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Determination of thermophysical properties of cupuassu (*Theobroma grandiflorum*) dry almonds

Determinação de propriedades termofísicas de amêndoas secas de cupuaçu (*Theobroma grandiflorum*)

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Resumo
Em comparação com o cacau, pouco tem sido reportado em relação à secagem das amêndoas secas de cupuaçu que podem ser empregadas na produção de *cupulate*, um produto tipo chocolate. Dessa forma, foram determinadas propriedades termofísicas das amêndoas de cupuaçu (umidade = 9,68 % b.s.) como: condutividade térmica (k) de 0,14 kW/(m.K), calor específico (c_p) de 2,86 kJ/(kg.K), difusividade térmica (α) de $4{,}8 \cdot 10^{-5}$ m²/s, difusividade efetiva (D_{eff}) de $9{,}94 \cdot 10^{-10}$ – $6{,}29 \cdot 10^{-10}$ m²/s e energia de ativação (E_a) de 14,90 kJ/mol. Estes resultados demonstraram uma similaridade entre os valores do cupuaçu e do cacau e permitem que estudos mais específicos sejam realizados para o desenvolvimento de secadores para as amêndoas do cupuaçu.
Palavras-chave: Curva de resfriamento. Curva de secagem. Lei de Fourier. Modelo de Fick. Modelo de Wiebull.

Abstract
In comparison to cocoa, little has been reported on the drying of cupuassu almonds that can be used to produce *cupulate*, a chocolate type product. Thus, in this study thermophysical properties of cupuassu dry almonds (moisture = 9.68 % d.b.) were determined as: thermal conductivity (k) of 0.14 kW/(m.K), specific heat (c_p) of 2.86 kJ/(kg.K), thermal diffusivity (α) of 4.8·10-5 m²/s, effective diffusivity (D_{eff}) of $9.94 \cdot 10^{-10}$ - $6.29 \cdot 10^{-10}$ m²/s and activation energy (E_a) of 14.90 kJ/mol. These results showed a similarity of values between cupuassu and cocoa and allows to perform more specific studies for the development of dryers for the cupuassu almonds.
Keywords: Fick's model. Fourier's law. Cooling curve. Drying curve. Weibull's model.

Nomenclature
c_p = specific heat, kJ/(kg.K);
C_p = calorific capacity, kJ/°C;
COA = cocoa almonds;
CUA = cupuassu almonds;
d.b. = dry basis;
D_{eff} = effective diffusivity, m²/s;
E_a = activation energy, kJ/mol;
k = thermal conductivity, kW/(m.K);
l = thickness of the tablets, mm;
L = position of the thermometers before or after the tablets, mm;
m = mass, g or kg;
M = moisture content, % (w/w);
MR = moisture-ratio, dimensionless;
P = relative mean error, %;
r = equivalent radius, m;
R = ideal gas constant, J/(K.mol);
R^2 = coefficient of variation;
T = temperature (°C or K);
V = volume, mL or m^3;
w.b. = wet basis;
α = thermal diffusivity, m²/s;
ρ = specific mass, g/mL or kg/m^3

1. Introduction

Cupuassu (*Theobroma grandiflorum*, Schumann) is a fruit belonging to the Malvaceae family and native to the Amazon region. Its fruits can have a weight of 200 to 4,000 g containing from 15 to 50 seeds covered by a pulp (Novalli et al., 2015; Pereira et al., 2018; Ramos et al., 2020). Being cupuassu from the same family as cacao (*Thebroma cacao*), it shares certain sensory and physical-chemical properties with cacao. Standing out among these common properties, the capability of the beans to be fermented and dried/roasted becoming almonds of great value and, ultimately, the extraction of a "cupuasu butter" allow, together, the elaboration of a product very similar to chocolate which in Brazil is called *cupulate* or "cupuassu chocolate" (Lannes et al., 2002; Oliveira and Genovese, 2013).

The pulp of cupuassu has a sweet and citric flavor; it is very appreciated and consumed as juice and it is also used to produce sweets, ice cream or fermented beverages (Pereira et al., 2017; Quijano and Pino, 2007; Vriesmann and Petkowicz, 2019). While the extraction of pulp is still the destination of most of the cupuassu, there is a promising production of *cupulate* and the technological peculiarities between the liquor (fermented and dried/toasted almonds paste) and butter (extracted by pressing the paste) of cupuassu and cocoa should be considered.

In a recent study on the fermentation of cupuassu seeds, Ramos et al. (2020) reported the differences and similarities between cupuassu and cocoa fermentation. In addition, cupuassu liquor has been used alone (Lannes et al. 2002) or blended (Cohen et al., 2009) with cocoa liquor to obtain *cupulate*. The study by Oliveira and Genovese (2013), in turn, suggests that the frequent consumption of cupuassu liquor is capable of benefiting health in as many ways as cocoa liquor consumption. These studies indicate that chocolate technology can be successfully adapted for cupulate, resulting in products with good acceptance and benefits that go beyond the variability in fruit processing.

The processing of cocoa almonds (COA) to produce chocolate is consolidated and well documented (Jahurul et al., 2013; John et al., 2020; Konar, 2019; Sirbu et al., 2018); however, more technological information on cupuassu almonds (CUA) is needed. Although the drying of COA is crucial in the development of the sensory profile of chocolate, there is a lack of records about the particularities of the drying of CUA. The study by Barreto et al. (2011) reports that the compositions of mineral and dry matter of COA and CUA are similar, but the fat content in CUA (392.7 g/kg) was almost 51 % higher than in COA. These data reinforce that, despite the phylogenetic similarities, each almond should be individually investigated.

