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Original Article

Physical characterization and description of the drying period with constant rate of jambu leaf paste[1]

Caracterização física e descrição do período de secagem com taxa constante da pasta de folhas de jambu

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HIGHLIGHTS:
In the drying curves of jambu leaves there is a period of constant rate.
Solubility and cohesiveness, free flow, and good wettability are characteristics that add value to the raw material.
The critical moisture content of jambu ranges from 1.17 to 4.18 kg kg^{-1} solid.

ABSTRACT: The objective of this study was to describe the constant drying flux stage, as well as obtaining the critical moisture content during the convective drying of jambu leaf paste crushed under different conditions and characterizing the physical properties of the material after drying. Drying was carried out in an air circulation oven at a speed of 1.0 m s^{-1} and temperatures of 60, 70 and 80 ºC and layer thicknesses of 0.005 and 0.01 m. To determine the constant rate stage, the mass fluxes and the drying rate were calculated. Segmented polynomials were used to estimate the critical moisture content. Under the analyzed conditions, a typical drying behavior was found, demonstrating the existence of a significant period of constant drying rate for the mass of ground jambu leaves. Critical moisture content as a function of thickness and temperature did not show a trend. The material showed favorable physical characteristics, such as high solubility and cohesiveness, free flow, and good wettability, characteristics that add value to the raw material and for the availability of a new product to the market in the condition of packaging.

Key words: *Acmella oleracea* L., convective drying, critical moisture content, drying rate

RESUMO: Neste estudo objetivou-se descrever o estágio de fluxo de secagem constante, bem como obter o teor de água crítico durante a secagem convectiva da pasta de folhas de jambu trituradas em diferentes condições e caracterizar as propriedades físicas do material após a secagem. A secagem foi realizada em estufa de circulação de ar com velocidade de 1,0 m s^{-1} nas temperaturas de 60, 70 e 80 ºC e espessuras da camada de 0,005 e 0,01 m. Para a determinação do estágio de taxa constante, foram calculados os fluxos de massa e a taxa de secagem. Os polinômios segmentados foram utilizados para estimar o teor de água crítico. Nas condições analisadas houve um comportamento típico de secagem, demonstrando a existência de um expressivo período de taxa constante de secagem para a pasta de folhas de jambu trituradas. Os teores de água críticos em função da espessura e temperatura não apresentaram uma tendência. O material apresentou características físicas favoráveis, como alta solubilidade e coesividade, escoamento livre e boa molhabilidade, características que agregam valor à matéria-prima e para a disponibilização de um novo produto ao mercado em condição de acondicionamento.

Palavras-chave: *Acmella oleracea* L., secagem convectiva, teor de água crítico, taxa de secagem

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Introduction

Drying is one of the oldest and most important physical methods of food preservation and/or stabilization (Moses et al., 2014). Different drying methods have been used in the drying of fruits and vegetables in order to obtain safe and nutritious dried foods for consumption with a prolonged shelf life (Oladejo et al., 2023).

Convective drying is one of the drying methods that consist of a complex process, which involves two phenomena: the transfer of energy in the form of heat and mass between the drying air and the product to be dried, in which the rise in temperature causes an increase in the partial vapor pressure of the product and, consequently, the removal of water from the product (Khan et al., 2020).

During this period (constant rate stage), the drying rate is mainly controlled by the characteristics of the aerothermal process conditions at the air-product interface. The identification of these phases and the investigation of the constant flux period are essential for drying control (Rungsiyopas & Ruiz, 2018). For example, the physical properties of food powders play a key role in determining their tendency to segregate or mix properly during and after a mixing operation (Ghodki & Goswami, 2016).

