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Effect of Temperature and Air Velocity on the Drying Kinetics and Nutritional Properties of Flours from Three Varieties of Sweet Cassava (*Manihot esculenta* Crantz)

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Abstract

The drying kinetics of three varieties of cassava were evaluated in a tray dryer, using a completely randomized design with a three-factor factorial arrangement: temperature (50, 60, and 70 °C), air velocity (1, 2, and 3 m/s), and variety ("*Blanca Mona*", "*Ica Negrita*", "*Venezolana*"), with three replicates per treatment. The results obtained were used to construct drying curves, which showed that this process occurred in the decreasing period. The drying curves were adjusted to mathematical models, and the Page model was the best fit to the experimental data with R^2_{adj} values closer to 1 and RSS values less than 0.0086. The effective diffusivities (D_{eff}) in cassava flours were represented by the Arrhenius equation with values ranging from 5.24×10^{-10} to 1.58×10^{-9} m^2/s. The activation energy (E_a) recorded values between 20.34 and 28.32 kJ/mol. The flours from the three cassava varieties were obtained under the best drying conditions (70 °C and 3 m/s). The physicochemical characterization of fresh roots and flours from three cassava varieties revealed significant genotype-dependent differences in their proximal composition. *Blanca Mona* exhibited the highest ash content and the lowest total carbohydrates among fresh roots, while *Ica Negrita* stood out for its superior crude fiber content in flour. *Venezolana* flour stood out for its higher protein content (3.86 ± 0.04 g/100 g) and significant fiber content (1.39 ± 0.39 g/100 g), making it the flour with the best nutritional profile and greatest potential for food applications. Therefore, tray drying is recommended as one of the suitable methods for cassava flour production.

Keywords: cassava; drying kinetics; mathematical models; activation energy; nutritional properties

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1. Introduction

Cassava cultivation (*Manihot esculenta* Crantz) is one of the main food sources contributing to the rural economic development of millions of people in tropical countries, particularly in vulnerable regions of Africa, Asia, Latin America, and Oceania, which have marginal soils and limited access to other food crops. Recent estimates report that around 800 million people depend on cassava, making it a fundamental pillar of food security [1–3]. Nutritionally, cassava is characterized by being rich in carbohydrates, mainly starch, providing a significant amount of energy, as well as dietary fiber and essential micronutrients

such as potassium, calcium, and B vitamins (B_6, folic acid), which contribute to basic nutrition, maintenance of intestinal health, and prevention of chronic diseases [2]. Cassava is a highly usable food for making functional products and nutritional supplements, especially in regions where other food sources are not accessible [4]. However, despite its many benefits and widespread use, it faces significant challenges because it is highly vulnerable to post-harvest deterioration. With a moisture content of approximately 65%, it is highly perishable, thus creating strategic disadvantages in relation to its preservation during production, transport, and marketing. Its shelf life is shortened due to post-harvest physiological deterioration, making the roots unappealing [5,6]. It manifests itself through easily noticeable changes such as blue/black or brown discoloration in the vascular parenchyma, accompanied by loss of firmness and flavor, which reduces its commercial value and market acceptance [7]. The first symptoms of deterioration become apparent within 24 to 72 h after harvesting, although this time frame may vary depending on post-harvest handling [5].

Global post-harvest losses of cassava in 2021 exceeded 30 million tons, representing a critical challenge for their use and a decisive obstacle for agri-food systems and food security [8]. In light of this problem, post-harvest processing plays an important role in increasing the shelf life of perishable foods such as vegetables, fruits, and tubers such as cassava during storage [9].