The drying aims to reduce the moisture content of fermented COA from 50 – 55 % (w/w) (after fermentation) to 6 – 8 % (w/w) and plays, together with fermentation and roasting, an important role in obtaining the organoleptic characteristics associated with chocolate (Barreto et al., 2011). The drying can be carried out naturally, by sun exposure, or controlled with the aid of dryers. Previous studies propose the use of a solar-energy vertical dryer for the drying of COA, the internal temperature distribution being assessed with the aid of mathematical modeling (Botelho et al., 2016; Sales and Cândida, 2016; Santos and Sales, 2014). The literature offers further examples of the importance of mathematical modeling applied to the drying of food and the like, these including potato (Djebli et al., 2020), corn cob (Corrêa et al., 2004), meat (Trujillo et al., 2007), canola (Hemis et al., 2015), grape (Johann et al., 2018), jatropha (Keneni et al., 2009), kodo millet grains and fenugreek seeds (Yogendrasasidhar and Setty, 2018) and even the drying of cupuassu pulp (Perez et al., 2013), among others.

The description of the transport phenomena involved in the mathematical modeling of drying requires certain thermophysical parameters, such as: thermal conductivity [k, W/(m.K)], specific heat [c_p, kJ/(kg.K)] and thermal diffusivity (α, m²/s). For COA, these values have already been determined by Sasseron (1984) as, respectively, 0.144 - 0.388 W/(m.K), 2.999 - 3.177 kJ/(kg.K) and $4.0 \cdot 10^{-7}$ – $12.9 \cdot 10^{-7}$ m^2/s. In addition to the determination of these parameters, the study of drying can provide information on the effective diffusivity (D_{eff}, m²/s) and drying activation energy (E_a, kJ/mol) of the material investigated and other physical measures can be performed. Thus, the present study aimed to determine these thermal parameters of CUA, given the scarcity of these specific data, which are necessary for sequential studies of mathematical modeling and for the design of dryers for CUA, for example.

2. Material and Methods

The methodologies used in this study were defined based on previous studies (Andrade et al., 2004; Araújo et al., 2004; Efraim et al., 2010; Koua et al., 2019; Sasseron, 1984). The experiments were performed with the esteemed support of the Laboratory of Biotransformation and Organic Biocatalysis (LABIOCAT) and the Cocoa Innovation Center (CIC), both at the State University of Santa Cruz (UESC, Ilhéus, Bahia, Brazil), and the Executive Committee of the Cocoa Farming Plan (CEPLAC, Itabuna, Bahia, Brazil).

2.1 Fermentation of Seeds and Drying of Almonds

The cupuassu (*Theobroma grandiflorum*) and cocoa (*T. cacao*) seeds used in this study were acquired from producers from the region of Ilhéus (Bahia, Brazil) between October 2017 and June 2018. The seeds were individually fermented in wooden troughs with a capacity of up to 80 kg of seeds, at the CEPLAC facilities (Itabuna, Bahia, Brazil). Before fermentation, cocoa seeds were partially pulped and cupuassu seeds were totally pulped, as it has been reported that the presence of pulp in cupuassu seeds delays fermentation (Ramos et al., 2020 and 2016). The natural fermentation of the seeds lasted for 6 days and, from the third day of that period, the seeds were revolved every 24 h. The highest temperature in the troughs occurred on the last day of fermentation and reached approximately 47 °C. At the end of fermentation, the obtained cupuassu and cocoa almonds (CUA and COA, respectively) had a moisture content of 33.35 % (w/w, w.b.) and were naturally dried in the sun for 9 days until they reached a moisture content of 6 – 8 % (w/v) – measured with an infrared moisture analyzer (BEL, iThermo). These dried almonds were intended for physical characterization and determination of the thermophysical properties.

2.2 Characterization of the Dried Almonds

Naturally fermented and sun-dried CUA were characterized (quintuplicate) as to the mass of the almonds, cotyledon (peeled almond) and husks on a precision scale (BEL, L303i). Using an analog caliper, with a resolution of 0.01 mm, the dimensions *a* = length, *b* = width, and *c* = thickness of 10 almonds were determined. The equivalent radius (*r*, m), on the other hand, was determined (Eq. 1) by equalizing the volume (*V*, m^3) of the grain (determined from its perpendicular diameters, *a*, *b* and *c*) to the volume of a sphere, since such shape is the closest to that of the almonds.

$$V = \frac{\pi \cdot (a \cdot b \cdot c)}{6} = \frac{4\pi \cdot (r^3)}{3} \tag{1}$$

Moisture content was determined (triplicate) by gravimetry, from its initial wet weight (m_w, g) to its final dry weight (m_d, g) after 24 h of drying at 105 °C in an oven with air circulation and renovation (TECNAL TE-394/1). These values were applied in the calculation of moisture content on a dry basis [M_d, % w/w (d.b.)] (Eq. 2) and on a wet basis [M_w, % w/w (w.b.)] (Eq. 3). The moisture content of cotyledon was determined and compared with the moisture content of the almond in a moisture analyzer (BEL, iThermo 163L).

$$M_d = [(m_w - m_d)/m_d] \cdot 100\% \tag{2}$$

$$M_w = [(m_w - m_d)/m_w] \cdot 100\% \tag{3}$$

2.3 Determination of Thermophysical Properties

The dried CUA were manually peeled, then they were crushed in a domestic coffee grinder (CADENCE) and used for the determinations described in the following topics (Ribeiro et al., 2007; Sasseron, 1984). These determinations applied the principles of the dynamics of heat transfer between a body and the environment, which are based on Newton's Law of Cooling: $(dQ/dt) = (h \cdot A) \cdot (T - T_a)$ and Fourier's Law: $q = -(k.A) \cdot (dT/dx)$ (Silva et al., 2003).

