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Oven-Dried Cupuaçu and Bacuri Fruit Pulps as Amazonian Food Resources

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Abstract: The Amazon is one of the largest and most diverse biomes on the planet. Cupuaçu (*Theobroma grandiflorum* (Willd. ex Spreng.) Schum) and bacuri (*Platonia insignis* Mart.) are Amazonian fruit species appreciated for their sensory characteristics and promising availability of bioactive compounds. However, high moisture levels (>80%) make these pulps susceptible to deterioration during storage. In this study, the oven-drying process was monitored to produce dry and more stable pulps. The process was monitored at 40 °C, 55 °C and 70 °C, and the bioactive compounds and antioxidant capacity were determined as quality indicators. In general, drying at 70 °C for 340 min produced dried cupuaçu and bacuri pulps with high levels of total phenolic compounds: 288 and 652 mg gallic acid equivalents/100 g, respectively. The hygroscopic evaluation suggested that both of the dried pulps should be stored at a relative humidity of <40% to avoid rapid water adsorption and it is advised to carry out the oven-drying process until up to 12% moisture is reached for cupuaçu and 9% for bacuri to avoid unnecessary energy consumption. Thus, this study expands the potential of bacuri and cupuaçu pulps for application in food industries, contributing to the economic and social development of the Amazon region.

Keywords: *Theobroma grandiflorum*; *Platonia insignis*; drying kinetics; bioactive compounds; hygroscopicity

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1. Introduction

The Amazon rainforest displays some of the most incredible biodiversity in the world, ranging from food to therapeutic plants. The Amazonia biome in Brazil comprises more than 13,000 species of trees, with more than 2900 endemic plants, being one of the most extensive intact forests and the largest biome in the world (representing 49.29% of the Brazilian territory and 40% of the South American continent) [1–3]. Many of these plant species are fruit trees, representing great nutritional and economic potential to local people, but have been little explored as ingredients by the food industry. In addition, Amazonian fruits contribute to food intake diversification by offering high contents of bioactive compounds helpful in improving consumer health [4,5]. Thus, Amazonian fruits certainly have a high potential for scientific research and the development of new food products as long as sustainable approaches enable industrial exploitation. Among the native fruits available in the Amazonia biome, cupuaçu (*Theobroma grandiflorum* (Willd. ex Spreng.) Schum) and bacuri (*Platonia insignis* Mart.) are two famous Amazonian fruits, being the focus of our study since they are abundantly distributed in the Brazilian Amazonia and already known abroad due to their remarkable sensory characteristics.

Cupuaçu belongs to the Sterculiaceae family, and its genus *Theobroma* comprises other species, including cocoa (*Theobroma cacao* L.). This similarity gave rise to its name; in the indigenous people's language (*Tupi* indigenous people), *kupu* means "cocoa-like", and *uasu* means "big" [6,7]. The pulp of cupuaçu fruits has high economic potential due to its appreciable sensory characteristics, such as its aroma, flavor, and texture. Furthermore, the high contents of bioactive compounds, such as phenolic compounds (flavonoids) and ascorbic acid, are important attributes that highlight cupuaçu's relevance as a promising food for human health [8,9]. Bacuri belongs to the Clusiaceae family (also known as the Guttiferaceae family) and its name also comes from the indigenous language (*Tupi*), in which *waku'ri* means "to fall soon", since the fruits fall as soon as they ripen [10,11]. Bacuri fruits are among the most important fruits in the Amazon due to their delicate flavor, which makes them highly appreciated and consumed by locals. Research carried out on the pulp of bacuri fruits showed the presence of promising bioactive compounds, such as phenolic compounds (flavonoids) and vitamins E and C [12,13].

In the Amazon, fresh cupuaçu and bacuri pulps are widely consumed in the form of juices, ice creams, pastes, jellies, sweets, liqueurs, and wines, among others [11,14]. Although the benefits of consuming fresh fruits are notable, they are more susceptible to spoilage by microorganisms and degradation by chemical and enzymatic reactions, mainly due to their high moisture content [15]. Some studies have explored drying methods for these pulps, including the air convection drying method [16], freeze-drying [17], and spray-drying [18], although studies have been carried out, the most widely used preservation method is still pasteurization followed by freezing.

It is known that each method has its own set of advantages and limitations. Thus, technological strategies to overcome the limitations of foods with a high moisture content can be adopted, such as drying using an oven, a method commonly used to increase the shelf life of fruits, so they can be easily used or transported by the food industry [15,19,20]. In addition, drying not only allows for timely and efficient processing, but also improves the natural flavor and taste of the fruit, offering consumers a wider range of options [21] and enables its use in the development of new products.

Successful oven-drying processes require knowledge of the physicochemical mechanisms that occur during water removal at high temperatures, since heat transfer processes are complex [22], and influence the characteristics of dehydrated products. Furthermore, many nutrients and other bioactive compounds are heat-sensitive, such as phenolic compounds, which may undergo changes during processing [23–26]. However, the impact of the method proposed in this study on the phenolic compound content of the pulps remains uncertain.

The quality parameters of dry products depend not only on the process employed but also on the storage conditions, such as the relative humidity (%), temperature (°C), and packaging material [27,28]. In this context, the study of moisture sorption isotherms provides information on the interaction between food and the storage environment. Sorption isotherms are unique to a specific food component and, therefore, are evaluated experimentally [27]. They are mainly used to determine the most appropriate packaging material, predict the shelf life and model moisture changes during storage, as it describes the relationship between the equilibrium moisture content and the relative humidity/water activity [27,28].

Given this framework, with the aim of extending the shelf life of cupuaçu and bacuri fruit pulps, and to preserve the high contents of phenolic compounds, our investigation focused on the study of oven-drying kinetics to predict the drying parameters that must be controlled to conduct this process successfully, followed by an evaluation of the moisture sorption isotherms for the dried products at the most promising drying condition.

2. Materials and Methods

2.1. Materials

Ripe cupuaçu (~4 kg) and bacuri (~10 kg) fruits (Figure 1) were obtained from street markets in Belém-PA (Latitude 01°27′21″ S and Longitude 48°30′16″ W). The access to the selected fruits was registered in the Brazilian National System for the Management of Genetic Heritage and Associated Traditional Knowledge (SisGen, A8E1050). The fruits were selected and sanitized by immersion in a sodium hypochlorite solution (100 µg/mL) for 10 min. The soft pulps from each fruit were manually separated from the epicarp and seeds using scissors and stainless steel knives, being divided into two portions: one portion was frozen at −18 °C for freeze-drying (control experiments), and the other portion was immediately subjected to the oven-drying process. The process previously described as well as the packaging and storage method were carried out individually for each pulp.

