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Mathematical modeling, volumetric shrinkage, and thermodynamic properties of acerola fruit drying

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ABSTRACT

Brazil is the largest producer, consumer, and exporter of acerola fruit, but there is significant post-harvest waste due to the fruit's high water content and perishability. This study aimed to evaluate and model the drying phenomenon at different temperatures, volumetric shrinkage, and process energy through thermodynamic properties. For the drying process, a forced-air circulation oven was used. The fruits were weighed during this process, and their axes were measured until a constant value was reached. Finally, the thermodynamic properties were calculated for each temperature. The Midilli and Adapted Exponential models best fit the experimental data for the drying kinetics and volumetric shrinkage of acerola fruits, respectively. Additionally, during the drying process, increasing the temperature led to a decrease in Δh and Δs and an increase in ΔG. In conclusion, raising the drying air temperature significantly influences the drying time of acerola, reducing the energy required to remove water, increasing system order, and enhancing the non-spontaneity of the process.

Keywords: Conservation, Energy, Fruits, Processing.

Modelagem matemática, contração volumétrica e propriedades termodinâmicas da secagem dos frutos de acerola

RESUMO

O Brasil é o maior produtor, consumidor e exportador da fruta acerola, mas há um desperdício pós-colheita significativo devido ao seu alto teor de água e à sua perecibilidade. O objetivo deste estudo foi avaliar e modelar o fenômeno da secagem em diferentes temperaturas, a contração volumétrica e a energia do processo por meio das propriedades termodinâmicas. Para o processo de secagem, utilizou-se um forno com circulação de ar forçada. Durante esse processo, as frutas foram pesadas e seus eixos foram medidos até que se atingisse um valor constante. Por fim, as propriedades termodinâmicas foram calculadas para cada temperatura. O modelo de Midilli e o modelo Exponencial Adaptado foram os que melhor se ajustaram aos dados experimentais para a cinética de secagem e a contração volumétrica das frutas de acerola, respectivamente. Além disso, durante o processo de secagem, o aumento da temperatura levou à diminuição de Δh e Δs e ao aumento de ΔG. Conclui-se que a elevação da temperatura do ar de secagem influencia significativamente o tempo de secagem da acerola, reduzindo a energia necessária para a remoção de água, aumentando a ordem do sistema e intensificando a não-espontaneidade do processo.

Palavras-chave: Conservação, Energia, Frutas, Processamento.

1. Introduction

Brazil ranks third in global fruit production, behind China and India (FAO, 2023). Regarding acerola, the country is the largest producer, consumer, and exporter of this fruit, with the Northeast region concentrating most of the national production (Santos and Villwock, 2024; Ferreira et al., 2021b).

Malpighia emarginata Sessé & Moc. ex DC., commonly known as acerola, is a fruit introduced to Brazil in the past century. This plant belongs to the Malpighiaceae family, originating from Central America and the northeastern region of South America (Dala-Paula, 2019). When cultivated in tropical regions, the acerola tree, which has a shrubby growth habit, can bear fruit year-round (Silva et al., 2016).

According to Vilvert et al. (2024), acerola fruits exhibit rounded, oval, or conical shapes and are considered a “superfruit,” as highlighted by Prakash and Baskaran (2018) in their studies on acerola’s potential. The ascorbic acid content in the green fruit ranges from 500 to 4000 mg per 100g of pulp (Moreira-Araújo et al., 2019). According to Rezende et al. (2017), other potential benefits include the fruit’s antioxidant and antimicrobial properties. In Brazil, acerola is mainly marketed to the pharmaceutical industry for ascorbic acid extraction, while fresh consumption is the second most common form of use (Miskinis et al., 2023).

Approximately 55% of fruit production is wasted in Latin America (Bojanic, 2021). Acerola is highly perishable, increasing the likelihood of production losses if factors like harvesting at the appropriate ripeness stage and quality preservation methods are not considered (Freitas et al., 2020). According to Caixeta-Filho and Péra (2018), post-harvest losses in fruits, vegetables, grains, and cereals are inevitable but can be minimized through proper processing techniques.

Among the processing techniques for preservation, drying is one of the most widely used. According to Estevam et al. (2018), drying involves applying controlled heat to maximize water removal from the product. This process also reduces water activity (a_w), consequently inhibiting microbial growth and enzymatic reactions, thus extending the product shelf life (Ertekin and Firat, 2017; Li et al., 2018). Additional benefits include facilitating transportation and storage by reducing mass and volume (Onwude, 2016; Rabello et al., 2021; El-Mesery et al., 2024).

Drying acerola and its by-products contributes to the preservation of vitamin C and other bioactive compounds by reducing water content and, consequently, preventing microbiological deterioration. This process increases product stability and enables the use of these ingredients in various applications within the food industry (Garcia et al., 2020). However, if heat is not properly applied to a specific product, it can cause degradation of various thermolabile compounds (Teles et al., 2017; Mahanta et al., 2021; Duc Pham et al., 2019).

Another important aspect to consider during drying is volumetric shrinkage. Due to their high water content, fruits and vegetables undergo dimensional changes, affecting their physical properties and ultimately impacting product quality (Jiang et al., 2017). This compromise occurs because shrinkage can reduce porosity, increase hardness, and cause changes in shape and texture (Mayor and Sereno, 2004).

In addition to these physical changes, understanding the sorption behavior and energy dynamics involved in drying is essential for process optimization. When exposed to the environment, agricultural products can gain or lose water depending on whether they are dry or humid until they reach an equilibrium point between their water content and the relative humidity of the air. This point is known as hygroscopic equilibrium and is described by mathematical equations called water sorption isotherms (Isquierdo et al., 2020). According to Sousa et al. (2014), these sorption curves are essential for understanding drying and storage processes of agricultural products. Furthermore, kinetic and thermodynamic parameters are crucial in designing appropriate drying equipment. Additionally, calculating the energy required for drying, rehydration rate properties, changes in food appearance, and microstructure evaluation are critical factors (Yamchi et al., 2024; Nadew et al., 2024).

Based on the above, this study aimed to model the drying kinetics, volumetric shrinkage, and determination of the thermodynamic properties of acerola fruits.