Thermal conductivity [*k*, W/(m.K)]: For the determination of *k*, tablets with dried and crushed CUA or COA almonds were prepared (triplicates) with the aid of a cylindrical mold of 41.50 mm in diameter and a pneumatic press (SPECAC) applying a pressure of 2.5 tons. The obtained CUA and COA tablets had mass (*m*) and thickness (*l*), respectively, of: 12.86 ± 0.86 g and 10.80 ± 0.84 mm, and 13.91 ± 2.47 g and 11.51 ± 0.83 mm. These tablets were used in an experimental equipment composed of a cylindrical tube of insulating material (thick cardboard), 65.00 cm in length and 6.00 cm in diameter, and a 15 W incandescent lamp at one end, as shown in Figure 1. The tube had two cuts, at the distances (*L*, cm) of 24 and 30 cm from the lamp. In the first cut, the only used in this study, a tablet (CUA or COA) was placed, and two analog mercury thermometers were accomodated at a distance of 3.0 cm before and after the tablet. The equipment was plugged into a 127 V outlet to lit the lamp which transfered heat along the tube; temperatures T_1 (before the tablet) and T_2 (after the tablet) were then monitored, until reaching an equilibrium temperature (~ 60 min), which were, for T_1 and T_2 for CUA, respectively, of 40.5 ± 0.9 °C and 26.7 ± 0.8 °C, and for cocoa, respectively, of 39.5 ± 1.4 °C and 26.5 ± 0.7 °C.

The calculation of *k* was made under the assumption that the two tablets are subjected to the same energy rate: q (W) $= (k \cdot A) \cdot (\Delta T/\Delta L)$; knowing the temperature gap (T_1 and T_2, K), the position of the thermometers before and after the tablet (L_1 and L_2 mm) and the tablet area (*A*, mm^2). Since the value of A is the same for cupuassu and cocoa tablets, and since the value of k_{coa} (for COA) is known as 0.1523 W/(m.K) (Sasseron, 1984), the expression can be summarized as presented in Equation 4; in this equation the subscript “cua” referrers to cupuassu and “coa” to cocoa.

$$k_{cua} = k_{coa} \cdot \left[\frac{(T_1 - T_2)_{coa}}{(T_1 - T_2)_{cua}}\right] \cdot \left(\frac{L_{cua}}{L_{coa}}\right) \quad (4)$$

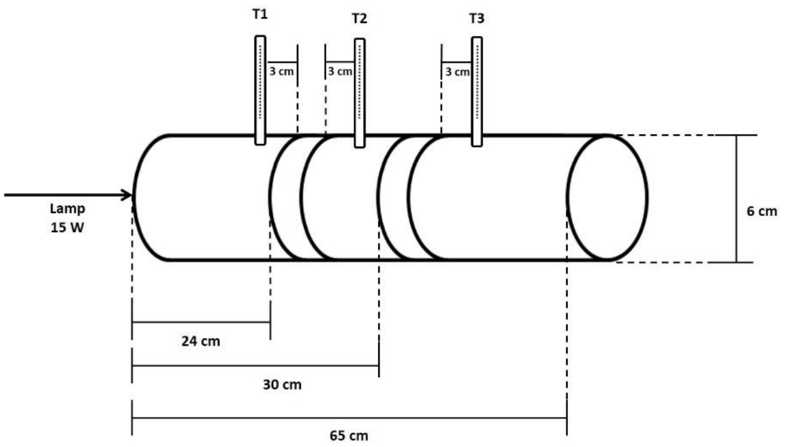

Figure 1 - Representation of the equipment used to determine the thermal conductivity of cupuassu and cocoa tablets indicating the positions for three thermometers (T1, T2 and T3) and for two tablets (L1 = 24 cm and L2 = 30 cm).

Specific mass [ρ, g/mL or kg/m^3]: The determination of ρ for the dried CUA was carried out (10 replicates) based on the displacement of the water volume (V_{dw}, mL) in a 10 mL graduated cylinder containing no more than 8 mL of water, after the addition of 1.0 – 1.5 g of dried almonds (m_d, g) according to Equation 5:

$$\rho = (m_d / V_{dw}) \quad (5)$$

Specific heat [c_p, kJ/(kg.°C)]: The determination of c_p of dried CUA was determined using a thermometer with an accuracy of 0.1 °C and a vessel thermally insulated with Styrofoam (experimental calorimeter). The first stage of the experiment consisted of calibrating the calorimeter (triplicate) by inserting 50 g of water (m_c = 0.05 kg) at room temperature (T_c = 25 – 27 °C) into the calorimetric vessel and then mixing 100 g of water (m_h = 0.10 kg) previously heated (T_h = 50 – 52 °C) to finally note the equilibrium temperature of the system (T_{eq} = 41 – 43 °C). Since the specific heat of water ($c_{p.w}$) is known as 4.187 kJ/(kg.°C), the calorific capacity of the calorimeter ($C_{p.cal}$) was calculated as 0.014 ± 0.002 kJ/°C based on the relation also applied by Ribeiro et al. (2007): $C_{p.cal} = [(m_f \cdot c_{p.w})(T_c - T_{eq}) + (m_h \cdot c_{p.w})(T_h - T_{eq})]/(T_{eq} - T_c)$. A similar procedure was followed (triplicate) with the same mass of hot (T_h = 52 – 53 °C) and cold (T_c = 25.5 – 26.0 °C) water and a sample of CUA (m_{cua} = 0.02068 – 0.02277 kg), reaching an equilibrium temperature between 41.5 – 42.0 °C. The c_p [kg/(kJ.K)] was then calculated according to Equation 6; in this equation, the subscripts "cua" refers to cupuassu.

$$c_p = \frac{(m_c \cdot c_{p.w}) \cdot (T_c - T_{eq}) + (C_{p.cal})(T_c - T_{eq}) + (m_h \cdot c_{p.w}) \cdot (T_h - T_{eq})}{(m_{cua}) \cdot (T_{eq} - T_c)} \quad (6)$$

Thermal diffusivity [α, m^2/s]: From the values of specific mass (ρ), thermal conductivity (k) and specific heat (c_p) of CUA, the thermal diffusivity (α) was determined indirectly through Equation 7 (Andrade et al., 2004).