In the literature there are some studies on jambu, such as that by Neves et al. (2019), who characterized jambu and evaluated the effects of the boiling process on its chemical composition. Barbosa et al. (2016) studied jambu (*Acmella oleracea* L.) after freeze-drying microbiologically and sensorially and Gomes et al. (2018) studied the drying kinetics of the crushed mass of jambu leaves. However, there are no reports on the influence of temperature on the physical and physicochemical quality of jambu powders. The objective of this study was to describe the constant drying flux stage, as well as obtaining the critical moisture content during the convective drying of jambu leaf paste crushed under different conditions and characterizing the physical properties of the material after drying.

Material and Methods

Jambu (*Acmella oleracea* L.) plants were acquired in Macapá, Amapá state, Brazil, and the experiment was carried out at the Food Laboratory of the Brazilian Agricultural Research Corporation - EMBRAPA (Macapá, AP), at the approximate geographic coordinates of Latitude 0° 00’ 44” South and Longitude 51° 04` 46” West of Greenwich, with altitude around 460 m.

The jambu leaves were crushed (without water addition) in a food processor, resulting in a homogeneous mass. This material was subjected to convective drying in a forced air circulation oven (air velocity of 1.0 m s^{-1}), at temperatures of 60, 70, and 80 °C and with two layer thicknesses, 0.005 and 0.010 m. The mass was evenly distributed in rectangular stainless-steel trays (27.8 x 17.8 cm), forming a thin layer. The trays were weighed at regular intervals until reaching a constant mass over three consecutive weighing procedures.

To determine the initial moisture content of the jambu leaf paste and the final dehydrated material, it was dried in an oven at 105 ± 1 °C for 24 hours (IAL, 2008).

Heating foods at a constant temperature generally implies a typical drying curve with three distinct periods (Zhang et al., 2006); in the first heating period, the temperature of the product increases over time and the material begins to lose water at relatively low rates. In the second period of constant drying rate, a stable temperature profile is established and the drying rate is high and constant, that is, all the energy supplied to the system is used for water evaporation; in the third period, there is a progressive decrease in the water removal rate, a period of decreasing flux (Rungsiyopas & Ruiz, 2018).

During the constant drying rate period, the mass flux is constant and influenced only by external conditions (air flow, temperature, and relative air humidity).

From the experimental data of the drying kinetics, the drying rate (Eq. 1) and the mass fluxes (Eq. 2) were calculated. The drying rate was obtained by employing the derivative of the moisture contents as a function of the drying time, and the mass flux of the product QV (kg m^{-2} s^{-1}) was calculated by multiplying the mass rate, that is, the mass of water evaporating per time unit, by the exchange surface area.

$$qV = \frac{dx}{dt} \quad (1)$$

$$QV = \frac{dx}{dt} \cdot A \quad (2)$$

where:

dx - moisture content (kg);
dt - time (s);
qV - drying rate (kg s^{-1});
A - area (m^2); and,
QV - mass flux (kg m^{-2} s^{-1})

The exchange surface area (A) was calculated from the dimensions of the length (L) and width (L) of the rectangular tray used during the drying of the jambu leaf crushed paste.

To determine the critical moisture content that represents the transition between the period of constant flux and the first period of decreasing flux, segmented polynomials were employed using freeknotsplines data packages from the R program (R Core Team, 2019) to estimate the “knots” points.

After drying, the powders were analyzed, in triplicate, for the parameters of wettability time (g min^{-1}) at 25 °C (Lannes & Medeiros, 2003) and powder yield (% m m^{-1}), which was determined using the ratio between the mass of powder and paste of jambu leaves, calculated according to Eq. 3.

$$R = \frac{Mf}{Mi} \cdot 100 \quad (3)$$

where:

R - yield (% m m^{-1});
Mf - final mass of the powder product (g); and,
Mi - initial mass of the paste (g).

To determine the angle of repose (θ), 10 g of powder was placed in a funnel with a known diameter and sealed at the exit; then, the powder was released to flow over a Petri dish. The height between the funnel and the Petri dish was constant (5 cm) for all evaluated samples, calculated according to Eq. 4.

$$\theta = \frac{\text{arctg } 2h}{D} \quad (4)$$

where:

θ - repose angle (°);
h - height of the resulting pile (cm); and,
D - diameter of the pile (cm).