2. Material and Methods

This study was conducted in the agricultural product processing laboratory of the Agricultural Engineering Program at the Federal University of Lavras. Acerola fruits were collected from the rural area of Elói Mendes, Minas Gerais, Brazil. The fruits were visually classified according to their maturity stage, following the methodology described by Ferreira et al. (2009), with stage 5 corresponding to fruits exhibiting red pulp coloration, no visible injuries, and uniform size before the analyses.

To determine the initial water content for drying, the oven-drying method at 105 ± 3 °C was used (Brazil, 2009). The final water content was calculated based on the final and initial mass difference. Whole acerola fruits were subjected to 30, 40, 55, and 70 ºC drying air temperatures in an oven with forced air circulation. This temperature range was selected based on its relevance in previous studies involving tropical fruits, including acerola, and its representativeness of typical ranges used in convective drying systems. For each temperature, two repetitions were performed with six acerolas each.

At the beginning of drying, measurements of mass reduction due to water loss were taken every two, four, six, and eight hours on the 1st, 2nd, 3rd, and 4th days, respectively. The mass reduction of water in the product was measured using an analytical balance with a precision of 0.001 g. Weighing the acerola fruits for each temperature was concluded when no further mass variation was observed. Using the data on water content reduction over time, the water ratio (XR) was calculated according to Equation 1. Commonly used mathematical models to represent drying processes in agricultural products were fitted to the experimental water ratio (MR) data over time for each temperature. The models used are shown in Table 1.

$$RX=(WC-WCe)/(WCi-WCe) \quad (1)$$

Where RX = water content ratio of the product (dimensionless), WC = average water content of the product over time (kg of water kg of dry matter^{-1}), WCi = initial water content of the product (kg of water kg of dry matter^{-1}), and WCe = equilibrium water content of the product (kg of water kg of dry matter^{-1}).

The equilibrium water content was estimated based on the final drying point, where the sample mass remained constant. According to Chen and Jayas (1998), when the sample mass becomes constant, the corresponding water content can be considered the equilibrium water content for modeling purposes.

Table 1. Mathematical Models applied to the experimental data for determining drying kinetics.

Model name	Model	Equation	References
Henderson and Pabis[1]	$RX = k_0 \exp(-k\ t_i)$	(2)	Henderson and Pabis (1961)
Midilli[2]	$RX = k_0 \exp(-k\ t_i^c) + a\ t_i$	(3)	Midilli et al., (2002)
Newton[3]	$RX = \exp(-k\ t_i)$	(4)	Lewis (1921)
Page[4]	$RX = \exp(-k\ t_i^c)$	(5)	Page (1949)

Where: RX = water ratio of the product (dimensionless) at time i in hours; k_0 = initial water content condition of the grain, approximately equal to 1; k = represents the variation of water content concerning the process time, with values ranging between 0 and 1; c = dimensionless parameter associated with the relative humidity of the air; a = model constant, without direct interpretation; t_i = drying time in hours.

Equation 6 presents the liquid diffusion model used for fitting the experimental drying data, considering the spheroidal shape.

$$RX = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2}\, e^{\left[-\frac{n^2 \pi^2 D\, t_i}{9}\left(\frac{3}{r}\right)^2\right]} \quad (6)$$

Where: RX = water ratio of the product (dimensionless); n = number of terms in the equation; D = effective diffusivity ($m^2\ s^{-1}$); r = equivalent sphere radius (m); t_i = drying time in seconds.

To verify normality, homoscedasticity of residuals, and residual autocorrelation, the Shapiro-Wilk (SW), Breusch-Pagan (BP), and Durbin-Watson (DW) tests were used as validity assumptions for the evaluated models, as performed in Gonzaga et al. (2024). The least squares method and the Gauss-Newton convergence algorithm were used for parameter estimation, and to evaluate the model fit in estimating the parameters, the adjusted coefficient of determination (R^2aj), the Bayesian Information Criterion (BIC), and the Akaike Information Criterion (AIC) were used.

The best model was selected based on the highest R^2aj and the lowest BIC and AIC values. This entire process was conducted using the open-access statistical software R (R CORE TEAM, 2024).

To understand in which stages of the process (time) water is removed more quickly and when the process slows down, the Water Reduction Rate (WRR) was calculated. This represents the reduction of water mass concerning dry matter and time (Corrêa et al., 2001), as shown in Equation 7.

$$WRR = \frac{(Mw_o - Mw_i)}{(Mdm * (t_i - t_o))} \quad (7)$$

Where WRR = water reduction rate (kg kg^{-1} h^{-1}), Mw_o = previous total water mass (kg), Mw_i = current total water mass (kg), Mdm = dry matter (kg), t_o = total previous drying time (h), and t_i = current total drying time (h).

To determine the volume necessary to calculate the volumetric shrinkage index, measurements were made of the diameter and height for each of the six acerola fruits in every treatment during the drying process with the help of a digital caliper. Measurements were made every 4 hours on the first day and from the second day every 8 hours until drying was complete. To calculate the volume of the acerola during the process, equation 8 was used, considering the fruit in the shape of a spheroid as shown in Figure 1, while equation 9 was used to calculate the volumetric shrinkage index.

$$V = \frac{\pi\ (a^2 b)}{6} \quad (8)$$

Where, a = radius in the horizontal direction (mm); b = radius in the vertical direction (mm).

$$\Psi = \frac{V}{V_0} \quad (9)$$

Where, V = volume of the acerola at each water content (m^3); V_0 = initial volume of the acerola at the beginning of drying (m^3).

Different mathematical models were fitted to the experimentaldata of the volumetric shrinkage index as a function of the product’s water content during drying, to describe this phenomenon, as shown in Table 2. The minimum energy required for the drying process of acerola fruits to begin, known as activation energy, was estimated using the Arrhenius equation (Equation 16).

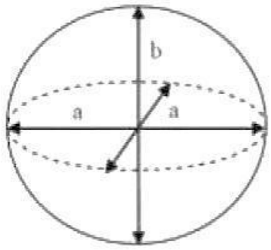

Figure 1. Drawing of a spheroid with semiaxes a and b.

Table 2. Mathematical models applied to water reduction data to represent volumetric shrinkage in acerola fruits.