$$\alpha = \frac{k}{\rho . c_p} \quad (7)$$

2.4 Drying Curves

To obtain the profiles for the decay of moisture that occurs during the drying carried out under controlled conditions, the following definition was applied for the moisture-ratio dimensionless parameter (*MR*) calculated as indicated in Equation 8, which requires the values of the following water contents (%, w/w) (decimal, d.b.): initial (M_i), at the time analyzed (M_t), and equilibrium (M_e) (Camicia et al., 2015; Silva et al., 2014). Thus, the initial weight of the CUA samples and the temperatures analyzed were: 102.50 g / 40 °C, 103.26 g / 55 °C, and 99.73 g / 70 °C. The samples were taken and weighted hourly and, once completed a 9 h period, they were kept in the oven for another 24 h to reach constant weight: 44.14 g / 40 °C, 44.54 g / 55 °C and 42.93 g / 70 °C. The initial moistures of the samples were: 1.322, 1.318 and 1.324 % w/w (decimal d.b.).

$$MR = \frac{(M_t - M_e)}{(M_i - M_e)} \qquad (8)$$

Mathematical modelling of drying curves: The moisture values obtained during drying were adjusted to mathematical models (Guiné et al., 2019; Ju et al., 2018; Reis et al., 2015; Silva et al., 2014; Silva et al., 2015) presented in Table 1 with the aid of LABfit software, version 7.2.50. The adjustment of the experimental data to the mathematical models was evaluated through the coefficient of variation (R^2) and through the relative mean error, calculated by the expression: *P* (%) = [(experimental value - predicted value)/experimental value]·100%. Additionally, the Fick's model (Tab. 1), truncated into up to four terms, was used in determining the effective diffusivity (D_{ef}, m²/s) – for the three temperatures analyzed – and the Arrhenius equation (Eq. 9) was applied to estimate the activation energy of the drying process (E_a, J/mol), considering: D_o a constant, *T* the temperature (K) of analysis and *R* the ideal gas constant [8.314 J/(K.mol)] (Reis et al., 2015; Silva et al., 2014).

$$D_{ef} = D_o \cdot exp[-(E_a/R \cdot T)] \qquad (9)$$

Table 1. Theoretical and semi-empirical mathematical models for drying curve modeling, where *t* is the drying time (s), *k* is the drying constant (dimensionless), *α*, *n* and *β* are model coefficients and *r* is the radius (m) and D_{ef} the effective diffusivity (m2/s) of the dried product.

Model	Type	Equation	Reference
Fick	Theoretical	$r_X = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{-n^2.\left(\frac{\pi^2.D_{ef}}{r^2}\right).t}$	Silva et al. (2014)
Henderson-Pabis	Semi-empirical	$r_X = ae^{-kt}$	Reis et al. (2015)
Page	Semi-empirical	$r_X = e^{-kt^n}$	Guiné et al. (2019)
Weibull	Semi-empirical	$r_X = e^{-(\frac{k}{\beta})^a}$	Ju et al. (2018)
Peleg	Semi-empirical	$X = X_0 - \frac{t}{k_1 + k_2 t}$	Silva et al. (2015)

2.5 Cooling Curves

The cooling curves of COA and CUA tablets (obtained as described before) were calculated starting at the temperature of 70 °C. To reach this temperature, the tablets were exposed to heat on an oven with air circulation and renovation (TECNAL TE-394/1). Upon reaching the predetermined temperature, the tablets were removed from the oven and the temperature was monitored with an infrared digital thermometer with Scantemp laser sight (INCOTERM, St-0600) for 60 min at equally spaced intervals.

3. Results and Discussion

3.1 Characterization and Determination of Thermophysical Properties

The cotyledon of dried CUA was determined as 76.3 % of the total weight of almonds; the average weight was 2.832 ± 0.252 g and, consequently, the husks corresponded to 25.57 % of almonds. The dimensions were determined as a = 2.53 ± 0.08 cm, b = 1.88 ± 0.09 cm and c = 1.41 ± 0.16 cm, and the equivalent radius was determined as r = 0.94 ± 0.09 cm. Moisture content were determined as 9.69 ± 0.03 % (w/w, d.b.) and 8.84 ± 0.02 % (w/w, w.b.). The moisture of the cotyledons (w.b.) presented a value about 21 % lower than that of the whole almond, proving that water retention occurs mainly in the cotyledon. The moisture contents of COA were: 7.04 ± 0.08 % (w/w, d.b.) and 6.58 ± 0.07 % (w/w, w.b.). The specific mass (ρ) determined for CUA and COA were, respectively: 999.8 ± 71.4 kg/m^3 and 917.7 ± 109.9 kg/m^3.

The determination of the thermophysical properties for dried CUA [moisture content of 9.69 % (w/w, d.b.)] were performed and the obtained values are presented in Table 2, along with those previously determined for COA (Almeida, 1979; Sasseron, 1984). The results obtained confirm the expected similarities between the two almonds; some differences are observed if the property is determined for its apparent form (considering the intergranular air mass in the bed of the almonds) instead of its real form (intrinsic to the almonds).

Many other food and food-related products have already had their thermophysical properties determined, in order to enable the industry to better dimensioning individual processing steps, such as the drying and/or storage. Some examples can be cited, but only in a quantitative aspect, as the differences between the species and moisture values [M, % (w/w), d.b.] must be considered. The thermal conductivity (k) of pearl millet grains (*P. americanum*) was determined as being between 0.1241 – 0.1421 W/(m.°C) [11 % < M < 25 %] (Corrêa et al., 2004); the specific heat (c_p) of cassava starch pellets (M. *esculenta crantz*) was determined as being around 1.5 kJ/(kg.°C) [M = 4 % (w/w)] (Moreno et al. 2014); the specific mass (ρ) of corn grains (*Z. mays)* with M ~ 9 % (w/w) was reported as being around 720 – 730 kg/m^3 (Andrade et al., 2004) and thermal diffusivity values (α) have been reported as: $1.64 \cdot 10^{-7}$ – $1.65 \cdot 10^{-7}$ m^2/s for cashew almonds (*S. mombin*) (7.81 % < M < 14.04 %) (Gama et al. 2012).

