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Fits of Models and Thermodynamic Properties in Drying of Mass of Jambu Leaves

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Abstract: The objective of this study was to evaluate the drying kinetics of the mass of jambu leaves and mass of jambu leaves in foam mat at different temperatures (50, 60 and 70 °C and thickness of 1.0 cm). The physicochemical characterization of the materials was performed before and after drying. Twelve different drying models were fitted to the drying kinetics data and the thermodynamic properties were calculated. The physicochemical parameters for the mass of leaves and foam after drying were moisture content from 2 to 7%, ash from 13 to 17%, protein content from 22 to 30%, lipids from 0.6 to 4% and total titratable acidity from 0.20 to 0.28% of tartaric acid. Wang & Singh and Midilli models were recommended for describing the drying kinetics. The use of foam mat promoted higher values of effective diffusion coefficient and activation energy and lower values of enthalpy and entropy, thus enhancing the reduction of drying time.

Keywords: Acmella oleracea, Foam Mat, Drying Kinetics

1. Introduction

Several vegetables are limited to some regions; consequently, they are not well known and are little consumed in other regions of Brazil, and many of them contain higher levels of micro and macro nutrients when compared to conventional plants [1,2]. The small number of studies with neglected plants shows that the potential value of these species is little explored and their introduction as alternatives to conventional vegetables has increased the availability of species that contribute to food security [1].

Jambu (*Acmella oleracea*) is an abundant vegetable in the Northern region of Brazil, where its different plant organs (flowers, leaves and stems) are consumed in preparations of typical foods of the Amazon region and as traditional medicinal herb in the treatment of diseases of mouth and throat [2–4]. The species *Acmella oleracea* is investigated for several applications, including

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evaluation of larvicidal activity of different crude extracts of leaves, as well as antioxidant and immunomodulatory properties, and many studies have focused on its use for centuries in the treatment of oral pain due to its analgesic properties [4–6].

Jambu is a perishable vegetable and requires post-harvest treatment in order to prevent and minimize losses that occur during its marketing, seeking to reduce to a minimum the losses of the active ingredients of interest and compounds aimed at adding flavor or aroma to food [7,8]. Conservation processes include artificial drying by hot air convection, one of the oldest and widely used methods. In industries, more than 85% of dryers are convective, although it has disadvantages such as high energy consumption [9].

Traditional drying methods result in many unfavorable changes in the plant, such as excessive shrinkage, discoloration, oxidation of functional ingredients, severe deterioration of nutritional and sensory properties, and radical changes in quality from the consumer's point of view. Therefore, the use of low-temperature drying and the reduction of drying time through the application of new drying techniques (accelerating heat and mass transfer) have been suggested [10].

Foam-mat drying is a process in which liquid or semi-liquid foods are transformed into a stable form of foam by incorporating air through aeration in the presence of a foaming agent and are subsequently dried [11]. The pore structure of the foam and the large surface area exposed to drying air cause high mass transfer rates when compared to solid food, leading to a shorter period of dehydration [12].

Drying of agricultural products can be organized in several ways in which drying kinetics data can be represented by theoretical, semi-theoretical and empirical mathematical models [13]. Drying kinetics reveals information on the conformity of drying conditions, typical drying behaviors, heating, the period of fast drying due to the constant rate and the falling rate periods [14].

Therefore, *Acmella oleracea* is a plant of commercial interest, due to its pharmacological properties, but there are few studies assessing its processing and application of conservation methods [15,16]. Thus, the objective of this study was to evaluate the drying kinetics of the mass of jambu leaves and mass of jambu leaves in foam mat at different temperatures (50, 60 and 70 °C and thickness of 1.0 cm), determine thermodynamic properties and evaluate its physicochemical characterization.

2. **Material and Methods2.1 Obtaining of raw material and drying**

Jambu plants were collected on a family farm in the municipality of Macapá, AP (0°01′26.0″ South and 51° 06′ 53.5″ West of Greenwich), and the experiment was conducted at the Food Laboratory of the Federal Institute of Amapá - IFAP (0°05′12.3″ North and 51° 05′ 31.0″ West of Greenwich).