Model name	Model	Equation
Adapted exponential	Ψ =(a(exp(bWC(T^c))))	(10)
Adapted Linear	Ψ =(a+(bWC))T^c	(11)
Adapted Rahman	Ψ =(1+(a(WC-WCi)))T^b	(12)
Adapted Bala & Woods	Ψ =(1-(a(1-exp(-b(WCi-WC)))))T^c	(13)
Adapted Corrêa	Ψ =1/(a+b exp(WC)) T^c	(14)
Adapted polynomial	Ψ =(a+bWC+cWC^2) T^c	(15)

Where, Ψ = volumetric shrinkage index (decimal); WC = water content of the product (db, decimal); WCi = initial water content (db, decimal); T = drying air temperature (ºC); a, b, c = model constants, dimensionless.

The minimum energy required for the drying process of acerola fruits to begin, known as activation energy, was estimated using the Arrhenius equation (Equation 16). This formula also correlates the drying constant k of the model that most adequately described the process for the products, as identified by Oliveira et al. (2015).

$$k = A_0 e^{\left(-\frac{Ea}{RT_{abs}}\right)} \quad (16)$$

Where, A_0= pre-exponential factor (min^{-1}); Ea= activation energy (J mol^{-1}); R= universal gas constant (8.314 J mol^{-1} K^{-1}); T_{abs}= absolute temperature (K).

The thermodynamic properties of enthalpy, entropy, and Gibbs free energy, associated with the drying of acerola fruits, were calculated using Equations 17, 18, and 19, as described by Jideani & Mpotokawana (2009).

$$\Delta h = Ea - RT_{abs} \quad (17)$$

$$\Delta s = R\left(\ln A_0 - ln\frac{k_B}{k_p} - \ln T_{abs}\right) \quad (18)$$

$$\Delta G = \Delta h - T_{abs}\,\Delta s \quad (19)$$

Where, Δh= enthalpy change (J mol^{-1}); Δs= change in entropy (J mol^{-1} K^{-1}); ΔG= variation in Gibbs free energy (J mol^{-1}); k_B= Boltzmann constant (1.38 x 10^{-23} J K^{-1}); k_p= Plank's constant (6.626 x 10^{-34} J s^{-1}).

3. Results and Discussion

The initial water content of the acerola fruits was 11.45 g g^{-1} (dry basis) for all treatments. The final water content values for each drying temperature were as follows: 30 °C: 0.28 g g^{-1}, 40 °C: 0.20 g g^{-1}, 55 °C: 0.24 g g^{-1}, and 70 °C: 0.17 g g^{-1}.

For drying air temperatures of 30, 40, 55 and 70 ºC, the model that best represented the experimental data on water reduction as a function of time was that of Midilli, presenting the highest values of the adjusted coefficient of determination (R2aj) and the lowest values of the Akaike (AIC) and Bayesian (BIC) information criteria as presented in Tables 3, 4, 5 and 6. The Midilli model presented an adjusted coefficient of determination (R2aj) of 0.99 for the four temperatures studied. The second-best model was the Page model, which can also represent the experimental data adequately. Note in Tables 3, 4, 5, and 6 that the assumptions used to validate the models were met while for the test of normality (SW), homoscedasticity (BP), and independence of residuals (DW), indicating that the adjusted models can represent the experimental data well, except for the liquid diffusion model at temperatures of 30 ºC and 40 ºC and that of Henderson & Pabis at a temperature of 70 ºC as it does not fulfill the assumption of normality (SW).

Table 3. Parameters of the mathematical models and statistical decision evaluators of water reduction in acerola fruits concerning the time for the drying temperature of 30 ºC.

Name	k_0	k	c	a	D	SW	BP	DW	R^2aj	AIC	BIC
Henderson & Pabis	1.059	0.042	-	-	-	0.593	0.102	0.273	0.975	-42.757	-40.439
Midilli	0.971	0.012	1.326	0.001	-	0.682	0.092	1.123	0.996	-69.106	-65.243
Newton	-	0.039	-	-	-	0.107	0.080	0.219	0.971	-41.254	-39.709
Page	-	0.013	1.337	-	-	0.239	0.115	0.522	0.992	-60.530	-58.213
Liquid diffusion	-	-	-	-	$68.240x10^{-13}$	0.023	0.729	0.103	0.841	-14.191	-12.646

Where, SW = Shapiro-Wilk test; BP = Breusch-Pagan test; DW = Durbin-Watson test.

Table 4. Parameters of the mathematical models and statistical decision evaluators of water reduction in acerola fruits concerning the time for the drying temperature of 40 ºC.

Name	k_0	k	c	a	D	SW	BP	DW	R^2aj	AIC	BIC
Henderson & Pabis	1.040	0.053	-	-	-	0.264	0.071	0.294	0.987	-47.640	-45.723
Midilli	0.988	0.030	1.135	-0.001	-	0.156	0.548	1.545	0.998	-71.682	-68.487
Newton	-	0.051	-	-	-	0.153	0.061	0.219	0.985	-46.666	-45.388
Page	-	0.028	1.205	-	-	0.560	0.517	0.638	0.995	-62.075	-60.158
Liquid diffusion	-	-	-	-	$75.579x10^{-13}$	0.048	0.807	0.100	0.867	-15.903	-14.625

Where, SW = Shapiro-Wilk test; BP = Breusch-Pagan test; DW = Durbin-Watson test.

Silva et al. (2021a) evaluated three mathematical models to represent the drying kinetics of acerola seeds; among them, the Page model and the two-part model proposed by the authors were the ones that best fit the experimental data. On the other hand, studying the drying and shrinkage of fresh acerola fruits at temperatures of 40, 55, and 70 ºC up to a water content of 0.25 db. D'Andrea et al. (2015) found that the Midilli and Polynomial models were the ones that best fit the experimental data.

The parameter k_0 in the Midilli model for the studied temperatures of 30, 40, 55, and 70 ºC presents values close to 1, being predictable because, as explained by Gonzaga et al. (2024), this parameter represents the water content of the product at the beginning of drying.

The estimates for the parameter k at different temperatures increased with increasing temperature, being 0.012, 0.030, 0.065, and 0.076 for temperatures of 30, 40, 55, and 70 ºC, respectively. Silva et al. (2021b) found k parameters of 0.0027, 0.0029, 0.0035, and 0.0038 for drying air temperatures of 40, 50, 60, and 70 ºC for acerola seeds. D'Andrea et al. (2015) found values for the k parameters of 0.004, 0.010, and 0.042 for temperatures of 40, 55, and 70 ºC.

