midilli	(Midilli et al., 2002)	$RX = a . \exp(-k . t^n) + b . t$	(6)

RX - Moisture ratio, dimensionless; a, b, k, n, q – Parameters of the model, dimensionless; t - Drying time, min

The flours were made by grinding the dry mesocarp. The contents of protein and fiber present in the mesocarp were evaluated before and after drying according to the methodology described by IAL (2008). Each sample was evaluated in triplicate.

The results of protein and fiber were compared in a completely randomized design with three replicates per sample. The data were analysed using the program Sisvar version 5.6 (build 86) (Ferreira, 2011). Then, the means were compared by Tukey test at 0.05 probability level.

Results and Discussion

The oven drying at temperatures of 40, 50 and 60 °C required times of 730, 430 and 370 min, respectively, to reach the equilibrium water content (7.61, 5.83 and 4.62%, respectively) (Figure 1A). In the solar dryer, the samples required 6 days to reach the equilibrium water content of 8.07%, at mean temperature of 33.6 °C (29.6 and 49 °C, minimum and maximum), and relative air humidity of 49.87% (42 and 83%, minimum and maximum) inside the dryer (Figure 1B). The increase in drying air temperature reduced the time for water removal from the mesocarp, consequently decreasing the drying time. The same behavior was observed by Silva & Viotto (2010) and Santos et al. (2013), drying fibrous flour of Sicilian lemon and residual grain flour of annatto, respectively.

The mathematical models fitted to the experimental data of oven drying at temperatures of 40, 50 and 60 °C and in the solar dryer showed R^2 values higher than 0.98 (Table 2). In the solar dryer, the best fit was obtained with the Midilli model (Table 2) and, according to Kashaninejad et al. (2007), this indicates a satisfactory representation of the drying process by these models. However, it must be pointed out that the coefficient of determination only is not a good criterion to select nonlinear

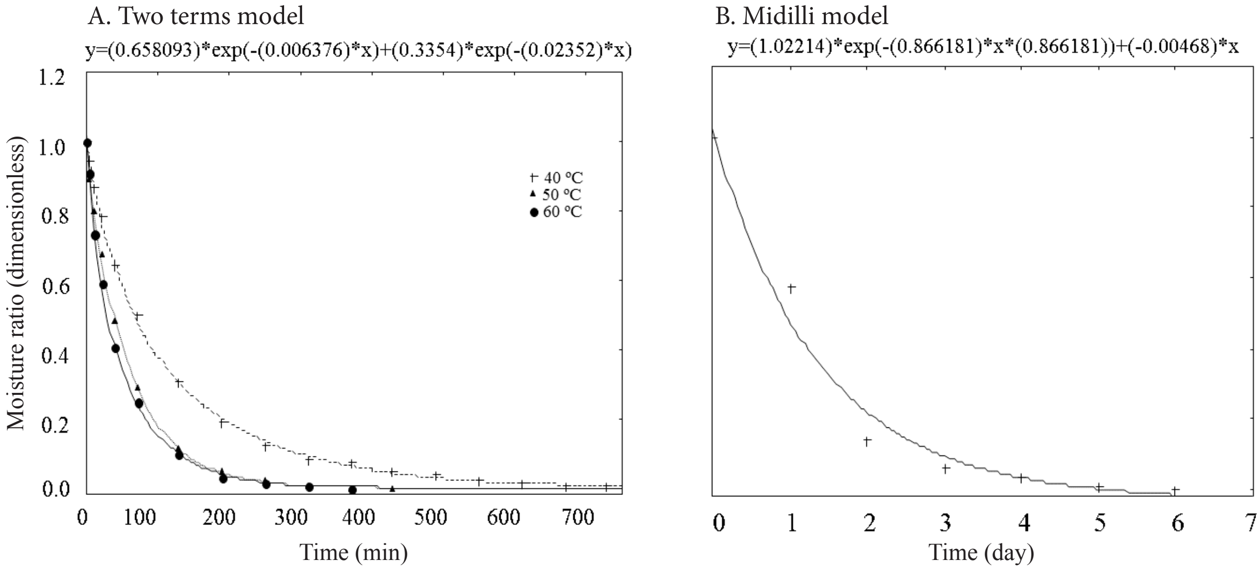

Figure 1. Experimental and predicted drying curves of babassu mesocarp: Two terms model in forced-air oven at 40, 50 and 60 °C (A); Midilli model in solar dryer