Bulk density (ρ_{bulk}) was determined by the ratio between mass and volume occupied in the container (beaker). The compacted density (ρ_{comp}) was determined according to the methodology of Tonon et al. (2013). Hausner factor (HF) is the ratio between the compacted density (ρ_{comp}) and the bulk density (ρ_{bulk}). Compressibility index (CI%) was quantified according to the methodology of Bhusari et al. (2014). Mean particle diameter was determined according to the method using Tyler standard series sieves (ASABE, 1998). Solubility was determined according to Cano-Chauca et al. (2005).

The data were analyzed using a spreadsheet software package and the R statistical software (R Core Team, 2019) to estimate the mass flux at a constant rate and the critical moisture content. To assess the degree of fit of the linear and quadratic polynomial models, the Akaike Information selection criterion (AIC) was used, according to Eq. 5.

$$\text{AIC} = -2\log L + 2p \quad (5)$$

where:

p - number of the parameters of the model; and,
L - maximum likelihood.

The physical characterization data were subjected to a completely randomized design, in a 3 x 2 factorial scheme, corresponding to 3 drying temperatures (60, 70 and 80 °C) x 2 thicknesses (0.005 and 0.01 m), and 3 replicates, using the software program Sisvar 5.6 (Ferreira, 2014), and the means were compared by Tukey test at $p \leq 0.05$.

Results and Discussion

The initial moisture content of the ground jambu leaf paste was 92.99% (w.b.) and the final average after drying was 4.35% (w.b.). From the experimental data of the drying kinetics, the mass flux (kg m^{-2} s^{-1}) was calculated as a function of the moisture content (kg kg^{-1} dry matter), at temperatures of 60, 70, and 80 °C and thicknesses 0.005 and 0.010 m, as represented in Figure 1.

The results (Figures 1A, B, C, D, E and F) show that in the initial drying period, there was the heating of the crushed leaf paste with a small reduction in moisture content, characterizing the beginning of water movement in the product. Then, the constant rate period is established, in which the drying rates are high and all the energy supplied is used to evaporate water from the material. Therefore, the ground jambu paste showed a period of constant drying rate. Wang et al. (2021) report that, as air moves across the surface of the food, surface moisture is adsorbed, creating internal and external moisture gradients that help remove water from the food.

During drying, the constant rate period showed a significant range in the moisture content of the ground pulp of jambu leaves, ranging from 13.70 to 1.17 kg kg^{-1} solid for different temperature conditions and layer thicknesses (Figure 1B). In the final stage of drying, there is a decrease in the mass flux, after reaching the critical water content that defines the beginning of the period of decreasing drying rate.

This relationship of drying time is confirmed when observing the mass flux results, when at lower drying temperatures they showed lower mass flux values for the constant drying rate stage for both thicknesses. In addition, the mass flux was lower for the 0.01 m thickness at different temperatures.

The transition data between the period of constant flux and the first period of decreasing flux (critical moisture content) and the values of the Akaike Information selection criterion (AIC) are shown in Table 1.

In analyzing the drying curves of crushed jambu leaves (Figure 1), it is possible to observe a typical behavior for plant products, so linear and quadratic polynomial expressions and the evaluation of their fits could have been used. For the selection criterion of AIC models, the drying conditions of 60 and 80 °C in both thicknesses showed the best fit by the linear equation. At 70 °C, both drying layer thicknesses were better described by the quadratic expression. The AIC criterion demonstrates the predominance of data fit (Gomes et al., 2018), with lower AIC values reflecting a better fit of the data to the evaluated models (Akaike, 1974). Therefore, for the conditions of 60 and 80 °C (in both thicknesses), the data showed a better fit of the linear equation and for the temperature of 70 °C, in both layer thicknesses, the quadratic model stands out.