Table 2. Thermal conductivity (k), specific heat (c_p), specific mass (ρ) and thermal diffusivity (α) determined for cupuassu almonds compared to previously determined values for cocoa almonds. The moisture content [M, % (w/w), dry basis] is indicated for each one.

Properties	Cupuassu M = 9.69 % (d.b.)	Cocoa M = 9.69 % (d.b.)*	Cocoa M = 9.69 % (d.b.)**
k, W/(m·°C)	0.1378 ± 0.0164	0.16	0.09 #
c_p, kJ/(kg·°C)	2.86 ± 0.12 #	3.25 #	2.39 #
ρ, kg/m^3	917.7 ± 109.9	926.75 #	876.88
α, m^2/s	$4.83 \cdot 10^{-5}$	$4.41 \cdot 10^{-5}$	$9.25 \cdot 10^{-8}$

Sources: * Sasseron (1984), ** Almeida (1979); # apparent property.

3.2 Drying of Cupuassu Almonds

The drying profiles obtained for CUA are represented in Figure 2 and are in accordance with the drying curves reported in literature (Reis et al., 2015; Silva et al., 2014). It is worth to remember that the completion of a drying carried out at a temperature close to room temperature tends to require more time, and the growth of deteriorating microorganisms may occur; on the other hand, extremely high temperatures may reduce the sensory/nutritional quality or induce the migration of butter to the surface of the bean (Efraim et al., 2010).

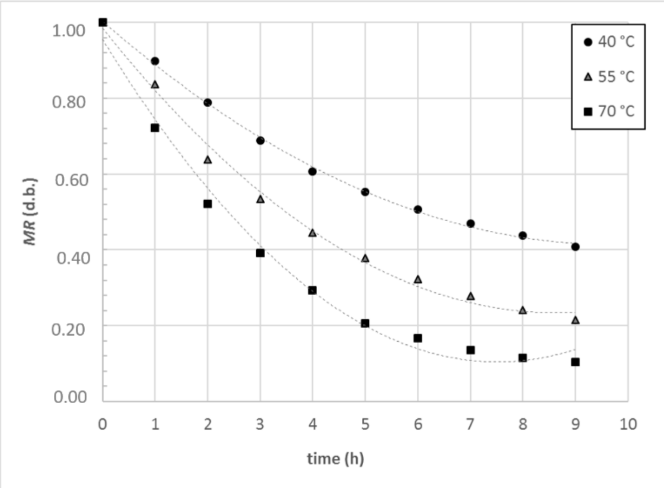

Figure 2 - Moisture ratio (*MR*, decimal, dry basis) as a function of the drying time of cupuassu almonds in an oven at 40, 55 and 70 °C. Dotted lines only indicate the trend between experimental values.

From the values presented in Figure 2, the data were mathematically adjusted to the selected models (Tab. 1) and Table 3 presents the values of the coefficients for each model and temperature. In general, the four models presented correlation coefficients (R^2) greater than 0.99, indicating a good mathematical adjustment. Considering the largest R^2 coefficients and the smallest errors (P), Weibull's was the best model for the temperature of 40 °C, the Henderson-Papis was the best for 55 °C, and Peleg's model was the best for 70 °C. Conducting the experiment with greater number of points in the drying curves would allow a more detailed evaluation of the models and would also allow the adjustment to models with a larger number of terms. The study by Reis et al. (2015), for example, which analyzed the drying of peppers at 50 °C and with air circulation speed of 2 m/s, presented a better fit with a different model, Midilli and Kucuk's, obtaining R^2 = 0.9997 and P = 0.2040 %. Other works can be cited such as Menges and Ertekin (2006) who investigated fourteen models for the drying of apple slices from 60 to 80 °C and velocities of air from 1 to 3 m/s and the work of Ju et al. (2018) who investigated the Weibull and Bi-Di models to describe the drying of slices of yam with different thickness.

Table 3. Coefficients (a, k, n, β, k_1 and k_2) of Henderson-Papis, Page, Weibull and Peleg models for drying kinetics, adjusted to the experimental data obtained at temperatures (T) of 40, 55 and 70 °C, with respective correlation coefficients (R^2) and mean relative error (P, %).

T (°C)	Model	Coefficients							
		a	k	n	β	k_1	k_2	R^2	P (%)
40	Henderson-Papis	1.1707	0.0053	---	---	---	---	0.9929	4.26
	Page	---	0.0009	1.2933	---	---	---	0.9988	8.44
	Weibull	1.2933	---	---	225.34	---	---	0.9989	2.24
	Peleg	---	---	---	---	5.4778	0.6326	0.9950	7.09
55	Henderson-Papis	1.1218	0.0058	---	---	---	---	0.9952	3.33
	Page	---	0.0022	1.1623	---	---	---	0.9955	14.19
	Weibull	1.1623	---	---	195.90	---	---	0.9955	4.00
	Peleg	---	---	---	---	3.2392	0.5908	0.9940	5.91
70	Henderson-Papis	1.0719	0.0071	---	---	---	---	0.9954	4.06
	Page	---	0.0038	1.1079	---	---	---	0.9969	11.36
	Weibull	1.108	---	---	163.51	---	---	0.9969	2.91
	Peleg	---	---	---	---	1.9307	0.5899	0.9960	1.42