Jambu leaves were washed, sanitized (solution composed of 2.5% sodium hypochlorite, for 15 minutes) and crushed (without

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adding water, for 2 minutes) in a food processor to obtain a homogeneous mass.

The foam was prepared by the mixture and aeration for 15 minutes in a domestic mixer of the mass of jambu leaves, 1% of a stabilizing agent (Super Liga Neutra®) combined with 2% of an emulsifier (Emustab®). The mass of leaves and the foam were subjected to thin-layer convective drying.

Drying was carried out in a forced air circulation oven, at temperatures of 50, 60 and 70 °C and air velocity of 1.0 ms-1 (measured in a digital anemometer). The materials (mass of leaves and foam) were spread evenly in rectangular stainless steel trays (25.5 x 13.5 cm), forming a thin layer of 1.0 cm thickness measured with a digital caliper.

During drying, the trays were weighed at regular intervals until they reached constant mass. The experiment was carried out in triplicate. The dehydrated material was removed from the tray with a spatula and crushed in a household food processor for 1 minute to obtain the flours, which were subsequently placed in laminated packages composed of one layer of transparent PET (transparent low-density polyethylene terephthalate) and another layer of metalized PET (metalized polyethylene terephthalate).

2.1.1 Physicochemical characterization

The mass of leaves, foam and flours were evaluated for the following physicochemical parameters: water, ash, lipids, protein and total titratable acidity, according to the methodologies of the Adolfo Lutz Institute [17].

2.2. Mathematical Modeling

From the experimental data of drying kinetics, the values of the moisture content ratio were calculated according to Eq. 1.

$$RX = \frac{X - X_e}{X_i - X_e} \quad (1)$$

Where: RX: moisture content ratio of the product, dimensionless; X; moisture content of the product (d.b.); Xi: initial moisture content of the product (d.b.); Xe: equilibrium moisture content of the product (d.b.).

Table 1 presents the mathematical models widely used to describe drying kinetics of vegetables. The models were fitted by nonlinear regression analysis using the Gauss-Newton method.

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Table 1 - Empirical and semi-empirical equations used to represent drying kinetics.

	Model Designation	Model	Equation
1	Page	$RX = exp\ exp\ (-k * t^n)$	(2)
2	Midilli	$RX = a * exp\ exp\ (-k * t^n) + b * t$	(3)
3	Henderson & Pabis	$RX = a * exp\ exp\ (-k * t)$	(4)
4	Approximation of Diffusion	$RX = a * exp\ exp\ (-k * t) + (1-a) * exp\ exp\ (-k * b * t)$	(5)
5	Two Terms	$RX = a * exp\ exp\ (-k_0 * t) + b * exp\ exp\ (-k_1 * t)$	(6)
6	Two-Term Exponential	$RX = a * exp\ exp\ (-k * t) + (1-a) * exp\ exp\ (-k * a * t)$	(7)
7	Logarithmic	$RX = a * exp\ exp\ (-k * t^n) + c$	(8)
8	Thompson	$RX = \frac{(-a-(a^2+4*b*\ t)^{0,5})}{2} * b$	(9)
9	Newton	$RX = exp\ exp\ (-k * t)$	(10)
10	Verma	$RX = a * exp\ exp\ (-k * t) + (1-a) * exp\ exp\ (-k_1 * t)$	(11)
11	Wang & Singh	$RX = 1 + a * t + b * t^2$	(12)
12	Valcam	$RX = a + b * t + c * t^{1,5} + d * t^2$	(13)

RX - Moisture content ratio of the product, dimensionless; k, k_0, k_1 - Drying constants; h^{-1}; a, b, c, n - Coefficients of the models; t - Drying time, h.