The critical moisture contents that describe the transition between constant and decreasing drying rates did not show a clear trend as a function of temperature and layer thickness. In general, the critical moisture content ranged from 1.17 to 4.18 kg kg^{-1} solid, for the assessed conditions of temperature and layer thickness (Figures 1B and E). May & Perré (2002) described values of 2.1, 2.8, and 1.6 kg kg^{-1} dry matter of critical moisture content for avocado, carrot, and potato, respectively.

As for the results of the technological parameters of the ground jambu paste after drying, they are summarized in Table 2. For the results of the powder yield, no difference was observed as a function of temperature and drying thickness, with an average yield value of 8.26%. This result suggests that a temperature of 60 °C is efficient for the treatment.

The wettability time ranged from 0.33 to 0.85 g min^{-1}, with the highest level at temperature of 80 °C and thickness of 0.005 m. Samples subjected to a temperature of 80 °C differed in terms of wettability time ($p \leq 0.05$) in 0.005-m and 0.01-m thickness layers. Wettability is defined as the ability of a mass of powder to penetrate a liquid, favored by capillary forces (Caliskan & Dirim, 2016). Thus, the samples with 0.005-m layer showed greater resistance to water penetration.

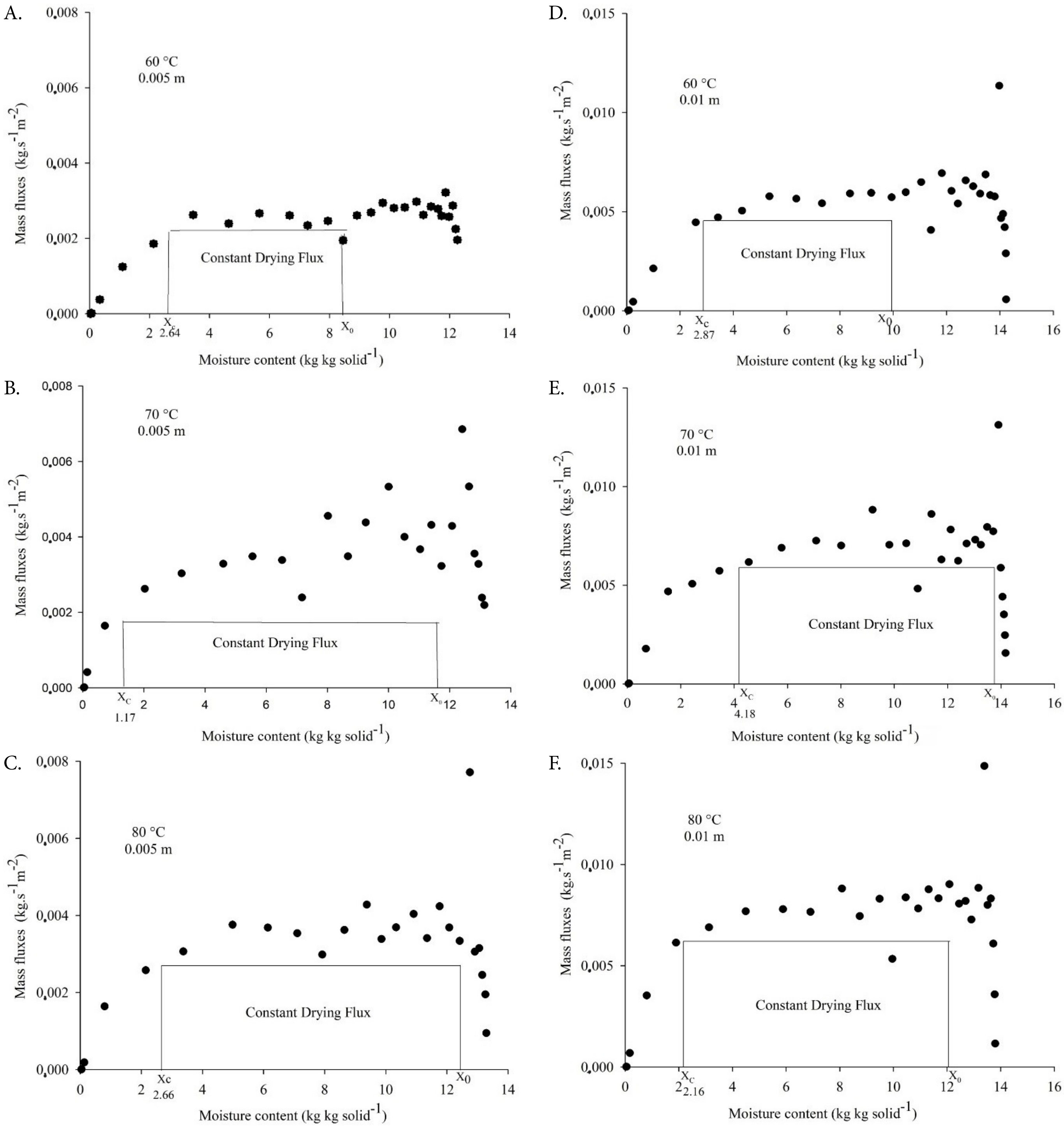

Figure 1. Experimental data of mass flux as a function of moisture content during convective drying of crushed jambu leaf paste at temperature 60 °C and thickness 0.005 m (A), temperature 70 °C and thickness 0.005 m (B), temperature 80 °C and thickness 0.005 m (C), temperature 60 °C and thickness 0.01 m (D), temperature 70 °C and thickness 0.01 m (E), and temperature 80 °C and thickness 0.01 m (F)