Fick's model (Tab. 1), with four terms in the series, was then applied in the calculation for the estimative of the effective diffusivity (D_{ef}) as and drying activation energy (E_a). The obtained values of D_{ef} (10^{-10} m^2/s^2) / R^2 for each temperature were: 3.94 / 0.9976 (40 °C), 4.65 / 0.9999 (55 °C) and 6.29 / 0.9975 (70 °C). As expected, the effective diffusivity of CUA increases with increasing the temperature, since this parameter expresses how easy water diffuses into the environment. These values of D_{ef} were used in the estimation of the activation energy (E_a) by linearization of the Arrhenius ratio, which resulted in a value E_a = 13.90 kJ/mol (R^2 = 0.9637). It is important to point out that for the determination of a more precise value it would be necessary to define D_{ef} at more temperature values. Even so, the values of D_{ef} and E_a estimated in this study are consistent with values previously reported for other materials, considering their differences in composition, such as: grape seeds ($4.36 \cdot 10^{-10} – 6.82 \cdot 10^{-10}$ m^2/s^2 and 11.29 to 12.83 kJ/mol) (Lozano et al., 2013), thistle flower ($1.30 \cdot 10^{-9} – 5.35 \cdot 10^{11}$ m^2/s^2 and 56.48 kJ/mol) (Guiné et al., 2019) and beans ($2.10 \cdot 10^{-10}$ - $6.8 \cdot 10^{-10}$ m^2/s^2 and 34.51 kJ/mol) (Silva et al., 2014) among others.

3.3 Cooling Curve of Cupuassu and Cocoa Almonds

The tablets prepared for the determination of thermal conductivity were used for the monitoring of the temperature decay, due to their greater homogeneity and similar dimensions, which favors the dynamics of heat-transfer with the environment (Silva et al., 2003; Silva, 2010). Figure 3 presents the two cooling profiles, for CUA and COA, the two curves showing a similarity that, again, corroborates with the similarities of thermophysical properties of the two almonds (Barreto et al., 2011; Lima and Sales, 2017). The temperature of environmental equilibrium (25.4 ± 0.3 °C) was reached by the two tablets in approximately 48 min and only for the first 18 min of cooling it was possible to identify up to 1.0 °C difference between the tablets (Fig. 3).

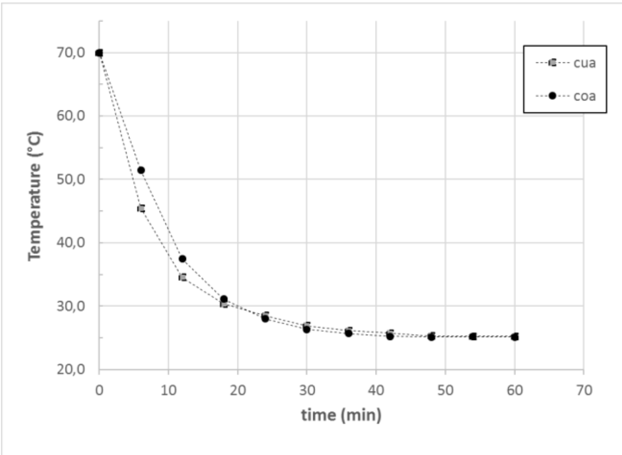

Figure 3 - Temperature decay over time for cupuassu (cua - gray squares) and cocoa (coa - black circles) almonds. Dotted lines only indicate the trend between experimental values and bars indicate the deviation.

4. Conclusions

The similarities between cocoa and cupuassu almonds are known by those who consume or process them. However, the proper development of equipment and technologies intended to these almonds requires specific data from each one, such as some thermophysical properties. The properties of cocoa have already been well defined, but there is still a lack of specific data regarding the cupuassu and the use of its dried almonds in the production of cupulate. The data obtained in this study become the first set of data related to cupuassu almonds, and they prove the similarity of some properties between the two species, thus reinforcing the idea that it is feasible to adapt chocolate technology to cupulate. Knowledge of the properties of cupuassu almonds will also allow future research on the mathematical modeling of drying and, consequently, the improvement of the desing of dryers for cupuassu almonds, as it has been done for cocoa almonds.

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References

Almeida, B. V. (1979) Determinação de propriedades físicas de amêndoas de cacau (*Theobroma cacao, L.)*. Doctorade Thesis. Federal University of Viçosa. Viçosa, MG, Brazil.

Andrade, E. T.; Couto, A. M.; Queiroz, D. M. & Peixoto, A. B. (2004) Determination of corn thermal properties. *Ciência Agrotecnologia*, 28(3), 488-498. https://doi.org/10.1590/S1413-70542004000300002.

Araújo, J. L.; Queiroz, A. J. M. & Figueirêdo, R. M. F. (2004) Termophysical properties of cupuaçu pulp at different solids contents. *Ciência e Agrotecnologia*, 28(1), 126-134. https://doi.org/10.1590/S1413-70542004000100017.

Barreto, W. S.; Barreto, F. S.; Ribeiro, M. A. Q.; Valle, R. R.; Sacramento, C. K. & Neto, B. A. M. (2011) *Comparação de características químicas de polpas e amêndoas de cacau e cupuaçu*. 51° Congresso Brasileiro de Química, São Luís - MA, Brazil. Available at: <http://www.abq.org.br/cbq/2011/trabalhos/3/3-57-10279.htm>. Accessed on February 18th, 2021.

Botelho, F. M.; Correa, P. C.; Botelho, S. C. C.; Vargas-Elias, G. A.; Almeida, M. D. S. D. & Oliveira, G. H. H. (2016) Physical properties of robusta coffee berries during drying: determination and modelling. *Coffee Science*, 11(1), 65-75. https://doi.org/10.25186/cs.v11i1.972.

Camicia, R. G. M.; Christ, D.; Coelho, S. E. M.; Camicia, R. F. M. (2015) Modeling of the drying process the seeds of cowpea. *Revista Caatinga*, 28(3), 206-214. https://doi.org/10.1590/1983-21252015v28n323rc.

Cohen, K.; Sousa, M. V. & Jackix, M. N. H. (2009) *Documentos 267 - Produto alimentício elaborado com sementes de cupuaçu e cacau*. EMBRAPA Cerrados, Planaltina, DF, Brazil.