The drying constant (k) represents the effect of temperature on water removal and is related to effective diffusivity and liquid diffusion, which govern water transport during the falling rate period of the drying process (Madamba et al., 1996; Babalis and Belessiotis, 2004).

In Figure 2, the Midilli model can be observed estimating the water reduction as a function of time at the temperatures of A: 30 ºC, B: 40 ºC, C: 55 ºC, and D: 70 ºC; the continuous line estimated by the model is close to the experimental data of this work.

Table 5. Parameters of the mathematical models and statistical decision evaluators of water reduction in acerola fruits concerning the time for the drying temperature of 55 ºC.

Name	k_0	k	c	a	D	SW	BP	DW	R^2aj	AIC	BIC
Henderson & Pabis	1.046	0.128	-	-	-	0.224	0.196	0.808	0.984	-26.769	-26.177
Midilli	0.993	0.065	1.289	-0.001	-	0.362	0.840	2.597	0.997	-42.110	-41.123
Newton	-	0.122	-	-	-	0.332	0.429	0.539	0.983	-26.869	-26.474
Page	-	0.065	1.303	-	-	0.295	0.546	2.381	0.998	-44.450	-43.858
Liquid diffusion	-	-	-	-	$223.8x10^{-13}$	0.403	0.223	0.269	0.882	-9.673	-9.279

Where, SW = Shapiro-Wilk test; BP = Breusch-Pagan test; DW = Durbin-Watson test.

Table 6. Parameters of the mathematical models and statistical decision evaluators of water reduction in acerola fruits concerning the time for the drying temperature of 70 ºC.

Name	k_0	k	c	a	D	SW	BP	DW	R^2aj	AIC	BIC
Henderson & Pabis	1.043	0.145	-	-	-	0.031	0.810	0.802	0.986	-28.021	-27.430
Midilli	0.993	0.076	1.288	0.000	-	0.939	0.439	1.942	0.997	-42.238	-41.252
Newton	-	0.138	-	-	-	0.107	0.142	0.528	0.985	-28.255	-27.860
Page	-	0.078	1.287	-	-	0.341	0.165	1.762	0.998	-45.492	-44.901
Liquid diffusion	-	-	-	-	223.9×10^{-13}	0.164	0.191	0.285	0.896	-10.656	-10.261

Where, SW = Shapiro-Wilk test; BP = Breusch-Pagan test; DW = Durbin-Watson test.

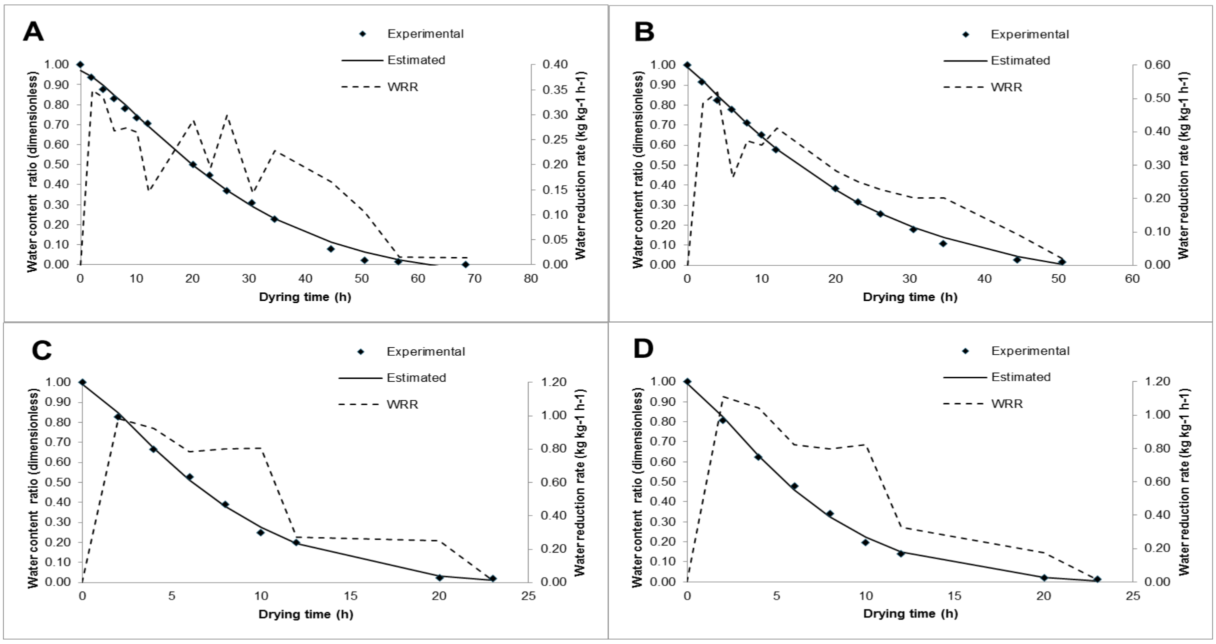

Figure 2. Experimental drying kinetics and estimated by the Midilli model, and water reduction rate during drying of acerola fruits for temperatures A: 30 ºC, B: 40 ºC, C: 55 ºC, and D: 70 ºC.

The initial volumetric shrinkage index (Ψ) was 1.00 at the beginning of the drying process for all temperature treatments, as expected for fresh fruits. The final values of Ψ for each drying temperature were: 30 °C: 0.1342, 40 °C: 0.1245, 55 °C: 0.2054, and 70 °C: 0.1940. Table 7 presents the estimated parameters of the models adjusted to experimental volumetric shrinkage data for different water contents and drying air temperatures of acerola fruits.

The adapted Exponential model not only met the assumptions of homoscedasticity and independence of residuals but also achieved the highest adjusted coefficient of determination (0.965) and the lowest Akaike (AIC, -81.646) and Bayesian (BIC, -76.041) information criteria values. In Figure 3, the adapted Exponential model can be seen, estimating the volumetric shrinkage as a function of the water content for each drying air temperature.

Ferreira et al. (2021a) studied the volumetric shrinkage of Itália grapes under different temperatures and observed that shrinkage was most pronounced during the initial hours of drying, particularly at the highest temperature. In this same study, the model that best fitted the data for volumetric shrinkage at a temperature of 60 ºC was Corrêa's, and for a temperature of 70 ºC it was exponential.