Table 2. Coefficients of determination (R^2), magnitude of the mean relative error (P), standard deviation of the estimate (SE) and trend of residual distribution of the tested models for babassu mesocarp drying kinetics in oven and solar dryer

Equation	Method	Temperature (°C)	R^2	P	SE	Residuals
Two terms	Oven	40	0.9998	15.49	5.25E-05	Random
		50	0.9999	17.63	1.32E-05	Random
		60	0.9992	16.99	0.0003	Random
	Solar dryer	-	0.9896	38.27	0.0060	Random
Henderson & Pabis	Oven	40	0.9981	28.48	0.0005	Biased
		50	0.9995	12.50	0.0001	Biased
		60	0.9970	25.26	0.0010	Biased
	Solar dryer	-	0.9896	46.05	0.0045	Random
Modified Henderson & Pabis	Oven	40	0.9981	28.48	0.0006	Biased
		50	0.9999	12.50	0.0002	Biased
		60	0.9970	25.26	0.0014	Biased
	Solar dryer	-	0.9896	46.05	0.0090	Random
Logarithmic	Oven	40	0.9989	72.04	0.0003	Biased
		50	0.9996	54.78	0.0001	Biased
		60	0.9974	51.48	0.0010	Biased
	Solar dryer	-	0.9908	48.38	0.0052	Random
Midilli	Oven	40	0.9986	71.31	0.0004	Biased
		50	0.9995	42.43	0.0002	Biased
		60	0.9972	20.42	0.0013	Biased
	Solar dryer	-	0.9904	26.08	0.0082	Random

models, which require joint evaluations of other statistical parameters (Madamba et al., 1996).

The values of mean relative error (P) indicate deviation of the observed values in relation to the curve estimated by the model (Kashaninejad et al., 2007), and values below 10% are recommended for the selection of models that adequately represent the drying phenomenon (Mohapatra & Rao, 2005). However, none of the models tested for the drying in both oven and solar dryer showed values lower than 10%. For the oven drying, the models Two terms at 60 and 40 °C, Henderson & Pabis and Modified Henderson & Pabis at 50 °C exhibited their lowest values, while in the solar dryer, the Midilli model showed lower values compared with the others (Table 2).

The mathematical model Two terms showed lower magnitude of the standard deviation of the estimate (SE) in the oven drying for the different temperatures and the models Henderson & Pabis and Logarithmic, for the drying in solar dryer (Table 2). The literature indicates that the capacity of a model to accurately describe a certain physical process is inversely proportional to the SE value, i.e., the lower the SE, the better the fit of the model (Draper & Smith, 1998; Siqueira et al., 2013; Mendonça et al., 2015).

The model Two terms in the oven drying exhibited random distribution at all drying temperatures tested; while in the solar dryer all tested models showed this random distribution (Table 2), which makes them acceptable.

The parameter "k" in the models Midilli and Henderson & Pabis decreased with the increase of drying temperature, while in the other models there was an increment in the value of the parameter with the increase in drying temperature. For the drying in solar dryer, the Midilli model showed the highest magnitude of the parameter "k" (Table 3).

The drying constant (k) can be used as approximation to characterize the effect of temperature and is related to the effective diffusivity in the drying process in the decreasing period and to the liquid diffusion that controls the process (Babalis & Belessiotis, 2004), i.e., the higher the magnitude of the parameter "k", the higher the diffusivity in the drying process.

The parameter "n" decreased with the increase of temperature in the Midilli model (Table 3). This parameter has effect of moderation of time, correcting probable errors resulting from the internal resistance to water transfer (Guedes & Faria, 2000).

For the parameters "a", "b" and "c", there was not a defined trend regarding drying temperatures and types of dryers (Table 3).