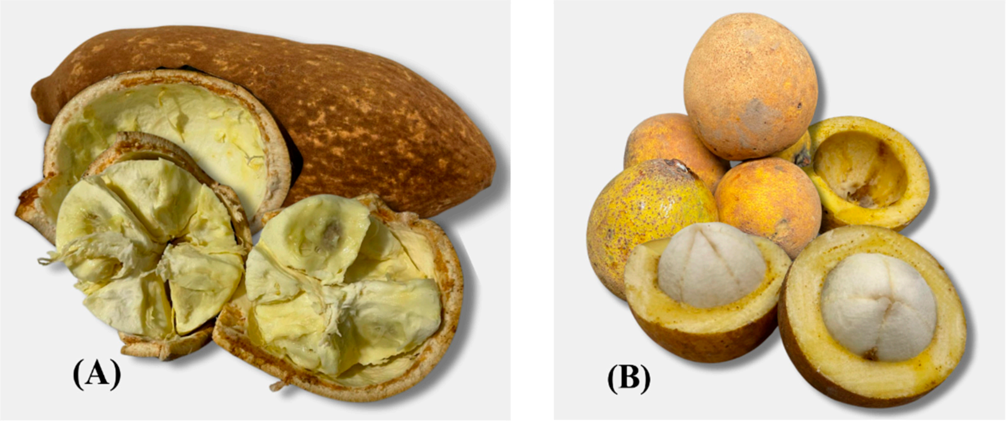

Figure 1. Cupuaçu (**A**) and bacuri (**B**) fruits.

2.2. Oven-Drying Experiments

The fruit pulps were dried (thin-layer drying) in a convection oven (Luca80/42, Lucadema, São José do Rio Preto, São Paulo, Brazil). For this purpose, they were placed in aluminum trays, and the pulp thickness was 4 mm (cupuaçu) and 3 mm (bacuri), distributed on the oven shelves and the fruit pulps were dried individually. Temperatures of 40 °C, 55 °C and 70 °C were set based on data already described in the literature for drying other fruit pulps [16–18] and which should have enabled the obtainment of the desired texture, which was a product dry enough to be transformed into powder. During drying, the sample masses were monitored on a semi-analytical balance (precision ± 0.01 g) and the drying process was stopped when there were no noticeable changes in sample weight for the last three data points, which indicated that equilibrium had been reached. All drying experiments were performed in triplicate. The moisture ratio (MR) to obtain the drying curves, as a function of time, were calculated using Equation (1):

$$MR = \frac{X - X_e}{X_0 - X_e} \tag{1}$$

The experimental data of the drying curves were fitted using five mathematical models, described in Equations (2)–(6) [29]:

$$\text{Page}: \; MR = exp^{(-kt^n)} \tag{2}$$

$$\text{Henderson and Pabis}: \; MR = a \times exp^{(-kt)} \tag{3}$$

$$\text{Newton}: \; MR = exp^{(-kt)} \tag{4}$$

$$\text{Logarithmic}: \; MR = a \times exp^{(-kt)} + b \tag{5}$$

$$\text{Wang and Singh}: \; MR = 1 + at + b \times t^2 \tag{6}$$

2.3. Determination of Effective Diffusivity and Activation Energy

The effective diffusivity (D_{eff}), a property that characterizes the mass transfer during drying processes, was determined from Fick's second law using Equation (7) [30,31]. The calculation was carried out by linear regression, considering the temperature and a bed thickness of 4 mm for the cupuçu pulp and 3 mm for the bacuri pulp. Furthermore, the activation energy (E_a) was calculated using Equation (8). The E_a value indicates the degree of water diffusivity in the material during drying [31].

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{D_{eff}\,\pi^2}{L^2} t\right) \tag{7}$$

$$D_{eff} = D_0 \ \exp\left(-\frac{E_a}{RT}\right) \tag{8}$$

2.4. Moisture Contents and Water Activity (a_w)

The moisture contents of dried cupuaçu and bacuri pulps were determined by drying them in a drying oven at 105 °C to constant weight [32]. The a_w values were directly determined using a hygrometer (Aqualab, 4TE, Dew Point Water Activity Meter, Pullman, WA, USA). The analyses were carried out in triplicate.

2.5. Instrumental Color (CIELAB)

Instrumental color determination was carried out with a portable colorimeter (model CR-400 Konica Minolta, Tokyo, Japan), according to the following parameters: diffuse illumination, specular included, observer angle of 2°, and illuminant D65. The following color parameters were obtained using the CIELAB system: L^* (luminosity), the color coordinates a^* (red to green) and b^* (yellow to blue), chroma (C^*_{ab}) (Equation (9)), hue angle ($h^\circ{}_{ab}$) (Equations (10) and (11)) and total color difference (ΔE) (Equation (12)):

$$C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2} \tag{9}$$

$$h^{\circ}_{ab} = arctang\left(\frac{b^*}{a^*}\right), \text{ when } +a^* \text{ and } +b^* \text{ (first quadrant)} \tag{10}$$

$$h^{\circ}_{ab} = 180 + arctang\left(\frac{b^*}{a^*}\right), \text{ when } -a^* \text{ and } +b^* \text{ (second quadrant)} \tag{11}$$

$$\Delta \mathrm{E} = \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2} \tag{12}$$

2.6. Bioactive Compound Determination

The extracts used for the determination of the total phenolic compounds and flavonoids were obtained from ~5 g of freeze-dried and oven-dried cupuaçu and bacuri pulps. The extract preparation was carried out with methanol/water (8:2, *v*/*v*) [33] in conical test tubes using Ultra Turrax (Ultra Turrax Tube Drive model UTT, IKA, Wilmington, NC, USA) for 2 min, followed by centrifugation up to 12,570× *g*. The supernatant was collected, and the solid residue was subjected to the same extraction procedure five times. The combined liquid supernatants of each pulp comprised a single extract to determine total phenolic compounds and total flavonoids.

The contents of total phenolic compounds were determined by spectrophotometry at 750 nm after a colorimetric reaction with the Folin–Ciocalteu reagent [34]. The results (n = 3) were expressed as mg gallic acid equivalent (GAE)/100 g dried pulp (db), calculated using external seven-point analytical curves of gallic acid standard (1–100 µg/mL). The total flavonoid content was determined by spectrophotometry at 435 nm after a colorimetric reaction with $AlCl_3$ [35]. The results (n = 3) were expressed as mg quercetin equivalent (EQ)/100 g dried pulp (db), calculated using external seven-point analytical curves of the quercetin standard (1.56–100 µg/mL).

2.7. Scavenging Capacity Against ABTS Radical by Direct Measurement with the Dried Solid Pulps (QUENCHER Method)

The scavenging capacity was determined directly with the solid powders of freeze-dried and oven-dried cupuaçu and bacuri pulps, according to the QUENCHER method, based on the scavenging of $ABTS^{\bullet+}$, as described by [36] with adaptations. Briefly, before measurement, the dried pulps were pulverized in a mortar and sieved to obtain powders with smaller particle sizes (0.1–0.3 mm). The reaction mixture was composed of the powders (1.0–4.5 mg), followed by the direct addition of $ABTS^{\bullet+}$ solution and vortex agitation for 30 s. Then, the mixture was immediately centrifuged at 12,000× g for 2 min, and the absorbance of the supernatant was read at 734 nm. The results (n = 3) were plotted as percentage of scavenging $ABTS^{\bullet+}$ (%) versus the mass of each dried powder to calculate the IC_{50} values, which were the amount of powder (mg) that decreased the absorbance of $ABTS^{\bullet+}$ by 50%.