Table 1. Estimates of the critical moisture content and AIC fitting criteria for the linear and quadratic polynomials during convective drying of crushed jambu leaf paste at temperatures of 60, 70, and 80 °C and thicknesses of 0.005 and 0.01 m

Temperature (°C)	Critical moisture content ($kg\ kg^{-1}$ solid)		AIC			
			Linear		Quadratic	
	Thickness (m)					
	0.005	0.01	0.005	0.01	0.005	0.01
60	2.64	2.87	-473.12	-437.45	-471.92	-374.21
70	1.17	4.18	-312.36	-340.54	-370.94	-356.21
80	2.66	2.16	-389.69	-404.16	N/C	-241.50

N/C - No convergence was observed, AIC - Akaike, °C - Degrees Celsius, m - Meter, kg - Kilogram

Table 2. Mean values of the technological parameters of crushed jambu paste after drying at temperatures of 60, 70, and 80 °C and thicknesses of 0.005 and 0.01 m

Technological parameters	Thickness (m)	Temperature (°C)		
		60	70	80
Yield (%)	0.005	9.61 aA	7.97 aA	7.96 aA
	0.01	8.17 aA	7.88 aA	7.94 aA
Wettability time (g min^{-1})	0.005	0.40 bA	0.52 bA	0.85 aA
	0.01	0.33 bA	0.37 bB	0.57 aB
Static repose angle (θ)	0.005	13.29 aA	12.61 aB	13.29 aA
	0.01	13.53 aA	13.56 aA	13.32 aA
Bulk density (g cm^{-3})	0.005	0.47 aA	0.44 abB	0.44 bA
	0.01	0.47 aA	0.47 aA	0.45 aA
Compacted density (g cm^{-3})	0.005	0.64 aB	0.59 aB	0.61 aA
	0.01	0.71 aA	0.68 aA	0.63 bA
Hausner Factor	0.005	1.37 aB	1.35 aB	1.38 aA
	0.01	1.50 aA	1.43 aA	1.41 aA
Compressibility index (%)	0.005	26.67 aB	25.67 aB	27.67 aA
	0.01	33.33 aA	30.33 aA	29.00 aA
Solubility (%)	0.005	98.95 aA	98.27 aA	97.67 aA
	0.01	98.33 aA	96.47 aA	95.51 aA
Granulometry (mm)	0.005	1.91 aA	2.13 bA	1.88 aB
	0.01	1.78 bB	1.79 bB	2.02 aA