The preliminary criteria to select the model with best fit were: coefficient of determination (R^2), relative mean error (P), estimated mean error (SE) and the mean chi-square (χ^2).

$$\chi^2 = \sum \frac{(Y-\hat{Y})^2}{DF} \quad (14)$$

$$P = \frac{100}{n} \sum \frac{|Y-\hat{Y}|}{Y} \quad (15)$$

$$SE = \sqrt{\frac{\sum (Y-\hat{Y})^2}{DF}} \quad (16)$$

Where: Y: experimental RX value; $\hat{Y}$: RX value estimated by the model; n: number of observations; DF: degrees of freedom of the model (observations minus the number of model parameters).

In order to select a single model to describe the drying process under each condition, those models that preliminarily obtained the best fits (according to the criteria R^2, P and SE) were subjected to the selection criteria of Akaike Information (AIC) and Schwarz's Bayesian Information (BIC).

The information criteria were determined by the following equations:

$$AIC = -2logL + 2p \quad (17)$$

$$BIC = -2logL + plog(N-r) \quad (18)$$

Where: p: number of model parameters; logL: logarithm of the likelihood function considering the estimates of the parameters; N: total observations; r: matrix X rank (incidence matrix for fixed effects).

Fick's diffusive model was fitted to the drying data considering the geometric shape of flat plate (18), with eight-terms approximation (19), according to Eq. 19, for the determination of effective diffusivity.

$$RX = \left(\frac{8}{\pi^2}\right) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-(2n+1)^2 \pi^2 D \frac{t}{4L_0^2} \frac{S}{V}\right)$$

(19)

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Where: RX: moisture content ratio, dimensionless; D: effective diffusion coefficient, m2 s-1; S: equivalent plate area, m2; V: equivalent plate volume, m3; L0: mass thickness, m; n: number of terms of the equation; t: time, s.

The expression described by Arrhenius (Eq. 20) was applied, relating the dependence of effective diffusivity as a function of temperature.

$$D = D_0 \exp\left(\frac{-E_a}{RT_a}\right) \quad (20)$$

Where: Do: pre-exponential factor; Ea: activation energy, kJ mol-1; R: universal constant of gases, 8.314 kJ kmol-1. K-1; Ta: absolute temperature, K.

The Arrhenius equation was used to calculate the activation energy from the linearization of the coefficients of the equation, applying the logarithm as follows:

$$\mathrm{Ln}\, D = \mathrm{Ln} D_0 - \frac{E_a}{R} \cdot \frac{1}{T_a} \quad (21)$$

2.3 Thermodynamic Properties

The thermodynamic properties of the drying process of the mass of leaves and foam determined were: enthalpy, entropy and Gibbs free energy, according to Equations 22, 23 and 24, respectively.

$$\Delta H = E_a - R . T_a \quad (22)$$

$$\Delta S = R . [\mathrm{Ln}(D_0) - \mathrm{Ln}\left(\frac{K_B}{h_p}\right) - \mathrm{Ln}(T_a)] \quad (23)$$

$$\Delta G = \Delta H - T_a . \Delta S \quad (24)$$

Where: ΔH - specific enthalpy, J mol-1; ΔS - specific entropy, J mol-1 K-1; ΔG - Gibbs free energy, J mol-1; KB - Boltzmann constant, 1.38 × 10-23 J K-1; hp - Planck constant, 6.626 × 10-34 J s-1; T - temperature, °C.

3.0 RESULTS AND DISCUSSION

3.1 Physicochemical Characterization

Table 2 shows the means of the evaluations of physicochemical composition of the mass of jambu leaves, foam and flours obtained at different temperatures.

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Table 2. Mean values of the physicochemical composition of the mass of jambu leaves, foam and flours obtained under different drying conditions.