2.8. Moisture Sorption Isotherms

Moisture sorption data were acquired at 25 °C for both pulps by the Vapor Sorption Analyzer (VSA, Pullman, WA, USA) using the dynamic vapor sorption method (DVS), which consists of monitoring the moisture and water activity (a_w) values of a sample exposed to environments with different relative humidity (RH) levels [37]. About 2 g of powdered dried pulps was weighed, and before running the adsorption, the ground sample was placed inside a glass desiccator, with silica gel at the base, under vacuum at room temperature for 24 h, to reduce the a_w level of the dried sample. Afterward, a micro-analytical balance was used to weigh about 1600 to 1800 mg of the sample into the stainless steel capsule of the VSA. To obtain equilibrium data, the samples were exposed to different levels of RH, as induced by changes in the injection of dry and saturated vapor. For the adsorption (a_w 0.1–0.9) and desorption (0.9–0.1) isotherms, we adopted $\Delta_{mass}/\Delta_{time} \leq 0.1$ as the convergence criterion for the equilibrium measurements. After the analysis, the dry mass (%) was checked by gravimetry after drying in an oven at 105 °C.

The monolayer moisture contents (m_o) at 25 °C were determined for both the adsorption and desorption processes using the linear form of the BET equation (Equation (13)) [38] and all the experimental data were used to determine the best fit to the most used mathematical models proposed to predict the moisture sorption in foods (Equations (13)–(19)) [38–40]:

$$\text{Linearized BET}: \frac{a_w}{(1-a_w)\times m} = \frac{1}{m_o \times c} + \frac{(c-1)}{m_o \times c} \times a_w \tag{13}$$

$$\text{GAB}: m = \frac{m_o \times c \times k \times a_w}{[(1-k\times a_w)\times (1+(c-1)\times k \times a_w)]} \tag{14}$$

$$\text{Halsey}: m = \left[\frac{-a}{ln a_w}\right]^{\frac{1}{b}} \tag{15}$$

$$\text{Henderson}: m = a\left[\frac{-ln(1-a_w)}{a}\right]^{\frac{1}{b}} \tag{16}$$

$$\text{Oswin}: m = a\left[\frac{a_w}{1-a_w}\right]^{b} \tag{17}$$

$$\text{Smith}: m = a - b \times ln(1-a_w) \tag{18}$$

$$\text{Peleg}: m = k_1 \times a_w^{n_1} + k_2 \times a_w^{n_2} \tag{19}$$

2.9. Statistical Analysis

All the results (mean ± standard deviation), in triplicate, were subjected to an Analysis of Variance (one-way ANOVA), and the means were compared using the Tukey test at a 95%

significance level (p < 0.05) with Statistica 8.1 software (Statsoft, Tulsa, OK, USA). The best fit for the drying models was selected based on the highest coefficient of determination (R^2), lowest mean relative error (P), lowest estimated mean error (SE), and the result of the chi-square test (χ^2) at the level of significance of 0.05 ($p \leq 0.05$), according to Equations (20)–(22). The best fit for the sorption isotherm models was selected based on the highest R^2 and lowest P.

$$P = \frac{100}{n} \sum \frac{Y - \hat{Y}}{Y} \tag{20}$$

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{DF}} \tag{21}$$

$$\chi^2 = \frac{\sum (Y - \hat{Y})^2}{DF} \tag{22}$$

3. Results and Discussion

3.1. Oven-Drying Kinetics for Cupuaçu and Bacuri Pulps

Regardless of the type of pulp, the drying time decreased significantly with increased temperature, as expected. Based on the observed drying experiments (Figure 2), the expected times required for drying the fresh cupuaçu pulp were 580 min at 40 °C, 460 min at 55 °C, and 340 min at 70 °C, which mean that increasing the temperature above 40 °C would reduce the drying time by 22% at 55 °C and 42% at 70 °C. For bacuri, the fresh pulp required longer drying times than cupuaçu to reach the equilibrium condition for the complete removal of water by vaporization, requiring 820 min at 40 °C, 580 min at 55 °C and 340 min at 70 °C. As was also observed for cupuaçu, the increase in the drying temperature resulted in drying time reduced by 38% at 55 °C and 50% at 70 °C. These results showed that drying cupuaçu and bacuri pulps in drying ovens at 40 °C and 55 °C could be considered slower processes than that at 70 °C, with a greater energy expenditure, resulting in the excessive use of power resources in industry.

The drying curves for the cupuaçu and bacuri pulps showed exponential decay behavior during dehydration (Figure 2), indicating that oven-drying (thin-layer drying) occurred at decreasing rates over time for all the tested conditions. The drying rates for the cupuaçu pulp were in the range from 19 to 8 mg H_2O/min at 40 °C, 15 to 7 mg H_2O/min at 55 °C and 32 to 5 mg H_2O/min at 70 °C. For the bacuri pulp, lower drying rates were observed: 12 to 3 mg H_2O/min at 40 °C, 13 to 6 mg H_2O/min at 55 °C and 23 to 9 mg H_2O/min at 70 °C. As expected, the highest drying rates were observed for the highest temperatures, and the water content decreased quickly between 10 and 160 min of drying (Figure 2), with the initial drying rates being about 2 to 6.5 times greater than the final rates.

Similar drying behaviors have been reported in the literature, such as those for cupuaçu, banana and apple in convective dryers (35 °C to 60 °C) [15,16], and dehydrated mango in a heat pump dryer (40 °C and 50 °C) [41]. All of these authors observed faster initial drying rates, followed by a period of slow drying rates, which can be explained by the second law of thermodynamics, which states that water diffuses from the interior to the surface, moving from the points of the highest to the lower water contents [41,42]. Furthermore, selecting an appropriate temperature and time for drying each food product can provide efficient processes to produce stable products that retain their desirable sensory characteristics, such as color and flavor, for further applications.