Table 7. Parameters of the mathematical models and statistical decision evaluators of the volumetric shrinkage of acerola fruits for drying temperatures of 30, 40, 55, and 70 ºC.

Name	a	b	c	SW	BP	DW	R^2aj	AIC	BIC
Adapted exponential	0.145	0.154	0.026	0.041	0.371	1.649	0.965	-81.646	-76.041
Adapted Linear	0.036	0.039	0.164	0.317	0.315	0.946	0.910	-53.197	-47.592
Adapted Rahman	0.081	-0.029	-	0.011	0.294	0.838	0.902	-51.561	-47.357
Adapted Bala & Woods	1.012	0.166	0.004	0.011	0.386	1.562	0.965	-81.387	-75.782
Adapted Corrêa	2.935	-2.091	-5.352	0.001	0.004	0.906	0.574	-6.631	-1.026
Adapted polynomial	0.154	0.004	0.006	0.002	0.389	1.442	0.965	-81.552	-75.948

Where, SW = Shapiro-Wilk test; BP = Breusch-Pagan test; DW = Durbin-Watson Test.

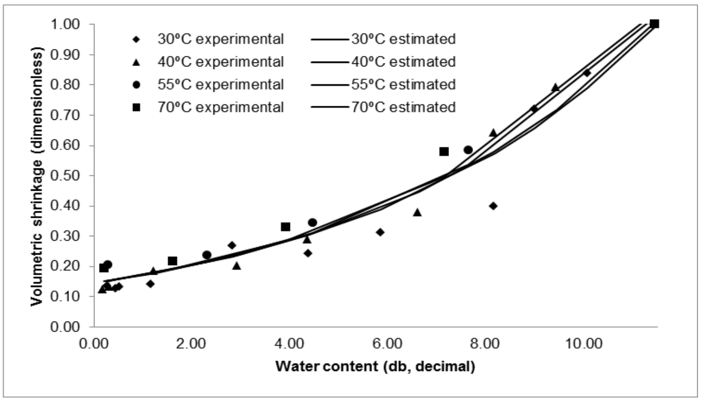

Figure 3. Volumetric shrinkage index of experimental acerola fruits and estimated by the Adapted Exponential model due to the water content for different drying temperatures.

Volumetric shrinkage modeling is important because it allows for the quantitative understanding and prediction of structural changes that occur in the product during drying (Mayor and Sereno, 2004). Moreover, shrinkage data is essential for coupling heat and mass transfer models, improving the accuracy of drying kinetics simulations (Curcio and Aversa, 2014).

The activation energy (Ea) was calculated through the orientation of the line of ln (k) vs 1/T as shown in Figure 4. The orientation of the line was multiplied by the universal gas constant to obtain the activation energy value of 40.079 kJ mol^{-1}. Santos et al. (2021) calculated the thermodynamic properties using the drying kinetics data of Okra fruit at different temperatures, and found that the activation energy was 26.12 kJ mol^{-1}.

According to Zogzas et al. (1996), activation energy values for agricultural products generally vary between 12.7 and 110.0 kJ mol^{-1}. This variation is associated with differences in the physical and chemical properties of the materials studied and the specific drying conditions evaluated.

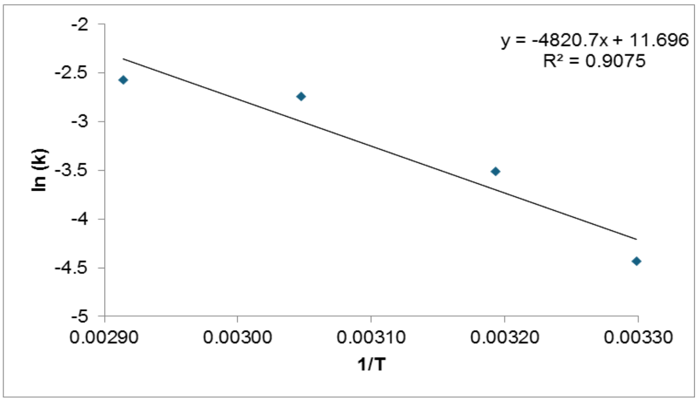

Figure 4. Relationship of the linear equation ln(k) vs 1/T with the activation energy (Ea) during the drying of acerola fruits.

Table 8. Thermodynamic properties and their values for different temperatures in the drying process of acerola fruits.

Temperature	Δh	Δs	ΔG	Δh	Δs	ΔG
(ºC)	J mol^{-1}	J mol^{-1} K^{-1}	J mol^{-1}	kJ mol^{-1}	kJ mol^{-1} K^{-1}	kJ mol^{-1}
30	37558.911	-224.599	105645.960	37.559	-0.225	105.646
40	37475.771	-224.868	107893.302	37.476	-0.225	107.893
55	37351.061	-225.257	111269.267	37.351	-0.225	111.269
70	37226.351	-225.629	114650.936	37.226	-0.226	114.651

Activation energy represents the minimum amount of energy required to overcome the resistance to the movement of water molecules in the material. It is essential to start the process of diffusion of water from the interior to the surface of the product (Kashaninejad et al., 2007). According to Amin et al. (2019), variations in activation energy can be attributed to differences in product characteristics, operational parameters used, or temperatures applied during the process.

The thermodynamic properties calculated from the experimental data are presented in Table 8. Concerning the increase in drying air temperature, the enthalpy variation varied from 37.559 to 37.226 kJ mol^{-1}, the entropy variation from -0.225 to -0.226 kJ mol^{-1} K^{-1}, and the Gibbs free energy from 105.646 to 114.651 kJ mol^{-1}. A similar pattern was observed by Ferreira Junior et al. (2020) in the drying of Tamarindus indica seeds, where enthalpy and entropy decreased from 32.51 to 32.14 kJ mol^{-1} and from -0.41626 to -0.41639 kJ mol^{-1} K^{-1}, respectively, while Gibbs free energy increased from 164.95 to 183.35 kJ mol^{-1} as the temperature rose from 45 to 90 ºC.