Material	Temperature °C	Analyses				
		Moisture content (% w.b.)	Protein %	Lipids %	Ash %	Total Titratable acidity* %
Mass of jambu leaves	---	92.71 ± 0.29	3.39 ± 0.23	0.24 ± 0.08	1.34 ± 0.04	0.03 ± 0.0
Foam	---	90.31 ± 0.05	3.30 ± 0.22	0.26 ± 0.07	1.31 ± 0.01	0.04 ± 0.0
Dried mass of jambu leaves	50	5.70 aA	28.33 aA	0.78 aB	17.18 aA	0.26 aA
	60	3.79 aB	30.44 aA	0.68 aB	16.28 aA	0.29 aA
	70	2.21 aB	28.48 aA	0.69 aB	16.32 aA	0.27 aA
Dried foam	50	6.29 aA	24.75 aA	4.72 aA	14.20 aB	0.24 aA
	60	7.67 aA	22.98 aB	4.71 aA	13.74 aA	0.24 aA
	70	6.58 aA	23.37 aA	4.09 aA	13.00 aB	0.20 aB

Lowercase letters in the column refer to the comparison between the different temperatures for the same material, and uppercase letters in the column refer to the comparison of the same temperature between the two materials, and the same letters do not differ from each other by Tukey test (p -0.05). *Tartaric Acid

The results found for the mass of jambu leaves and foam showed that they have a significant contents of moisture and protein and reduced contents of lipids, ash and total titratable acidity. These contents are close to those described by Neves et al. [1], who found moisture content of 89% w.b., ash of 1.11%, lipids of 0.16%, proteins of 2.44%. The moisture contents obtained in the drying of the mass of jambu leaves ranged from 5.77 to 2.2% w.b. and showed a non-significant decrease with the increase in temperature. For the drying of the foam, there was a higher moisture retention, significant at temperatures of 60 and 70 °C when compared with the dried mass of leaves, with no significant influence of the increase in temperature.

However, the mass of leaves and foam of jambu showed relevant contents of protein (3.39% and 3.3%, respectively) and lipids (0.24 and 0.26%, respectively), so drying led to a reduction in moisture content that contributed to a significant increase in the contents of proteins and lipids, and the lipid content found in the foam after drying was higher than that found in the mass of leaves. Values similar to those obtained here were reported by Gomes et al. [16], who found that jambu flours had moisture contents between 4 and 6% w.b. and lipid and protein parameters of 7% and 27%, respectively, with no significant degradation under the studied conditions.

For the ash content of the mass of jambu leaves and foam, there was no variation with the increase in temperature. It was found that the mass of leaves had higher percentages of ash, with values between 16 and 17%. The total acidity levels of the mass of leaves (0.26- 0.28% tartaric acid) and foam (0.20- 0.24 tartaric acid) after drying showed an acidic character compared with the fresh material (0.03 and 0.04% tartaric acid). The acidity content increased when drying was applied, possibly due to the conversion of sugars into organic acids [11]. In the comparison of the materials before and after drying, there was a reduction in moisture content, while the protein and lipid contents increased, and the dried foam stood out with higher values, but not differing from the mass of leaves. This increase may be linked to the addition of stabilizer and emulsifier used to obtain the foam.

Convective drying with forced air circulation is a method recommended for drying leaves because it helps reduce heat losses and improves quality [20]. The physicochemical parameters evaluated showed that the addition of stabilizers and emulsifiers did not cause significant changes in the material composition. And foaming was a positive factor in the process as it reduced drying time, since this is a limiting factor for the drying conditions (temperature, speed and relative humidity of the air, as well as thickness), which must be controlled to maintain the quality of the final product and reduce moisture content [12].

3.2 Mathematical Modeling

To better understand the drying kinetics of the crushed mass of jambu leaves and foam, different mathematical models were evaluated. Table 3 shows the values of the estimated mean error (SE), relative mean error (P), coefficient of determination (R^2) and chi-square test (χ^2) for the mathematical models fitted to the experimental data of the drying kinetics of the mass of jambu leaves and foam at temperatures of 50, 60 and 70 °C and thickness of 1.0 cm. Table 3

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Table 3. Estimated mean error (SE), relative mean error (P), coefficient of determination (R^2) and chi-square test (χ^2) for the twelve models analyzed in the drying of crushed mass of jambu leaves.