'Babassu' flours dried in oven and solar dryer exhibited an increase of protein in comparison to the fresh mesocarp (Table 4). In addition, as drying temperature increased, the percentage of crude fibers increased and the highest values were obtained with drying at 60 °C (Table 4). The water content of the 'babassu' flours dried in oven and solar dryer varied from 4.62 to 8.07%, being within the RDC standards nº 263/2005 of ANVISA, which requires maximum water content of 15% for flours obtained from seed parts (BRASIL, 2005). This water content is satisfactory for chemical and microbiological stability of the product due to the reduction in the kinetics of the chemical reactions, which cause alterations in the sensory, technological and nutritional characteristics (Cavalcante Neto, 2012).

In a similar study conducted by Nonato et al. (2013), these authors compared babassu mesocarp flours from different origins. The flours of the municipalities União and Água Branca, in the state of Piauí, showed protein contents of 1.60 and 1.16%, respectively, similar to those found in the present study. The protein contents were higher in the municipalities of Caxias and Parnarama, 5.57 and 4.84%, respectively, in Maranhão. It should be highlighted that the nutritional value

Table 4. Values of protein, fiber and water content of 'babassu' (*Orbignya phalerata* Mart.) mesocarp flours subjected to drying in oven and solar dryer

Flour sample	Total protein	Crude fiber	Water content
		(%)	
Fresh	0.88 b	0.35 b	42.87
Solar dryer	1.36 a	0.24 c	8.07
Oven 40 °C	1.33 a	0.25 c	7.61
Oven 50 °C	1.15 ab	0.41 b	5.81
Oven 60 °C	1.37 a	0.89 a	4.62
CV%	12.81	7.32	-

Same lowercase letters in the column are statistically similar at 0.05 probability level

Table 3. Parameters of the tested mathematical models in the drying of babassu mesocarp samples in oven and solar dryer

Equation	Method	Temperature (°C)	Parameters					
			A	B	C	K	q	n
Two terms	Oven	40	0.6580	0.3354		0.0063	0.0235	
		50	0.9156	0.0843		0.0162	0.1256	
		60	0.7101	0.3029		0.0154	0.0697	
	Solar dryer	-	0.5126	0.5126		0.7818	0.7818	
Henderson & Pabis	Oven	40	0.9609			0.0087		
		50	0.9754			0.0176		
		60	0.9728			0.0215		
	Solar dryer	-	1.0253			0.7819		
Modified Henderson & Pabis	Oven	40	0.3203	0.3203	0.3203	0.0876		
		50	0.3251	0.3251	0.3251	0.0176		
		60	0.3243	0.3242	0.3243	0.0215		
	Solar dryer	-	0.3417	0.3418	0.3417	0.7818		
Logarithmic	Oven	40	0.9445		0.0247	0.0095		
		50	0.9699		0.0074	0.0180		
		60	0.9610		0.0166	0.0226		
	Solar dryer	-	1.0543		-0.0332	0.7163		
Midilli	Oven	40	0.9653	0.00003		0.0953		0.0953
		50	0.9761	0.00001		-0.1331		-0.1331
		60	0.9744	0.00003		-0.1477		-0.1477
	Solar dryer	-	1.0221	-0.0046		0.8661		0.8662

of 'babassu' flour can be influenced by the collection period, type of soil, maturity of the fruits, species and also type of mesocarp processing, handcrafted or industrial.

The contents of total protein and crude fiber were higher in the studies that used 'babassu' flour as one of the components for animal feed, such as those conducted by Silva et al. (2012), who found 14.49% of protein used in bovine diet, and Carneiro et al. (2013), who found 3.29 and 2.66% of protein and fiber, respectively, used in the formulation of poultry feed.

Conclusions

1. The mathematical models Two Terms and Midilli showed the best fit to the experimental data, compared with the other tested models, for the drying in oven and solar dryer, respectively.

2. Drying, both in oven and solar dryer, led to increment in the protein percentage of the mesocarp flour.

3. The solar dryer proved to be efficient, despite the longer drying time compared with the oven, becoming an alternative for family farmers in the manufacture of new products based on babassu mesocarp.

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