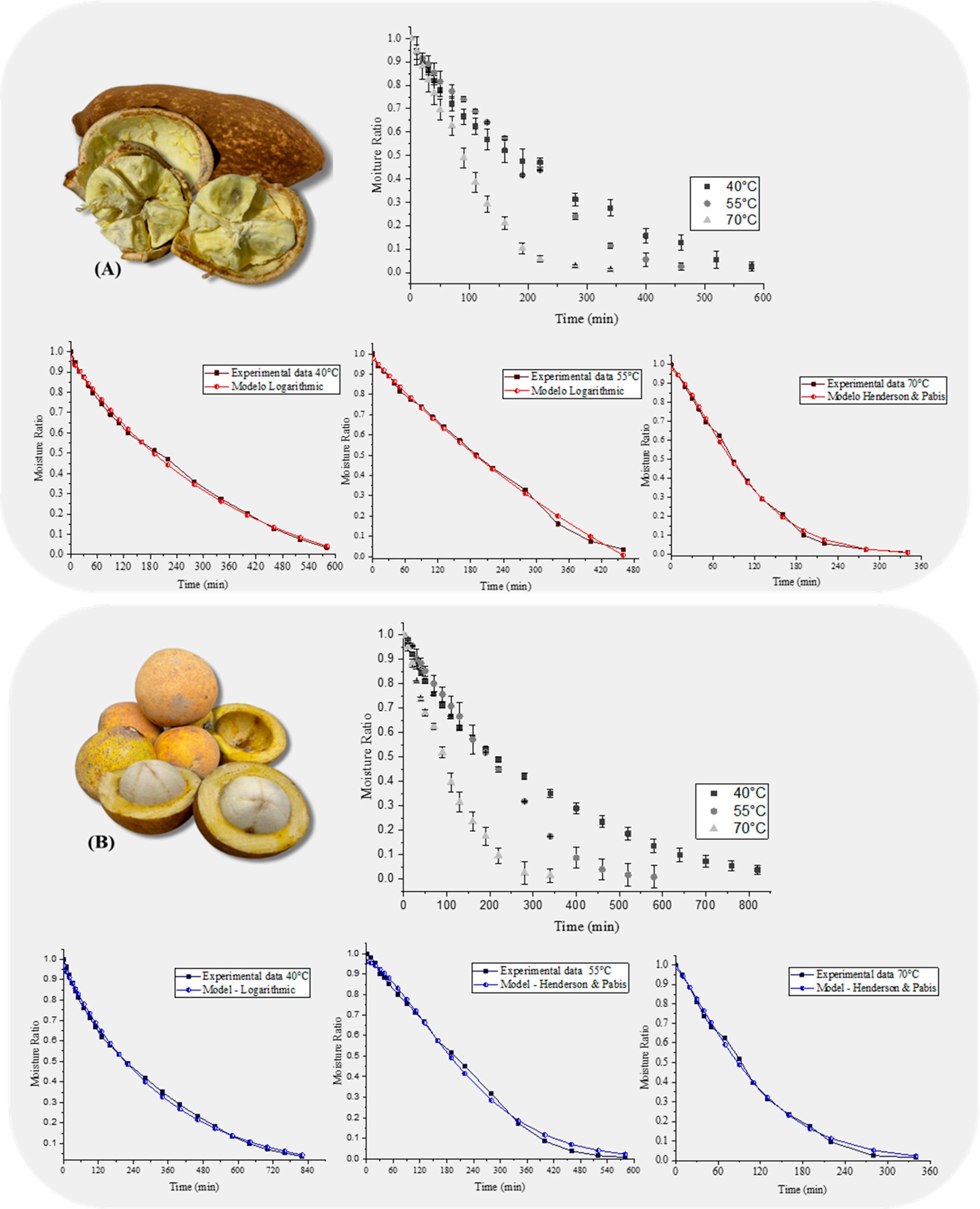

Figure 2. Oven-drying curves for cupuaçu (**A**) and bacuri (**B**) pulps at 40 °C, 55 °C and 70 °C, followed by the experimental drying data and curves predicted by the Logarithmic or Henderson and Pabis models.

The values of the effective diffusivity (D_{eff}) of water for the cupuaçu and bacuri pulps (Table 1) generally indicated that increasing the temperature, which consequently increases the vibration level of water molecules, contributes to faster diffusion [43,44], thus favoring the removal of water from fresh pulps, confirming what was observed in all the drying curves (Figure 2). D_{eff} values can be influenced by factors other than temperature, such as the relative humidity and the thickness of the material to be dried [45,46]. The D_{eff} values observed in this study were higher than those reported in the literature, such as for the convective drying of cupuçu pulps at 40 °C ($D_{eff} = 5.591 \times 10^{-10}$ m^2/s) and at 60 °C ($D_{eff} = 6.906 \times 10^{-10}$ m^2/s) [16], and for sun-drying gooseberries ($D_{eff} = 5.406 \times 10^{-11}$ m^2/s) [46]. On the other hand, D_{eff} values in the same order of magnitude were observed for drying mangoes in a heat pump dryer at different temperatures (40 °C = 6.18×10^{-8} m^2/s and 60 °C = 7.09×10^{-8} m^2/s) [41]. This indicates that the D_{eff} values are within those distributed for most food substances. Varietal, cellular and morphological disparities and the moisture content, as well as the drying method and type of dryer used, are largely responsible for the variations in the effective moisture diffusivity for different agricultural products [47].

Table 1. Values of effective diffusivity (D_{eff}) of water for drying cupuaçu and bacuri pulps.

	D_{eff} (m^2/min)		
	40 °C	**55 °C**	**70 °C**
Cupuaçu pulp	1.75×10^{-8}	9.08×10^{-9}	7.78×10^{-8}
Bacuri pulp	1.02×10^{-8}	1.46×10^{-8}	2.4×10^{-8}

Both of the pulps presented similar values of activation energy (E_a) for the oven-drying process (24.33 and 25.42 kJ/mol), which were about twice as high as that reported in another study for cupuaçu pulp dried in a convective dryer (E_a = 12.28 kJ/mol) [16]. The E_a required for drying agricultural products varies from 12.0 to 110 kJ/mol [47], with the E_a being an energy barrier to overcome in the process of starting water removal during the drying processes, the lower the E_a, the lower the effect of temperature on water diffusivity in the product [48].

Table 2 shows the kinetic parameters fitted to the mathematical models to predict the experimental data for oven-drying cupuaçu and bacuri pulps. Based on the selected parameters, the mathematical model that best described the oven-drying curves was the Logarithmic model for drying cupuaçu pulp at 40 °C and 55 °C and bacuri pulp at 40 °C (Figure 2). The Henderson and Pabis model (Table 1) was the model that presented the best fit for drying the cupuaçu pulp at 70 °C and bacuri pulp at 55 °C and 70 °C (Figure 2). Both of the mathematical models were already reported as efficient for predicting the convective drying of cupuaçu pulps [16] and sun-dried currants [46].

The literature mentions 67 mathematical models evaluated using at least 28 selection criteria. These criteria included the calculation of the correlation coefficient, modeling determination coefficient, R^2, chi-square, errors, and others. In addition to performing the calculations, it is necessary to correctly evaluate the criteria, such as selecting higher values of the correlation coefficient and lower values of the chi-square and errors. After evaluating all these criteria, the authors suggest that the Logarithmic and Henderson and Pabis models presented the best adjustment results, along with the Page model, diffusion approximation, two-exponential terms, and others [48]. Not only are the temperature and time parameters important in oven-drying processes, but so are the drying air speed, relative humidity, shape and type of the drying materials, design and geometry of the shelves, and conditions of the drying medium, among others, all depending on the type and configuration of the process. There is a lack of data in the literature regarding oven-drying cupuaçu and bacuri pulps, and this study contributes with relevant information to make oven-drying processes accessible in any industry.