Model	Mass of leaves											
	50 °C				60 °C				70 °C			
	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)
Wang & Singh	0.0074	6.90	0.055	99.94	0.009	7.075	0.09	99.91	0.011	4.2	0.13	99.87
Verma	0.0881	75.95	7.7532	91.79	0.180	167.9	32.51	68.31	0.012	4.9	0.15	99.85
Valcam	0.0363	35.56	1.3184	98.60	0.047	54.3	2.19	97.86	0.042	10.7	1.77	97.19
Thompson	0.0528	46.59	2.7902	96.96	0.051	56.8	2.65	97.33	0.060	27.5	3.54	96.36
Page	0.0234	20.44	0.5494	99.40	0.024	26.2	0.56	99.44	0.021	10.1	0.46	99.53
Newton	0.0521	46.58	2.7099	96.96	0.051	56.8	2.57	97.33	0.058	27.5	3.42	96.36
Midilli	0.0069	6.13	0.0480	99.95	0.009	8.2	0.07	99.93	0.006	2.4	0.03	99.97
Logarithmic	0.0083	8.22	0.0686	99.93	0.009	9.3	0.08	99.92	0.008	3.6	0.07	99.93
Henderson & Pabis	0.0460	41.13	2.1155	97.69	0.043	49.5	1.88	98.11	0.049	22.9	2.39	97.54
Two-term exponential	0.0528	46.58	2.7896	96.96	0.051	56.8	2.65	97.33	0.060	27.5	3.54	96.36
Two terms	0.0236	21.84	0.5576	99.43	0.045	49.5	2.01	98.11	0.024	11.5	0.57	99.46
Approximation of diffusion	0.0094	8.98	0.0882	99.91	0.011	10.6	0.13	99.87	0.012	4.9	0.15	99.85

Model	Foam											
	50 °C				60 °C				70 °C			
	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)	SE (decimal)	P (%)	χ^2 (decimal) x 10^{-3}	R^2 (%)

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Wang & Singh	0.006	4.1	0.03	99.97	0.010	6.2	0.10	99.90	0.016	7.3	0.27	99.77
Verma	0.242	154.6	58.38	44.48	0.346	217.0	119.56	0.00	0.439	313.1	192.32	0.00
Valcan	0.050	37.2	2.50	97.62	0.043	29.4	1.83	98.40	0.052	38.2	2.72	97.80
Thompson	0.049	35.8	2.43	97.61	0.060	39.8	3.59	96.73	0.064	46.4	4.08	96.52
Page	0.022	15.6	0.50	99.50	0.023	15.0	0.52	99.52	0.020	15.2	0.39	99.67
Newton	0.048	35.8	2.35	97.61	0.059	39.8	3.44	96.73	0.062	46.4	3.87	96.52
Midilli	0.008	5.0	0.06	99.95	0.007	4.8	0.05	99.95	0.008	4.3	0.06	99.95
Logarithmic	0.010	7.2	0.09	99.91	0.010	7.0	0.10	99.91	0.013	7.5	0.16	99.87
Henderson & Pabis	0.043	31.5	1.86	98.17	0.050	33.6	2.48	97.74	0.050	37.5	2.47	97.89
Two-term exponential	0.049	35.8	2.43	97.61	0.060	39.8	3.59	96.73	0.064	46.4	4.07	96.52
Two terms	0.021	15.8	0.46	99.58	0.025	17.0	0.62	99.48	0.053	37.5	2.76	97.89
Approximation of diffusion	0.010	7.4	0.10	99.91	0.013	8.3	0.17	99.86	0.019	10.4	0.37	99.70

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Wang & Singh, Midilli and Logarithmic models showed the best fits under all drying conditions according to the preliminary criteria of evaluation: R^2 higher than 99%, lower estimated mean error (SE) and chi-square test (χ^2), as well as relative mean error (P) lower than 10%, which is considered as an adequate representation of the model [21].