Corrêa, P. C.; Andrade, E. T. & Afonso Júnior, P. C. (2004) Propriedades térmicas da massa granular de milheto, alpiste e painço: determinação e modelagem. *Revista Brasileira de Produtos Agroindustriais*, 6(1), 39-45. https://doi.org/10.15871/1517-8595/rbpa.v6n1p39-45.

Djebli, A.; Hanini, S.; Badaoui, O.; Haddad, B. & Benhamou, A. (2020) Modeling and comparative analysis of solar drying behavior of potatoes. *Renewable Energy*, 145, 1494-1506. https://doi.org/10.1016/j.renene.2019.07.083.

Efraim, P.; Pezoa-García, N. H.; Jardim, D. C. P.; Nishikawa, A.; Haddad, R. & Eberlin, M.N. (2010) Influence of cocoa beans fermentation and drying on the polyphenol content and sensory acceptance. *Ciência e Tecnologia de Alimentos*, 30, 142-150. https://doi.org/10.1590/S0101-20612010000500022.

Gama, M. J. A.; Cavalcanti Mata, M. E. R. M.; Duarte, M. E. M.; Aragão, R. F. & Farias, P. A. (2012) Apparent thermal diffusivity of caja seeds in above freezing to ultra low temperatures. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 16(3), 303-308. https://doi.org/10.1590/S1415-43662012000300011.

Guiné, R. P. F.; Fontes, L. & Lima, M. J. R. (2019) Drying kinetics and mass transfer properties in the drying of thistle flower. *Brazilian Journal of Food Technology*, 22, 1-13. https://doi.org/10.1590/1981-6723.05119.

Hemis, M.; Choudhary, R.; Gariepy, Y. & Raghavan, V. G. S. (2015) Experiments and modelling of the microwave assisted convective drying of canola seeds. *Biosystems Engineering*, 139, 121-127. https://doi.org/10.1016/j.biosystemseng.2015.08.010.

Jahurul, M. H. A.; Zaidul, I. S. M.; Norulaini, N. A. N.; Sahena, F.; Jinap, S.; Azmir, J.; Sharif, K. M. & Omar, A. K. M. (2013) Cocoa butter fats and possibilities of substitution in food products concerning cocoa varieties, alternative sources, extraction methods, composition, and characteristics. *Journal of Food Engineering*, 117(4), 467-476. https://doi.org/10.1016/j.jfoodeng.2012.09.024.

Johann, G.; Silva, E. A. & Pereira, N. C. (2018) Modelling and optimisation of grape seed drying: Equivalence between the lumped and distributed parameter models. *Biosystems Engineering*, 176, 26–35. https://doi.org/10.1016/j.biosystemseng.2018.10.004.

John, W. A.; Böttcher, N. L.; Behrends, B.; Corno, M.; D'Souza, R. N.; Kuhnert, N. & Ullrich, M. S. (2020) Experimentally modelling cocoa bean fermentation reveals key factors and their influences. *Food Chemistry*, 302, 125335. https://doi.org/10.1016/j.foodchem.2019.125335.

Ju, H. Y.; Zhao, S.; Mujumdar, A. S.; Fang, X.; Gao, Z.; Zheng, Z.; Xiao, H. (2018) Energy efficient improvements in hot air drying by controlling relative humidity based on Weibull and Bi-Di models. *Food and Bioproducts Processing*, 111, 20–29. https://doi.org/10.1016/j.fbp.2018.06.002.

Keneni, Y. G. E.; Hvoslef-Eide, A. K. E. & Marchetti, J. M. (2009) Mathematical modelling of the drying kinetics of *Jatropha curcas* L. seeds. *Industrial Crops and Products*, 132, 12–20. https://doi.org/10.1016/j.indcrop.2019.02.012.

Koua, B. K.; Koffi, P. M. E. & Gbaha, P. (2019) Evolution of Shrinkage, Real Density, Porosity, Heat and Mass Transfer Coefficients during Indirect Solar Drying of Cocoa Beans. *Journal of the Saudi Society of Agricultural Science*, 18(1), 72–82. https://doi.org/10.1016/j.jssas.2017.01.002.

Lannes, S. C. S.; Medeiros, M. L. & Amaral, R. L. (2002) Formulation of cupuassu "chocololate" and rheology of liquid product. *Revista Brasileira de Ciências Farmacêuticas*, 38(4), 463-469. https://doi.org/10.1590/s1516-93322002000400009.

Lima, G. P. & Sales, J. H. (2017) Thermal diffusivity of the cocoa in the function model geometry. *Revista SODEBRAS*, 13(149), 31-34.

Lozano, J. V.; Lassman, A. A.; Cantu, N. A. V. & Telis-Romero, J. (2013) Sorption isotherms and drying kinetics of grapefruit seeds. *Acta Scientiarium Technology*, 35(4), 717-723. https://doi.org/10.4025/actascitechnol.v35i4.13658.

Menges, H. O. & Ertekin, C. (2006) Mathematical modeling of thin layer drying of Golden apples. Journal of Food Engineering, 77(1), 119-125. https://doi.org/10.1016/j.jfoodeng.2005.06.049.

Moreno, F.; Parra-Coronado, A. & Camacho-Tamayo, J. (2014) Mathematical simulation parameters for drying of cassava starch pellets. *Engenharia Agrícola*, 34(6), 1234-1244. https://doi.org/10.1590/S0100-69162014000600018.

Novalli, D. S.; Araújo Neto, S. E.; Silva, P. C. P. F.; Damasceno, R. G. L. & Silva, I. F. (2015) Morphoanatomy leaf of cupuassu plant established for diferent methods of spread and shadowing. *Revista Brasileira de Fruticultura*, 37(4), 934-942. https://doi.org/10.1590/0100-2945-205/14.

Oliveira, T. B. & Genovese, M. I. (2013) Chemical composition of cupuassu (*Theobroma grandiflorum*) and cocoa (*Theobroma cacao*) liquors and their effects on streptozotocin-induced diabetic rats. *Food Research International*, 51(2), 929-935. https://doi.org/10.1016/j.foodres.2013.02.019.