Table 2. Oven-drying kinetics and statistical parameters for cupuaçu and bacuri pulp as predicted by the drying models.

Model	Parameters	Cupuaçu Pulp			Bacuri Pulp		
		40 °C	55 °C	70 °C	40 °C	55 °C	70 °C
Page	k	0.0023	0.0010	0.0017	0.0045	0.0005	0.0013
	n	1.086	1.256	1.340	0.950	1.392	1.326
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
	P (%)	17.33	20.51	8.12	12.55	36.93	12.43
	SE ($\times 10^{-3}$)	1.178	3.130	1.162	1.89	1.824	1.037
	χ^2 ($\times 10^{-3}$)	0.0013	0.0009	0.0013	0.0035	0.00001	0.0010
Henderson and Pabis	a	0.961	0.937	0.9761	0.977	0.9613	0.9854
	k	0.0020	0.0002	0.0012	0.0031	0.0002	0.0024
	n	1.012	1.494	1.411	1.005	1.528	1.260
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
	P (%)	15.01	14.03	7.49	34.66	10.389	14.52
	SE ($\times 10^{-3}$)	3.03	3.83	1.089	1.716	2.780	1.373
	X^2 ($\times 10^{-3}$)	0.0092	0.0147	0.0012	0.0029	0.0077	0.0019
Newton	k	0.0039	0.0041	0.0087	0.0034	0.0040	0.0066
	R^2	0.99	0.98	0.98	0.99	0.98	0.99
	P (%)	18.21	34.72	56.75	10.18	5.51	4.89
	SE ($\times 10^{-3}$)	3.776	8.843	10.632	2.310	18.027	11.163
	χ^2 ($\times 10^{-3}$)	0.0044	0.0782	0.1130	0.0053	0.3250	0.1246
Logarithmic	a	1.1629	1.9670	1.177	1.0238	1.4098	1.1524
	k	0.0027	0.0014	0.0073	0.0028	0.0024	0.0069
	b	−0.198	−0.989	−0.136	−0.057	−0.389	−0.127
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
	P (%)	4.51	9.21	14.12	4.04	49.28	22.90
	SE ($\times 10^{-3}$)	1.186	1.180	3.81	1.371	2.177	1.724
	χ^2 ($\times 10^{-3}$)	0.0014	0.0013	0.014	0.0019	0.0047	0.0030
Wing and Singh	a	−0.0031	−0.0030	−0.0067	−0.0026	−0.0030	−0.0052
	b	0.000003	0.000002	0.00001	0.000002	0.000002	0.00007
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
	P (%)	11.99	7.53	13.59	17.183	32.50	6.05
	SE ($\times 10^{-3}$)	5.029	1.747	1.253	9.212	1.560	3.122
	χ^2 ($\times 10^{-3}$)	0.0253	0.0030	0.0016	0.085	0.0024	0.0098

The water activity (a_w) of the cupuaçu and bacuri pulps dried at different temperatures in a drying oven and by freeze-drying presented values ranging from 0.34 to 0.58 (Table 3). The lowest a_w values were observed for the cupuaçu (0.40) and bacuri (0.39) pulps dried at 70 °C; these values were obtained after the end of the drying process, which lasted 340 min, for both pulps. The a_w values in this study were lower than those reported for the convective drying of gooselia (0.57) [49] and the convective drying of laminated bacuri and green coconut fruits (0.65) [50], but were higher than the range reported for spray-dried powdered cupuaçu pulp (0.09–0.23) [43]. The a_w values provide information about the chemical, biochemical and microbiological stability of food, and based on this property, foods are classified as low-moisture foods ($a_w < 0.6$), intermediate-moisture foods ($0.6 < a_w < 0.9$) and high-moisture foods ($a_w > 0.9$) [51]. Given this, both the dried cupuaçu and bacuri pulps in this study were characterized as low-moisture foods and considered stable concerning microbial contamination since no microbial growth (fungi and bacteria) is expected for the observed a_w values [49].

Table 3. Water activity (a_w), instrumental color and contents of total phenolic compounds (TPC), total flavonoids (TF), and antioxidant capacity of cupuaçu and bacuri pulps after freeze-drying and oven-drying.

Parameters		**Cupuaçu Pulp**				**Bacuri Pulp**			
			Oven-Drying				**Oven-Drying**		
		Freeze-Drying	**40 °C**	**55 °C**	**70 °C**	**Freeze-Drying**	**40 °C**	**55 °C**	**70 °C**
a_w		0.34 ± 0.01^{d}	0.49 ± 0.02^{b}	0.58 ± 0.01^{a}	0.40 ± 0.02^{c}	0.38 ± 0.01^{b}	0.43 ± 0.02^{a}	0.43 ± 0.01^{a}	0.39 ± 0.01^{b}
Color	L	69.34 ± 3.9^{a}	40.86 ± 3.22^{b}	43.13 ± 2.73^{b}	32.46 ± 2.38^{c}	62.66 ± 4.31^{a}	43.12 ± 4.75^{b}	40.28 ± 4.20^{b}	27.98 ± 3.68^{b}
	a^*	-6.58 ± 0.40^{a}	3.9 ± 0.12^{c}	3.97 ± 0.34^{c}	5.85 ± 0.71^{b}	-4.30 ± 0.10^{a}	3.85 ± 0.77^{b}	3.5 ± 0.02^{b}	3.23 ± 0.67^{b}
	b^*	20.76 ± 1.62^{b}	29.27 ± 1.1^{a}	30.51 ± 4.69^{a}	24.36 ± 0.68^{b}	15.91 ± 0.61^{c}	30.12 ± 1.66^{a}	21.12 ± 0.55^{b}	22.12 ± 1.93^{b}
	C^*	21.79 ± 1.66^{b}	29.48 ± 1.13^{a}	30.77 ± 1.45^{a}	25.07 ± 0.86^{b}	16.50 ± 0.6^{c}	30.42 ± 1.71^{a}	21.13 ± 0.55^{b}	22.42 ± 1.94^{b}
	h^*_{ab}	107.72 ± 0.32^{a}	2.11 ± 0.06^{b}	2.08 ± 0.02^{b}	1.76 ± 0.07^{b}	104.61 ± 0.7^{a}	2.07 ± 0.04^{b}	2.42 ± 0.05^{b}	1.95 ± 0.04^{b}
	ΔE	-	40.32 ± 3.31^{b}	31.51 ± 0.80^{c}	45.89 ± 1.26^{a}	-	25.34 ± 0.91^{b}	26.52 ± 3.26^{b}	33.27 ± 144^{a}
TPC (mg GAE/100 g)		1011 ± 24.53^{a}	220.96 ± 7.37^{d}	313.38 ± 3.58^{b}	652.15 ± 10.81^{c}	722.13 ± 2.37^{a}	237.38 ± 15.48^{c}	229.06 ± 1.84^{c}	288.32 ± 17.92^{b}
TF (mg QE/100 g)		36.13 ± 1.2^{d}	82.08 ± 0.82^{c}	251.27 ± 2.65^{a}	233.23 ± 4.3^{b}	48.28 ± 0.52^{a}	33.58 ± 3.38^{b}	22.22 ± 0.59^{c}	43.6 ± 1.97^{a}
Antioxidant capacity (IC_{50} in mg)		97.88 ± 0.12% *	2.03 ± 0.14^{a}	1.56 ± 0.06^{b}	2.1 ± 0.14^{a}	97.63 ± 0.15% *	1.72 ± 0.11^{a}	1.62 ± 0.14^{a}	2.6 ± 0.29^{b}