Among the various methods of food preservation, drying is particularly effective, as it helps eliminate moisture that allows microorganisms to grow and enzymes to act, causing deterioration. This makes it easier to store and transport products for longer periods without losing quality [10]. In particular, tray drying is one of the most widely used methods due to its simplicity and adaptability to all types of food raw materials. Its importance lies in kinetically evaluating how the food matrix behaves, considering pre-established parameters (temperature, air velocity) that guarantee the analysis of the evaporation rate and optimization of the resulting flour [11]. The drying kinetics of tubers are fundamental for several reasons: preserving quality by identifying the optimal temperature, air velocity, and humidity conditions that minimize undesirable changes in nutritional and sensory compounds; improving energy efficiency by enabling the design of processes that reduce drying time and operating costs; and providing the kinetic data necessary for the design and scaling up of industrial dryers from the laboratory to production [12,13].

The kinetic evaluation of drying considers the dynamics of moisture loss and allows the process to be mathematically modeled to improve the efficiency and quality of the final product. The resulting drying curves, when fitted to mathematical models, help to better understand how moisture evaporates and how this process affects the physical, chemical, and nutritional properties of the product [14]. The Newton—Lewis, Page, Modified Page, and Henderson—Pabis models are widely used because they offer a simplified yet effective mathematical approach to describe the moisture removal kinetics during the thin—layer drying of food and biological materials, without the computational complexity of full theoretical models. Their primary justification is that they are derived as approximations or empirical modifications of the analytical solution to Fick's second law of diffusion, which is the theoretical foundation for moisture transport [15]. In addition, these models allow us to analyze the importance of each factor and how they relate to each other during the drying process [16].

Various studies have been conducted on mathematical model adjustments to drying kinetics, effective diffusivity calculations, activation energy, energy efficiency, and quality characteristics in tubers such as potatoes [17], yacon [18], sweet potato [19], and yam [20]. In particular, in cassava, its widespread industrial use has contributed to the bulk of research focusing on bitter varieties, concluding that the variety has a significant influence on parameters such as drying velocity [21]. With regard to sweet varieties, characterized by their

low cyanogenic glycoside content and intended mainly for fresh consumption [22], there is limited information, particularly on how drying kinetics are influenced by the characteristics of these varieties and how process conditions impact their nutritional properties. When subjected to drying processes, different cassava cultivars exhibit distinct drying kinetics, which affects both the drying process itself and sensory acceptance [23]. For this reason, this research focused on analyzing how drying kinetics influence the nutritional characteristics of three varieties of sweet cassava, with the aim of optimizing process conditions to obtain high—quality, stable flours. The goal is to improve the preservation, use, and value of this food product.

2. Materials and Methods

2.1. Obtaining and Preparing the Raw Material

The *Blanca Mona*, *ICA Negrita*, and *Venezolana* varieties of cassava were supplied by the Turipaná Research Center of AGROSAVIA (Colombia). Cassavas grown in the department of Córdoba (Colombia) were used, selecting cassavas with homogeneous sizes (4–6 cm thick). The raw materials were washed to remove dirt and impurities and sanitized in a 100 ppm sodium hypochlorite solution for 10 min. The peel was removed, and the cassava was cut into slices (3.4 cm in diameter and 0.15 cm thick) using a laboratory-scale food processor (Hobart FP100-1, Hobart Gmb, Hamburg, Germany).

2.2. Drying Kinetics

The cassava slices were dried using a convective tray dryer (see Figure 1) with an axial flow fan at temperatures of 50, 60, and 70 °C and air velocities of 1, 2, and 3 m/s, adopting a complete 3 × 3 × 3 factorial randomized design, generating 27 experimental combinations. All tests were performed in triplicate. Prior to drying, the dryer was run for 30 min to stabilize operating conditions and ensure uniform thermal conditions. The ambient temperature and relative humidity ranged from 30 to 34 °C and 78 to 80%, respectively. Once the temperature to be evaluated was reached, the cassava slice samples were distributed evenly on the trays and placed in the drying chamber, initiating the experimental process. The air temperature was measured using T-type thermocouples connected to a data logger with an accuracy of ±1 °C. The air velocity was measured using a hot wire digital anemometer, measuring to an accuracy of ±0.1 m/s.