Pereira, A. L. F.; Abreu, V. K. G. & Rodrigues, S. (2018) Cupuassu - *Theobroma Grandiflorum*. *Exotic Fruits*, 2010, 159–162. https://doi.org/10.1016/b978-0-12-803138-4.00021-6.

Pereira, A. L. F.; Feitosa, W. S. C.; Abreu, V. K. G.; Lemos, T. O.; Gomes, W. F.; Narain, N. & Rodrigues, S. (2017) Impact of fermentation conditions on the quality and sensory properties of a probiotic cupuassu (*Theobroma grandiflorum*) beverage. *Food Research International*, 100(1), 603-611. https://doi.org/10.1016/j.foodres.2017.07.055.

Perez, L. G.; Oliveira, F. M. N.; Andrade, J. S. & Moreira Filho, M. (2013) Kinetic drying of cupuaçu pulp (*Theobroma grandiflorum*) pre-dehydrated by immersion-impregnation.

Revista Ciência Agronômica, 44(1), 102-106. https://doi.org/10.1590/S1806-66902013000100013.

Quijano, C. E. & Pino, J. A. (2007) Volatile compounds of copoazú (*Theobroma grandiflorum* Schumann) fruit. *Food Chemistry*, 104(3), 1123-1126. https://doi.org/10.1016/j.foodchem.2007.01.006.

Ramos, S.; Salazar, M.; Nascimento, L.; Carazzolle, M.; Pereira, G.; Delforno, T.; Nascimento, M.; Aleluia, T.; Celeghini, R. & Efraim, P. (2020) Influence of pulp on the microbial diversity during cupuassu fermentation. *International Journal of Food Microbiology*, 318, 108465. https://doi.org/10.1016/j.ijfoodmicro.2019.108465.

Ramos, S. N.; Danzl, W.; Ziegleder, G. & Efraim, P. (2016) Formation of volatile compounds during cupuaçu fermentation influence of pulp concentration. *Food Research International*, 87, 161-167. https://doi.org/10.1016/j.foodres.2016.06.025.

Reis, D. R.; Santos, P.; Silva, F. S. & Porto, A. G. (2015) Influence of air characteristics on drying kinetics of beak pepper. *Brazilian Journal of Food Technology*, 18(2), 146-154. https://doi.org/10.1590/1981-6723.6214.

Ribeiro, D. M.; Corrêa, P. C.; Resende, O. & Botelho, F. M. (2007) Thermal properties of wheat grain: determination and modelling. *Ciência e Agrotecnologia*, 31(2), 462-467. https://doi.org/10.1590/S1413-70542007000200029.

Sales, J. H. & Cândida, T. (2016). Efeito da temperatura sobre a amêndoa de cacau: secador vertical. *Revista GEINTEC*, 6(3), 3437-3446. https://doi.org/10.7198/S2237-072220160003015.

Santos, E. C. & Sales, J. H. O. (2014) Vertical solar dryer for almond cocoa. *Revista GEINTEC*, 4(5), 1594-1605. https://doi.org/10.7198/S2237-0722201400050024.

Sasseron, J. L. (1984) *Avaliação de propriedades físicas e curvas de secagem, em camadas finas, de amêndoas de cacau (Theobroma cacao L.)*. Master Degree Dissertation. Federal University of Viçosa. Viçosa, MG, Brazil.

Silva, E. S.; Oliveira, J.; Machado, A. V. & Costa, R. O. (2015) Secagem de Grãos e Frutas: Revisão Bibliográfica. *Revista Brasileira de Agrotecnologia*, 5(1), 19-20.

Silva, L. M. M.; Sousa, F. C.; Sousa, E. P.; Moreira, M. E. R.; Mat, C. & Duarte, M. E. M. (2014) Prediction models of kinetic drying of pigeon pea grains. *Brazilian Journal of Food Technology*, 7(4), 310-318. https://doi.org/10.1590/1981-6723.3014.

Silva, S. F. (2010). Sobre o problema da variação de temperatura de um corpo. *Revista Eletrônica UNIVAG*, 5, 44-55. https://doi.org/10.18312%2F1980-7341.n5.2010.123.

Silva, W. P.; Precker, J. W.; Silva, C. M. D. P. S.; Silva, D. D. P. S. & Silva, C. D. P. D. (2003) Measurement of specific heat and Newton's law of cooling: a refinement in the analysis of the experimental data. *Revista Brasileira de Ensino de Física*, 25(4), 392-398. https://doi.org/10.1590/S1806-11172003000400010.

Sirbu, D.; Grimbs, A.; Corno, M.; Ullrich, M. S. & Kuhnert, N. (2018) Variation of triacylglycerol profiles in unfermented and dried fermented cocoa beans of different origins. *Food Research International*, 111, 361-370. https://doi.org/10.1016/j.foodres.2018.05.025.

Toker, O. S.; Palabiyik, I. & Konar, N. (2019) Chocolate quality and conching. *Trends in Food Science and Technology*, 91, 446-453. https://doi.org/10.1016/j.tifs.2019.07.047.

Trujillo, F. J.; Wiangkaew, C. & Pham, Q. T. (2007) Drying modeling and water diffusivity in beef meat. *Journal of Food Engineering*, 78(1), 74-85. https://doi.org/10.1016/j.jfoodeng.2005.09.010.

Vriesmann, L. C.; Petkowicz, C. L. O. (2019) Polysaccharides from the pulp of cupuassu (*Theobroma grandiflorum*): Structural characterization of a pectic fraction. *Carbohydrate Polymers*, 77(1), 72-79. https://doi.org/10.1016/j.carbpol.2008.12.007.

Yogendrasasidhar, D. & Setty, Y. P. (2018) Drying kinetics, exergy and energy analyses of Kodo millet grains and Fenugreek seeds using wall heated fluidized bed dryer. *Energy*, 151, 799-811. https://doi.org/10.1016/j.energy.2018.03.089.