All the values (mean ± standard deviation, n = 3, dry basis) with the same superscript letters in the same row are not statistically different ($p < 0.05$) (Tukey's test). TPC: total phenolic compounds; TF: total flavonoids. The contents (mean ± standard deviation, n = 3, dry basis) with the same superscript letters in the same line are not statistically different ($p < 0.05$) (Tukey's test). GAE: gallic acid equivalent; QE: quercetin equivalent. * Percentage of inhibition in 1 mg of freeze-dried pulp.

The attribute of color plays a crucial role in the acceptability of food products. The instrumental color parameters (Table 3) of dried cupuaçu and bacuri pulps were significantly affected depending on the temperature of the drying process, which can be confirmed visually (Figure 3). Comparing all the dried pulps, the L^* values decreased as the drying temperature increased, which means that the oven-dried pulps were remarkably darker than the freeze-dried pulps. According to the hue angle (h_{ab}^*) and chroma (C^*), the freeze-dried cupuaçu and bacuri pulps were characterized as yellowish and having a less vivid color as compared to the oven-dried pulps, which showed redder tones (h_{ab}^* = 1.7–2.4), with higher C^* values, being visually perceived as more vivid (Figure 3). The values of the a^* and b^* components increased for the oven-dried cupuaçu and bacuri pulps compared to the freeze-dried pulps, which were reddish. Furthermore, the high values of the total color difference (ΔE*) (Table 3) for all the oven-dried pulps highlighted the large visual difference compared to the freeze-dried pulps, making this difference even more evident for the pulps dried at 70 °C.

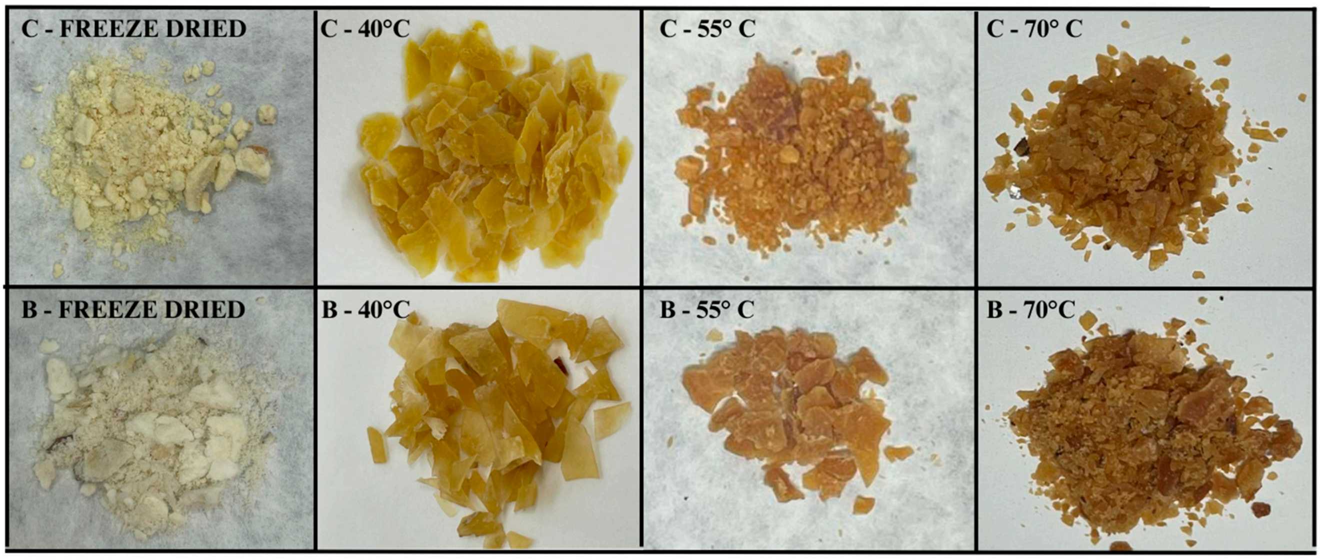

Figure 3. Cupuaçu (**C,** in the first row) and bacuri (**B,** in the second row) pulps after freeze-drying and oven-drying at 40 °C, 55 °C and 70 °C.

In this study, the development of darker colors in the oven-dried pulps may be largely associated with the non-enzymatic browning reactions (Maillard reaction) during the drying process at the selected temperatures. The Maillard reaction contributes significantly to the browning of foods subjected to increased temperatures due to the formation of dark polymers (melanoidins) formed by the initial reaction between reducing sugars and an amino group [52], which are naturally present in most foods, including cupuaçu and bacuri pulps [6,53]. In addition to the Maillard reaction browning reaction, the presence of enzymes, such as polyphenol oxidase, present in the cupuaçu and bacuri pulps [18,54,55], may also have contributed to the slight initial darkening of the pulps observed after pulping and before the start of the oven-drying process. Cupuaçu and bacuri pulps have high phenolic compound contents in their composition [6,13], which makes them an available substrate for polyphenol oxidase (PPO) to mediate the oxidation of these compounds into dark pigments (melanins) [40,56–58]. Similar behavior was reported for the convective drying of cape gooseliads [49] and dried plums in a vacuum pump dryer [57].

3.2. Bioactive Compounds and Antioxidant Capacity of Dried Cupuaçu and Bacuri Pulps

For both of the fruit pulps, the oven-drying process resulted in a significant decrease in the levels of total phenolic compounds when compared to the freeze-dried pulps, with decreases of about 35–78%, with the lowest percentages observed for the pulps dried at

70 °C (Table 3). These results are similar to those obtained for convectively dried strawberries (50 °C and 60 °C). There was a decrease in the content of total phenolic compounds by 60–78%, and this was higher when compared to oven-dried (80 °C) strawberry, apple, plum, blackberry, and apricot (14–30%) [58]. In contrast, a 1.5- to 4-fold increase in the content of total phenolic compounds was observed as the temperature increased (65, 70 and 75 °C) when drying three apple cultivars in a forced-air rotary dryer [59].