According to Nadi and Tzempelikos (2018), enthalpy is the energy required to remove water from a product during drying. The enthalpy decreases as the drying temperature increases, indicating that the water removal process becomes more efficient. Positive enthalpy values suggest that the reaction is endothermic, requiring a supply of heat to occur. Entropy, in turn, is related to the degree of disorder between the water and the product. As the drying temperature increases, entropy decreases, which indicates a greater organization of the system, a thermodynamically unfavorable phenomenon.

According to Oliveira et al. (2015), Gibbs free energy serves to quantify the total energy involved in a thermodynamic system. When its value is positive, it indicates a need for additional energy to allow the product to undergo a phase change, such as the transformation from liquid to vapor. This process involves the absorption of heat to overcome the intermolecular forces between the molecules of the liquid.

Convective hot-air drying is one of the most common post-harvest processes in the agricultural sector and a standard process in the food industry (Reyer et al., 2020). Kinetic and thermodynamic parameters are the most important part to design equipment suitable for drying agricultural products. Furthermore, calculating the energy required for product drying, rehydration rate properties, and changes in food appearance are crucial (Yamchi et al., 2024).

4. Conclusions

The results of the model adjustment method indicated that the Midilli model is the most appropriate for estimating the water ratio as a function of time, and the adapted Exponential model, the most suitable for estimating volumetric shrinkage as a function of water content and temperature; these two models can be used accurately.

Increasing the drying air temperature in acerola processing reduced the amount of energy used to remove water from the product and increased the system's order and non-spontaneity. Acerola water loss occurred during the drying period at a decreasing rate, and with the increase in drying temperature, the total process time was reduced.

Authors' Contribution

Data curation: Jose Renato Robles Padilla, Sthefany dos Santos Maidana Palacios, Pedro Henrique Toledo da Costa; Formal Analysis: Jose Renato Robles Padilla, Sthefany dos Santos Maidana Palacios, Pedro Henrique Toledo da Costa, Carla Simone Araújo Gomes Sarmento, Filipe da Silva de Oliveira; Investigation: Jose Renato Robles Padilla, Ednilton Tavares de Andrade. Methodology: Jose Renato Robles Padilla, Ednilton Tavares de Andrade, Sthefany dos Santos Maidana Palacios, Pedro Henrique Toledo da Costa, Carla Simone Araújo Gomes Sarmento, Emerson Gomes Ferreira; Software: Jose Renato Robles Padilla, Ednilton Tavares de Andrade. Supervision: Ednilton Tavares de Andrade; Writing - review and editing: Jose Renato Robles Padilla, Ednilton Tavares de Andrade, Carla Simone Araújo Gomes Sarmento, Filipe da Silva de Oliveira.

Bibliographic References

Amin, K., Islam, A., Akter, F., Islam, N., 2019. Kinetics of air drying of jackfruit and mango pulp and development of mixed leather. Fundamental and Applied Agriculture, 4, 1089-1096. https://doi.org/10.5455/faa.72409

Babalis, S.J. Belessiotis, V.G., 2004. Influence of the Drying Conditions on the Drying Constants and Moisture Diffusivity during the Thin-Layer Drying of Figs. Journal of Food Engineering, 65, 449-458. http://dx.doi.org/10.1016/j.jfoodeng.2004.02.005

Bojanic, A., 2021. Pérdida y el desperdicio de alimentos en la seguridad alimentaria y nutricional. In: CONAB. Perdas em transporte e armanenagem de grãos: panorama atual e perspectivas. Brasília, DF: Conab. p. 15-17. Available at: http://www.conab.gov.br

BRASIL, 2009. Ministério da Agricultura, Pecuária e Abastecimento. Regras para análise de sementes / Ministério da Agricultura, Pecuária e Abastecimento. Secretaria de Defesa Agropecuária. Brasília: Mapa/ACS. 399

Caixeta-Filho, J.C, Péra, T.G., 2018. Post-harvest losses during the transportation of grains from farms to aggregation points. Int. J. Logistics Economics and Globalisation. 7(3), 38. https://doi.org/10.1504/IJLEG.2018.093755

Chen, C., Jayas, D.S. (1998). Dynamic equilibrium moisture content for grain drying. Canadian Agricultural Engineering, 40, 299-304.

Corrêa, P.C., Machado, P.F., Andrade, E.D., 2001. Cinética de secagem e qualidade de grãos de milho-pipoca. Ciência e Agrotecnologia, 25(1), 134-142.

Curcio, S., Aversa, M. (2014). Influence of shrinkage on convective drying of fresh vegetables: A theoretical model. Journal of Food Engineering, 123, 36-49. https://doi.org/10.1016/j.jfoodeng.2013.09.014

D'Andrea, E.M., Andrade, E.T., Corrêa-Filho, L.C., Sousa, F.A., Figueira, V.G., 2015. Análise da cinética de secagem, contração volumétrica e difusão líquida da acerola "in natura". Revista Brasileira de Produtos Agroindustriais, 17(4), 399-408. https://doi.org/ 10.15871/1517-8595/rbpa.v17n4p399-408

Dala-Paula, B.M., Santos, T.P.D., Araújo, L.D.S., Bastos, R.R.A., Moraes, J.D.O., Carbonera, N., 2019. Domestic processing and storage on the physical-chemical characteristics of acerola juice (*Malpighia glabra* L.). Ciência e Agrotecnologia, 43, e021519. https://doi.org/ 10.1590/1413-7054201943021519

Duc Pham, N., Khan, M.I.H., Joardder, M.U.H., Rahman, M.M., Mahiuddin, M., Abesinghe, A.M.N., Karim, M.A., 2019. Quality of plant-based food materials and its prediction during intermittent drying. Critical reviews in food science and nutrition, 59(8), 1197–1211. https://doi.org/10.1080/10408398.2017.1399103

El-Mesery, H.S., Hu, Z., Ashiagbor, K., Rostom, M., 2024. A study into how thickness, infrared intensity, and airflow affect drying kinetics, modeling, activation energy, and quality attributes of apple slices using infrared dryer. Journal of food science, 89(5), 2895–2908. https://doi.org/10.1111/1750-3841.17064

Ertekin, C., Firat, M.Z., 2017. A comprehensive review of thin-layer drying models used in agricultural products. Critical reviews in food science and nutrition, 57(4), 701–717. https://doi.org/10.1080/10408398.2014.910493