Means followed by the same lowercase letter in the rows and uppercase letter in the columns are not different from each other by the Tukey test at $p \leq 0.05$

In analyzing the bulk density results for the thickness of 0.01 m, there was no difference between the treatments with the increase in drying temperatures, and only the bulk density in the treatment at 70 °C differed between the layer thicknesses. When analyzing the compacted density, only the treatment at 80 °C showed no difference among the layers. The same was observed in the 0.005 m thickness. In the 0.01 m thickness, there was a difference only at the temperature of 80 °C. The bulk and compacted densities are directly influenced by the structure of the material, which may have different particles, porosity, and spaces between particles according to the characteristics of the analyzed powder (Santos et al., 2023). Therefore, these characteristics may have led to the results achieved in this study.

The static repose angle (θ) was not significantly influenced by the temperatures employed in this experiment as they did not show statistical variations by Tukey's test. It was observed that at a temperature of 70 °C, there was a difference between the evaluated thicknesses, with the lowest value of 12.61° at temperature of 70 °C and layer of 0.005 m. Shittu & Lawal (2007) consider particulate solids with average values of up to 35° of the angle of repose as of good flowability, from 35 to 45° as weakly cohesive, from 45 to 55° as cohesive and above 55° as very cohesive. Therefore, the resulting particulate material can be characterized with good cohesion.

As for the results of the Hausner factor (HF), all powder particles showed values greater than 1.25 and the Carr index (CI) greater than 25%, which characterizes the powders with cohesion between the particles and classifies them as having poor flowability (Santhalakshmy et al., 2015). The compressibility index (CI), as well as the Hausner Factor (HF) are pieces of information that allow the evaluation of the flowability properties of the particles, as well as the angle of repose, which indicates greater powder flow for smaller magnitudes (Medeiros et al., 2001), essential features in the packaging stage.

Ong et al. (2014), when studying mango powder, observed HF greater than 1.2 and CI greater than 22%. Factors that can influence this parameter are the water content of the powder, water activity, particle size, and agglomeration (Medeiros et al., 2001).

Solubility is one of the parameters used to check the ability of the powder to remain in a homogeneous mixture with water (Vissotto et al., 2006). The solubility results for the assessed powders were greater than 90% and no difference was found under the experimental conditions. Because the solidification of powders is the ability to absorb water from the environment that surrounds them and thus there is the formation of bonds between food particles, especially on surfaces of amorphous products (Medeiros & Lannes, 2010), the investigated material may be susceptible to absorption of water from the environment.

Medeiros & Lannes (2010) reported that the characterization of a powder will be incomplete without granulometric distribution data because the size of the particles is directly related to the physical properties of the powder. Thus, the average size of the particles was determined by evaluating the granulometry of the powder, which showed value of 1.93 mm (Table 2). Barni et al. (2009), when studying the powder of *Ipomoea pes-caprae* (railroad vine or goat's foot), stated that different parts of the plant material showed a similar profile of granulometric distribution, and quantified more than 50% in the material in powder, obtained from the leaves of the plant, with size between 1.0 and 2.0 mm, close to that obtained in this study.

Conclusions

1. The jambu powders obtained under different conditions demonstrated the existence of a significant period of constant drying rate for the ground jambu leaf paste. For the AIC selection criterion of models, the fit by the linear equation was better under the drying conditions of 60 and 80 °C, in both layer thicknesses.

2. The quadratic expression represented the temperature of 70 °C in both thicknesses. Critical moisture content as a function of thickness and drying temperature did not show a clear trend.

3. The material showed favorable physical characteristics, such as high solubility and cohesiveness, free flow, and good wettability.

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