Regarding the total flavonoids, decreases in the total contents in the 9–53% range were observed after drying the bacuri pulp in the oven, with the smallest decrease found at 70 °C (Table 3). On the other hand, an increase in the total flavonoid contents was observed for the oven-dried cupuaçu pulps, with the highest levels observed in the pulps dried at 55 °C and 70 °C. Similar behavior was observed for the total flavonoid contents (a two-fold increase) after drying three apple cultivars in a forced-air rotary dryer [59]. Depending on the composition of the material, the thermal degradation of phenolic compounds, including flavonoids, can result in the formation of other compounds with lower molecular masses, derived from the breakdown of more complex structures, such as the partial degradation of lignin into acid derivatives like phenolics [60]. Furthermore, phenolic compounds can also be subject to oxidation reactions due to exposure to molecular oxygen in the atmospheric air during drying. Thus, shorter processing times expose foods to molecular oxygen for less time, resulting in less oxidative degradation [61,62]. In this study, the possible breakdown of conjugated compounds and the formation of new derivative compounds might positively affect the final retention of compounds quantified as total flavonoids in cupuaçu pulp [63].

A study carried out on 17 fruits from Ecuador classified them into three categories: low (<100 mg GAE/100 g), medium (100–500 mg GAE/100 g) and high (>500 mg GAE/100 g) [64]. According to this classification, cupuaçu pulp dried at 40 °C and 55 °C, and bacuri pulp, regardless of the drying temperature, can be considered medium sources of total phenolic compounds, while cupuaçu pulp dried at 70 °C can be classified as a high source of phenolic compounds.

Regarding the effect of drying on the scavenging capacity of the cupuaçu and bacuri pulps against $\text{ABTS}^{\bullet+}$, both the freeze-dried and oven-dried pulps showed a high antioxidant efficiency, even considering the decrease in the total contents of bioactive compounds after drying in an oven (Table 3), with the freeze-dried pulps being more efficient than the oven-dried pulps. It was not possible to calculate the IC_{50} for the freeze-dried pulps since 97% of the $\text{ABTS}^{\bullet+}$ inhibition was observed in 1 mg of dried pulp (the minimum limit of the analytical balance used).

A similar result was reported for apple chips dried at 70 °C and 75 °C, with an increase of approximately 1.75 to 2.3 times in the antioxidant capacity (ORAC and ABTS methods) compared to that in raw apples [59]. A 7–14% increase in the antioxidant capacity against $\text{ABTS}^{\bullet+}$ was also reported for blueberries dried by convective drying (50 °C, 70 °C and 90 °C) [65]. These results are relevant for valorizing both fruits since the oven-drying process maintained the high antioxidant capacity of the cupuaçu and bacuri pulps, enabling their application in food formulations with potential benefits to human health.

3.3. Hygroscopic Behavior of Cupuaçu and Bacuri Pulps Dried at 70 °C

The cupuaçu and bacuri pulps dried at 70 °C presented the highest contents of phenolic compounds, antioxidant capacity, and demanded the shortest drying time. Thus, these dried products were selected for further investigation of their hygroscopic behavior. According to the moisture sorption isotherms (Figure 4), the dried pulp of cupuaçu adsorbed 87% moisture and the dried pulp of bacuri adsorbed 75% at 25 °C at 90% of relative humidity, while, during desorption, the dried pulps reached 19% (cupuaçu) and 12% (bacuri pulp) at 10% of relative humidity, at 25 °C. Figure 4 also shows that the variation in the equilibrium moisture content is linear up to a_w of 0.4, increasing exponentially from this value, which indicates that both the dried products require greater care when being handled or stored in environments with a relative humidity higher than 40%. Above this value, both the products would be more susceptible to adsorbing high amounts of water and susceptible to deterioration caused by undesirable reactions and spoilage caused by microorganisms [49].

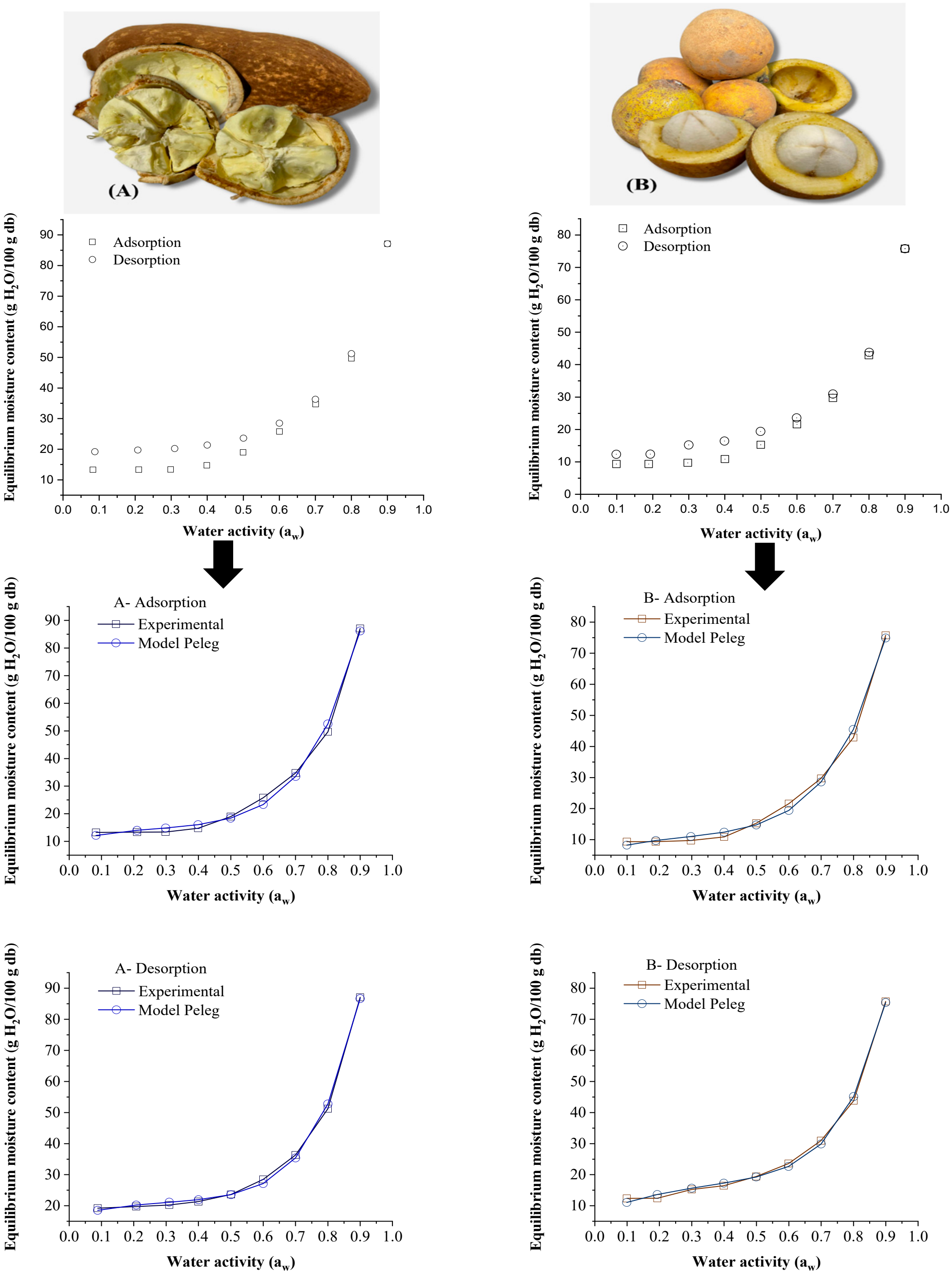

Figure 4. Moisture sorption isotherms of cupuaçu (**A**) and bacuri (**B**) pulps dried at 70 °C, followed by the adsorption and desorption fit by the Peleg model.