Estevam, M.I.F., Souza, P.A., Maracajá, P.B, Batista, E.M., Reges, B.M., 2018. Físico-química de variedades de acerola em dois estádios de maturação. Revista Verde, 13(4), 459-465. https://doi.org/10.18378/rvads.v13i4.5736

FAO. World Food and Agriculture – Statistical Yearbook 2023. Rome, 2023. https://doi.org/10.4060/cc8166en

Ferreira Junior, W.N., Resende, O., Pinheiro, G.K., Silva, L.C.D.M., Souza, D.G., Sousa, K.A.D., 2020. Modeling and thermodynamic properties of the drying of tamarind (*Tamarindus indica* L.) seeds. Revista Brasileira de Engenharia Agrícola e Ambiental, 25, 37-43. https://doi.org/10.1590/1807-1929/agriambi.v25n1p37-43

Ferreira, E.A., Neto, A.F., Costa, M.S., Costa, J. D.S., Coelho, B.E. S., Morais, D.Y.N., 2021a. Contração volumétrica da Uva 'Itália'. Revista em Agronegócio e Meio Ambiente, 14(2), 315-323. https://doi.org/10.17765/2176-9168.2021v14n2e8024

Ferreira, I.C., Silva, V.P., Vilvert, J.C., Souza, F.F., Freitas, S.T., Lima, M.S. 2021b. Brazilian varieties of acerola (*Malpighia emarginata* DC.) produced under tropical semi-arid conditions: Bioactive phenolic compounds, sugars, organic acids, and antioxidant capacity. Journal of food biochemistry, 45(8), e13829. https://doi.org/10.1111/jfbc.13829

Ferreira, R.M.A., Aroucha, E.M.M., Souza, P.A., Queiroz, R.F. 2009. Ponto de colheita da acerola visando à produção industrial de polpa. Revista Verde de Agroecologia e Desenvolvimento Sustentável, 4(2), 5.

Freitas, S.T., Barbosa, M.A.G., Rybka, A.C.P., 2020. Colheita e pós-colheita de acerola para o consumo in natura. Embrapa. Circular técnica, n. 123.

Garcia, V.A.D.S., Borges, J.G., Vanin, F.M., Carvalho, R.A.D. 2020. Vitamin C stability in acerola and camu-camu powder obtained by spray drying. Brazilian Journal of Food Technology, 23, e2019237. https://doi.org/10.1590/1981-6723.23719

Gonzaga, N.A., Azarias, E.C.P., Salvador, R.C., Muniz, J.A., Silva, E.M., Fernandes, T.J., 2024. Descrição da cinética de secagem de grãos de milho-pipoca por modelos de regressão não linear. Revista Foco, 17(1) e4176-e4176. https://doi.org/10.54751/revistafoco.v17n1-094

Henderson, S.M., Pabis, S., 1961. Grain drying theory. Temperature effect on drying coefficient. Journal of Agricultural Engineering Research, 6(3), 169- 174.

Isquierdo, E.P., Siqueira, V.C., Borém, F.M., Andrade, E.T., Luz, P.B., Quequeto, W.D., 2020. Isotermas de sorção e propriedades termodinâmicas de sementes de maracujá doce. Research, Society and Development, 9(5), e44952884-e44952884. https://doi.org/10.33448/rsd-v9i5.2884

Jiang, N., Liu, C., Li, D., Zhang, Z., Liu, C., Wang, D., Niu, L., Zhang, M., 2017. Evaluation of freeze drying combined with microwave vacuum drying for functional okra snacks: Antioxidant properties, sensory quality, and energy consumption. LWT - Food Science and Technology, 82(1), 216-226. https://doi.org/10.1016/j.lwt.2017.04.015

Jideani, V.A., Mpotokwana, S.M., 2009. Modeling of water absorption of Botswana bambara varieties using Peleg's equation. Journal of Food Engineering, 92, 182-188. https://doi.org/10.1016/j.jfoodeng.2008.10.040

Kashaninejad, M., Mortazavi, A., Safekordi, A., Tabil, L.G., 2007. Thin-layer drying characteristics and modeling of pistachio nuts. Journal of Food Engineering, 78(1), 98-108. https://doi.org/10.1016/j.jfoodeng.2005.09.007

Lewis, W.K., 1921. The drying of solid materials. Journal Industrial Engineering, 13(5), 427-33.

Li, H., Xie, L., Ma, Y., Zhang, M., Zhao, Y., Zhao, X., 2018. Effects of drying methods on drying characteristics, physicochemical properties and antioxidant capacity of okra. LWT - Food Science and Technology, 101, 630-638. https://doi.org/10.1016/j.lwt.2018.11.076

Madamba, P.S., Driscoll, R.H., Buckle, K.A., 1996. Thin-layer drying characteristics of garlic slices. Journal of Food Engineering, Essex, 29(1), 75-97. https://doi.org/10.1016/0260-8774(95)00062-3

Mahanta, B.P., Bora, P.K., Kemprai, P., Borah, G., Lal, M., Haldar, S., 2021. Thermolabile essential oils, aromas and flavours: Degradation pathways, effect of thermal processing and alteration of sensory quality. Food research international (Ottawa, Ont.), 145, 110404. https://doi.org/10.1016/j.foodres.2021.110404.

Mayor, L., Sereno, A.M. 2004. Modelling shrinkage during convective drying of food materials: a review. Journal of food engineering, 61(3), 373-386. https://doi.org/10.1016/S0260-8774(03)00144-4

Midilli, A., Kucuk, H., Yapar, Z., 2002. New model for single-layer drying. Drying technology, 20(7), 1503-1513. https://doi.org/10.1081/DRT-120005864

Miskinis, R.A.S., Nascimento, L.A., Colussi, R., 2023. Bioactive compounds from acerola pomace: a review. Food chemistry, London, 404, 134613. https://doi.org/10.1016 /j.foodchem.2022.134613

Moreira-Araújo, R.S.R., Barros, N.V.A., Porto, R.G.C.L., Brandão, A. C.A.S., Lima, A., Fett, R., 2019. Bioactive compounds and antioxidante activity three fruit species from the Brazilian Cerrado. Revista Brasileira de fruticultura, Jaboticabal, 41(3), 1-8. https://doi.org/10.1590/0100-29452 019011