Together with the previous statistical parameters (Table 3), the Akaike information criterion (AIC) and Schwarz's Bayesian Information criterion (BIC) were adopted as additional criteria to select the best model. The results of AIC and BIC for Wang & Singh, Midilli and Logarithmic models are described in Table 4.

Table 4. Akaike Information criterion (AIC) and Schwarz's Bayesian Information criterion (BIC) for the models that best fitted to the drying data of the crushed mass of jambu leaves.

Model		**Wang & Singh**		**Midilli**		**Logarithmic**	
Drying	**Temperature °C**	**BIC**	**AIC**	**BIC**	**AIC**	**BIC**	**AIC**
Mass of Leaves	50	-242.58	-247.33	-242.15	-250.07	-231.76	-238.10
	60	-205.62	-210.11	-207.35	-214.83	-207.87	-213.86
	70	-150.17	-154.48	-173.45	-180.62	-147.70	-153.43
Foam	50	-224.32	-228.62	-189.15	-194.88	-189.15	-194.88
	60	-156.83	-160.61	-169.75	-176.04	-154.81	-159.84
	70	-106.23	-109.36	-133.10	-138.32	-114.71	-118.88

Considering the lower values of the AIC and BIC information criteria as indication of better fit, Wang & Singh model showed the best fit to the experimental data for temperature of 50 °C of thin-layer and foam-mat drying. For the other treatment conditions, Midilli model obtained better fit to the experimental data. These results indicate that, regardless of the drying method used, the mathematical models fitted well to the data. Logarithmic and Midilli models were indicated as those with better fit to the experimental data of drying kinetics of the mass of jambu leaves [22].

Data of drying kinetics at different temperatures were analyzed in terms of moisture content ratio (RX), as shown in Figure 1. The moisture content ratio decreases continuously until the equilibrium is reached. The increase in air temperature resulted in a reduction in the time required to reach the equilibrium moisture content for the different conditions studied.

The moisture content ratio curve has been considered the best way to explain the behavior during the drying process [23]. Combined with the adequate model for drying kinetics, it is used to explain the total drying behavior [14]. As the model describes the mechanisms of heat and mass transport, it can be used to simulate other process conditions such as variation in thickness, foam composition and temperature, velocity and relative humidity of the air, among others [12].

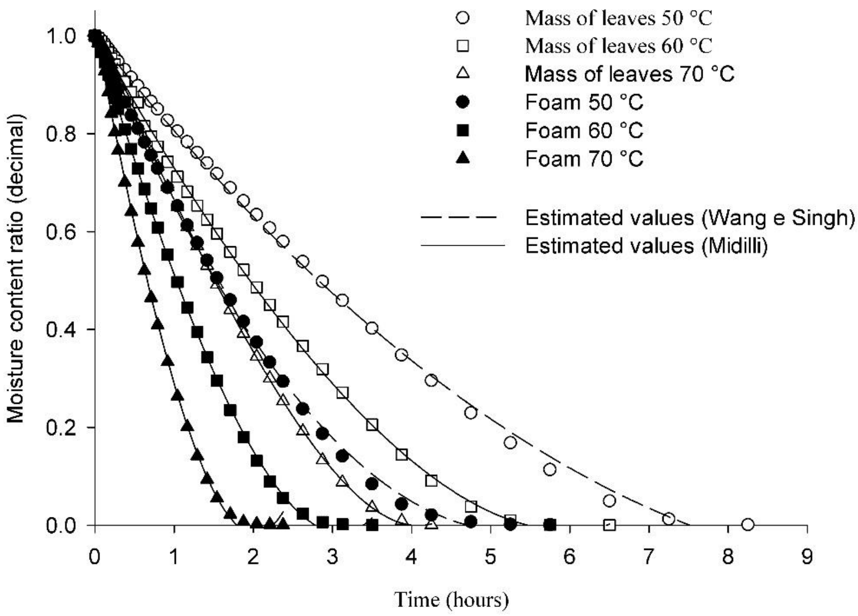

Fig. 1. Moisture content ratio in the drying of crushed mass of jambu leaves, obtained experimentally and estimated by the Wang & Singh and Midilli models for the different drying conditions.