The sorption isotherms presented a type-J curve shape, and, according to the IUPAC classification [66], showed type III behavior (Figure 4) for both the pulps. Type III curves were also observed for banana peel flour [67] and pomegranate peel flour [68]. Type III isotherms are typical of products with high soluble solid contents and are related to the physical adsorption of water in the multilayers at $a_w > 0.6$ [66]. Hysteresis was also observed in the range of a_w 0.1 to 0.6 for both the dried cupuaçu and bacuri pulps. Hysteresis in foods is not easy to explain and this is due to unique interactions, since foods are complex combinations of several constituents that absorb water independently and interact with each other [69]. However, in foods with high sugar and pectin contents, such as fruit pulp, hysteresis is more pronounced in the region of lower moisture content, as was also observed in our study (Figure 4) [70]. It is known that the higher the hysteresis, the lower the stability of the product, as dried foods might adsorb a high water content during storage [71]. Furthermore, the desorption monolayer moistures (m_o) were 12.34 g H_2O/100 g for cupuaçu and 9.9 g H_2O/100 g for bacuri pulp, and these values indicate the moisture contents to be reached during the oven-drying process to avoid unnecessary energy consumption.

Table 4 shows the parameters of the mathematical model fitted to the experimental data on the moisture sorption of the dried pulps. Models with *p* value lower than 10% are commonly considered acceptable for practical purposes [72]. According to the sorption data and statistical parameters, the mathematical model that best fit the experimental data was the Peleg model for both the dried pulps. The Peleg model has already been described as an adequate model for predicting the sorption isotherms of figs [73] and "Sarilop" and "Kadota" [74]. In our study, Peleg's model was the only one that presented *p* values below 8% for the adsorption and desorption isotherms, in addition to exhibiting a high R^2 (>0.99), and it was suggested as the best model to predict the hygroscopic behavior of the cupuaçu and bacuri pulps dried at 70 °C (Figure 4).

Table 4. Sorption data and statistical parameters for the oven-dried cupuaçu and bacuri pulps at 70 °C as predicted by the sorption isotherm models.

Model	Parameters	Cupuaçu Pulp		Bacuri Pulp	
		Adsorption	Desorption	Adsorption	Desorption
BET	m_0	8.540	12.390	6.238	9.901
	c	−27.881	−25.219	−29.685	−84.167
	R^2	0.996	0.993	0.999	0.999
GAB	m_0	10.830	13.456	8.994	10.353
	k	0.973	0.938	0.981	0.959
	c	37.576	43.802	25.080	78.050
	R^2	0.994	0.993	0.994	0.979
	P (%)	8.370	11.020	10.220	3.860
Halsey	a	39.536	126.627	23.451	53.643
	b	1.328	1.598	1.246	1.444
	R^2	0.996	0.987	0.997	0.997
	P (%)	9.603	11.666	10.450	7.490
Henderson	a	0.055	0.018	0.081	0.038
	b	0.843	1.108	0.779	0.966
	R^2	0.972	0.929	0.983	0.963
	P (%)	24.693	25.819	23.185	25.036
Oswin	a	21.090	26.595	16.857	20.680
	b	0.637	0.516	0.681	0.577
	R^2	0.989	0.968	0.994	0.987
	P (%)	15.809	17.529	14.460	14.677
Smith	a	1.05093	7.882	−1.302	3.368
	b	33.06005	29.793	29.910	27.788
	R^2	0.965	0.954	0.970	0.968
	P (%)	24.04	18.960	27.29	19.110
Peleg	k_1	17.596	23.763	14.786	22.785
	n_1	0.148	0.103	0.253	0.314
	k_2	124.589	124.890	108.738	110.490
	n_2	5.627	6.468	5.540	6.881
	R^2	0.997	0.999	0.998	0.999
	P (%)	6.15	2.720	7.560	4.420

4. Conclusions

In this study, the oven-drying of cupuaçu and bacuri pulps was monitored at 40 °C, 55 °C and 70 °C, making it possible to suggest that drying both fruit pulps by oven at 70 °C for 340 min produced dried pulps with high contents of total phenolic compounds and a high antioxidant capacity. Additionally, the Logarithmic and Henderson and Pabis mathematical models were shown to be the most efficient models for predicting the oven-drying processes for both the pulps for industrial purposes. For the first time, the desorption isotherms of cupuaçu and bacuri pulps dried at 70 °C were studied, and the hygroscopic evaluation suggested that both the dried fruit pulps should be stored at a relative humidity below 40% to avoid fast water adsorption. Furthermore, it is advised to carry out the oven-drying process until 12% moisture for cupuaçu and 9% for bacuri is reached to avoid unnecessary energy consumption, according to the desorption monolayer moisture contents. The results of this research indicated industrial process parameters suitable for use in the production of dried pulps.

However, efforts are still needed to develop more in-depth systematic studies focused on the effect of the process on the chemical composition and biological properties associated with the bioactive compounds present in both fruits, such as the determination of the antioxidant potential against reactive species of physiological and dietary relevance that allow us to more clearly visualize the beneficial potential of dried pulps for consumer health. In addition to studies that indicate better forms of storage, packaging, and shelf life, we can also include studies on the application of dried pulps in the development of new food products, and thus add value and contribute to the economic and social development of the Amazon region.

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Institutional Review Board Statement: The access to the selected fruits was registered in the Brazilian National System for the Management of Genetic Heritage and Associated Traditional Knowledge (SisGen, A8E1050).

Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

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Nomenclature

MR	Moisture ratio
X	Water content of the product
Xe	Equilibrium water content
X_0	Initial water content
R^2	Determination coefficient
a b n k	Empirical constants and coefficients in the equations

P	Mean relative error
SE	Estimated mean error
D_{eff}	Effective diffusivity coefficients (m^2/s)
L	Bed thickness (m)
t	Drying time
D_0	Pre-exponential factor of the Arrhenius-type equation (m^2/s)
E_a	Activation energy (J/mol)
R	Universal gas constant (J/mol K)
T	Absolute drying temperature (K)
m	Equilibrium moisture content (g H_2O/100 g db)
m_0	Monolayer moisture content
a_w	Water activity
Y	Experimental value of MR
$\hat{Y}$	Estimated value of the MR
n	Number of observations
DF	Model degrees of freedom
TPC	Total phenolic compounds
TF	Total flavanoids

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