Nadew, T.T., Tedla, T.S., Bizualem, Y.D., Abate, S.N., Teklehaymanot, L.T., 2024. Data on drying kinetics, moisture sorption isotherm, composition study of Ethiopian oyster mushroom (*Pleurotus ostreatus mushroom*) drying in tray dryer. Data in brief, 56, 110861. https://doi.org/10.101 6/j.dib.2024.110861

Nadi, F. Tzempelikos, D., 2018. Vacuum drying of apples (cv. Golden Delicious): drying characteristics, thermodynamic properties, and mass transfer parameters. Heat and Mass Transfer, 54(7), 1853-1866. https://doi.org/10.1007/s00231-018-2279-5

Oliveira, G.H.H., Aragão, D.M.S., Oliveira, A.P.L. R., Silva, M. G., Gusmão, A.C.A., 2015. Modelagem e propriedade termodinâmicas na secagem de morangos. Brazilian Journal of Food Technology, 18, 314-321. https://doi.org/ 10.1590/1981-6723.5315

Onwude D.I., Hashim N., Janius R.B., Nawi N.M., Abdan K., 2016. Modeling the Thin-Layer Drying of Fruits and Vegetables: A Review. Compr Rev Food Sci Food Saf. 15(3), 599-618. https://doi.org/10.1111/1541-4337.12196

Prakash, A., Baskaran, R., 2018. Acerola, an untapped functional superfruit: a review on latest frontiers. Journal of food science and technology, 55, 3373-3384. https://doi. org/10.1007/s13197-018-3309-5

R CORE TEAM, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/

Rabello, A.A., Resende, Ú.C., Gomes, F.D.C.O., Machado, A.M.R., Martins, E.C., Soares, Í.V., 2021. Utilização da radiação infravermelha na secagem de amostras de banana. Brazilian Journal of Development, 7(4), 39317-39330. https://doi.org/ 10.34117/bjdv7n4-407

Reyer, S., Awiszus, S., Meissner, K., Müller, J., 2020. High precision laboratory dryer for thin layer and bulk drying with adjustable temperature, relative humidity and velocity of the drying air. HardwareX, 8, e00133. https://doi.org/10.10 16/j.ohx.2020.e00133.

Rezende, Y.R.R.S., Nogueira, J.P., Narain, N., 2017. Comparison and optimization of conventional and ultrasound assisted extraction for bioactive compounds and antioxidant activity from agroindustrial acerola (*Malpighia emarginata* DC) residue. LWT – Food Science and Technology, 85, 158-169. https://doi.org/10.1016/j.lwt.2017.07.020

Santos, D.D.C., Leite, D.D.D.F., Lisbôa, J.F., Ferreira, J.P.D.L., Santos, F.S.D., Lima, T.L.B.D., Costa, T.N.D., 2019. Modelagem e propriedades termodinâmicas da secagem de fatias de acuri. Brazilian Journal of Food Technology, 22, e2018031. https://doi.org/10.1590/1981-6723.03118

Santos, F.S., Figueirêdo, R.M.F., Queiroz, A. J.M., Reis, C.G., Amadeu, L.T.S., Silva, L.P.F.R., Lima, T.L.B., 2021. Modelagem matemática e propriedades termodinâmicas na secagem do quiabo. Revista de Ciências Agrárias, 44(1). https://doi.org/10.5555/20210424489

Santos, P.H.S., Villwock, A.P.S. 2024. Análise da viabilidade econômica do cultivo de acerola em propriedade familiar do estado de Sergipe. Exten. Rur., Santa Maria, 31, e71667-e71667. https://doi.org/10.5902/2318179671667

Silva, P.C.C., Pereira, W.E., Alexandre, P.S., Lima, M.L.S., Alexandre, C.S., Cruz, J.O., Silva, N.C.C., 2016. Crescimento de mudas de *Malpighia emarginata* em diferentes substratos. Engenharia Ambiental: Pesquisa e Tecnologia, 13(2), 80-87. Available at: http://ferramentas.unipinhal.edu.br/engenh ariaambiental/viewarticle.php?id=1381

Silva, R.A.M., Martins, J.H., Mata, M.E.C., Duarte, M.E.M., 2021b. Use of diffusive and empirical models to predict drying rate of acerola seeds (*Malpighia* sp.). Global Journal of Engineering and Technology Advances, 8(1), 096-109. https://doi.org/10.30574/gjeta.2021.8.1.0098

Silva, V.M.A., Santos, N.C., Ribeiro, V.H.A., Almeida, R.L.J., Silva, G.M., Queiroga, A.P.R., Brito, A.C.O., 2021a. Acerola thermophysical properties, drying and new product development. Campina Grande: EPTEC. 102p. Available at: http://dspace.sti.ufcg.edu.br:8080/jspui/handle/riufcg/27057

Sousa, F.C., Rocha, A.P.T, Gomes, J.P., Martins, J.J.A., Martins, J.N., 2014. Isotermas de dessorção de folhas in natura de juazeiro e mororó. Pesquisa Agropecuária Tropical. 44(3), 304-310. https://doi.org/10.1590/S1983-40632014000300009

Teles, A.S.C., Chávez, D.W.H., Gomes, F.S., Cabral, L.M.C., Tonon, R.V., 2017. Effect of temperature on the degradation of bioactive compounds of Pinot Noir grape pomace during drying. Brazilian Journal of Food Technology, Campinas, 21. https://doi.org/10.1590/1981-6723.5917

Vilvert, J.C., Freitas, S.T., Santos, L.F.S., Ribeiro, T.D., Veloso, C.M., 2024. Phenolic compounds in acerola fruit and by-products: An overview on identification, quantification, influencing factors, and biological properties. Journal of Food Measurement and Characterization, 18(1), 216-239. https://doi.org/10.1007/s11694-023-02175-1

Yamchi, A.A, Sharifian, F., Khalife, E., Kaveh, M., 2024. Drying kinetic, thermodynamic and quality analyses of infrared drying of truffle slices. Journal of food science, 89(6), 3666–3686. https://doi.org/10.1111/1750-3841.17096

Zogzas, N.P., Maroulis, Z.B., Marinos-Kouris, D., 1996. Moisture diffusivity data compilation in foodstuffs. Drying Technology, 14, 2225-2253. https://doi.org/10.1080/07373939608917205