The results indicated that just as air temperature played an important role in reducing drying time, the use of foam mat enhanced this reduction. The drying time was between 4 and 7 hours in the drying of the mass of leaves and showed a considerable reduction in the drying of the foam, being between 2 and 5 hours.

Increase in drying temperature reduces the drying time due to molecular movement, thus increasing the rate of water removal from the sample, which results in the reduction of drying time [11]. Franco et al. [12] report that the porous structure of the foam and the large surface area in contact with the drying air cause higher mass transfer rates, thus leading to a reduction in drying time and, therefore, a final product with better quality. The coefficients of fits of the mathematical equations obtained under the different experimental conditions of drying kinetics are presented in Table 5.

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Table 5. Coefficients of the models that best fitted to the drying data of crushed mass of jambu leaves and foam.

Model	Temperature (°C)	Mass of Leaves				Foam			
		a	b	k	n	a	b	k	n
Midilli	50	0.997247	-0.014930	0.073879	1.142397	0.990898	-0.017696	0.157579	1.160437
	60	1.006883	-0.019378	0.127761	1.088324	0.998051	-0.032604	0.242910	1.185451
	70	1.003061	-0.031494	0.143453	1.178146	1.008538	-0.038754	0.444715	1.204884
Wang & Singh	50	-0.099148	0.002023	----	----	-0.186675	0.008153	----	----
	60	-0.146170	0.004782	----	----	-0.275789	0.016182	----	----
	70	-0.181939	0.005765	----	----	-0.435303	0.041703	----	----

Figure 2. shows the values of the effective diffusion coefficient during the drying of the crushed mass of jambu leaves and foam. The effective diffusion coefficient showed higher values at the higher drying temperatures and with application of the foam mat.

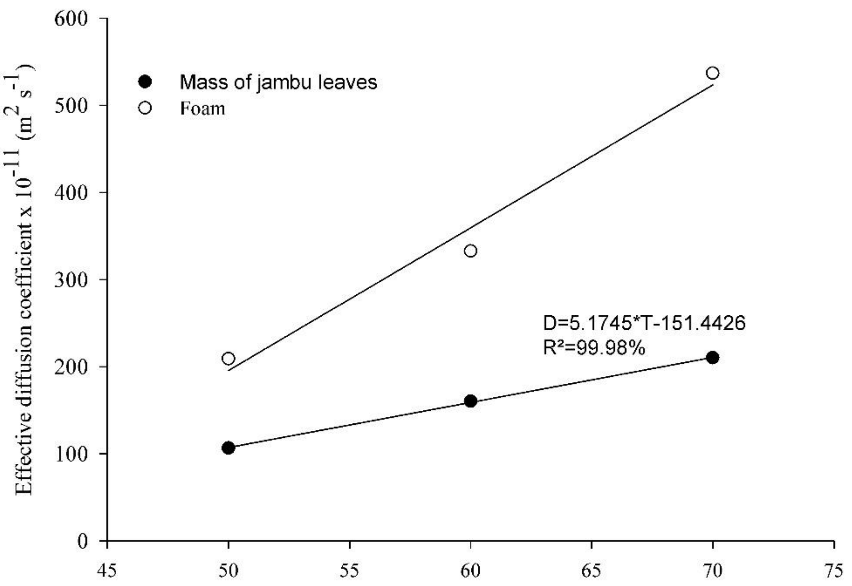

Fig. 2: Mean value of the effective diffusion coefficient (D) obtained in the drying of the crushed mass of jambu leaves and foam at temperatures of 50, 60 and 70 °C.

The effective diffusion coefficient showed a trend of linear increase as the drying air temperature increased. The use of foam mat promoted higher values of the effective diffusion coefficient compared to the material without foam mat for the three temperatures analyzed. The same was observed for the hot air drying of mint leaves, whose effective diffusivity was slightly higher when the air temperature was increased from 60 °C to 70 °C [24]. Gomes et al. [22] described a trend of increase in diffusion coefficient with the increase in drying air temperature and material layer thickness when studying the mass of jambu leaves.

The increasing values of effective diffusivity with the increase in temperature can be attributed to the fact that water molecules are more weakly bound to the food matrix at higher temperatures, requiring less energy for diffusion [25].

The activation energy increased with the application of the foam mat, from 31.31 kJ.mol-1 (samples without foam mat) to 43.48 kJ.mol-1 (samples with foam mat). These differences in activation energy may result from the variation in effective diffusivity, depending on the variability and physical structure of the sample, chemical composition, geometry and air drying temperature [26].

3.3 Thermodynamic Properties

The enthalpy values decreased with the increase in drying air temperature, and compared to the mass of jambu leaves, the smallest magnitudes are obtained with foam mat (Table 6). The lowest enthalpy value was observed with increased temperature, which indicates that the amount of energy needed to remove water bound to the product during drying was lower [25], showing that the foam-mat drying process required lower energy expenditure for water removal.

Table 6. Mean values of enthalpy (ΔH), entropy (ΔS) and Gibbs free energy (ΔG) obtained in the drying of the crushed mass of jambu leaves with and without foam mat at temperatures of 50, 60 and 70 °C.

Mass of Jambu Leaves			
Temperature (°C)	**ΔH (KJ mol^{-1})**	**ΔS (KJ mol^{-1} K^{-1})**	**ΔG (KJ mol^{-1})**
50	40.79223	-0.27725	130.3847
60	40.70909	-0.2775	133.1584
70	40.62595	-0.27775	135.9347
Foam			
Temperature (°C)	ΔH (KJ mol^{-1})	ΔS (KJ mol^{-1} K^{-1})	ΔG (KJ mol^{-1})
50	28.62219	-0.32029	132.1241
60	28.53905	-0.32054	135.3282
70	28.45591	-0.32079	138.5349

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Entropy was consistent with enthalpy, showing lower values for foam-mat drying. Such reduction indicates a lower excitation of water molecules and an increase in the degree of order of the water-foam system [27]. Regarding Gibbs free energy, the values were positive for both dried materials. According to Chen et al. [28], positive values of Gibbs free energy are characteristic of endergonic reaction, which indicates that the drying and absorption processes under the studied conditions were not spontaneous [25].

In a comparison of the thermodynamic properties for the different drying conditions, it is possible to observe that foam-mat drying shows a better performance. Drying is one of the most energy-consuming processes and is widely used in food industries, so increasing efficiency has the potential to reduce the energy demand of drying operations and, consequently, of the industry [29].

4. Conclusions

In the comparison of the material before and after drying, there was a reduction in moisture content, while protein and lipid contents increased. The addition of stabilizers and emulsifiers for foaming did not cause significant changes in the physicochemical composition of the material. Foaming was a positive factor in the drying process as it reduced the time required to achieve the equilibrium moisture content, also shown by the effective diffusion coefficients, which increased with the application of the foam mat, as well as the thermodynamic properties evaluated, which also pointed to this enhancing effect, with reduction of enthalpy and entropy and higher values of Gibbs free energy. The selection criteria indicated Wang & Singh and Midilli models to describe the drying kinetics of the mass of jambu leaves and foam.

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Conflict of Interest

The authors report there are no competing interests to declare.

AUTHOS' CONTRIBUTION

Francileni Pompeu Gomes: data collection, data analysis and interpretation, performing the analysis, drafting the article.

Osvaldo Resende: conception or design of the work, critical revision, final approval of the version to be published.

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