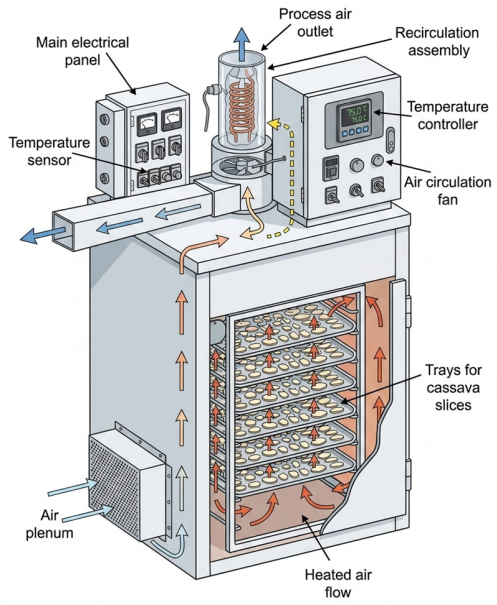


Figure 1. Representative diagram of the tray dryer used for drying kinetics.

The drying kinetics were determined by recording the weight variation of the samples with a Precisa 320XB analytical balance (precision 1 mg, Precisa Instruments Ltd., Dietikon, Switzerland) located near the dryer, which allowed the mass of the solid and the moisture loss to be recorded over time at intervals of 5 min during the first half hour, 10 min during the second half hour, 20 min during the third half hour, and subsequently every 30 min until a constant weight was reached, indicating moisture equilibrium [24]. The moisture ratio (*MR*) was calculated according to Equation (1) [25].

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (1)$$

where M_t is the moisture content of the cassava sample at a given moment during drying (g/100 g); M_e represents the moisture content at the end of drying, i.e., the equilibrium moisture content (g/100 g); M_i is the initial moisture content (g/100 g).

Equation (2) was used to calculate M_t.

$$M_t = \frac{W_t - W_s}{W_s} \quad (2)$$

where W_t represents the mass of the sample at time t, and W_s represents the final dry mass of the sample.

2.3. Mathematical Modeling of Drying Kinetics

The experimental data on moisture content versus time were fitted to the four mathematical empirical models or equations reported in the literature [15] (see Table 1). The quality of the fit was determined using the adjusted coefficient of determination (R^2_{adj}) and the residual sum of squares (*RSS*), according to Equations (3) and (4), respectively. The model with the highest R^2_{adj} value and lowest *RSS* was selected as the best model.

Table 1. Thin-layer mathematical models adjusted to the drying kinetics data of cassava roots.

Model	Equation
Newton–Lewis	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified Page	$MR = \exp(-kt)^n$
Henderson–Pabis	$MR = a \exp(-kt)$

MR is the moisture ratio (dimensionless), a and n are constants (dimensionless); k is the drying rate constant (min^{-1}), and t is the drying time (min).

$$R^2_{adj} = 1 - \left[\frac{(1 - R^2)(n - 1)}{n - p - 1}\right] \quad (3)$$

$$RSS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (4)$$

where R^2 is the coefficient of determination, n is the number of observations, p is the number of predictor variables, y_i is the actual value of the dependent variable for the i-th observation, and $\hat{y}_i$ is the predicted value from the regression model for the i-th observation.

2.4. Determination of Effective Moisture Diffusivity

To describe the speed at which water moves through the cassava samples, the effective diffusivity of water (D_{eff}) was calculated using the mathematical solution of Fick's second law for diffusion, according to Equation (5). To obtain representative values, it was assumed

that the cassava slices behave as an infinite sheet, that mass transfer is one-dimensional, and that drying times are long [26].

$$\ln(MR) = \ln(\frac{8}{\pi^2}) - \frac{\pi^2 D_{eff}}{4L^2} t \quad (5)$$

where L is the thickness of the cassava slice (m) and t is the drying time.

2.5. Estimation of Activation Energy

To evaluate the influence of drying temperature, the Arrhenius equation was used, which allows the diffusion of moisture to be correlated with the activation energy, according to Equation (6) [27].

$$D_{eff} = D_0 \exp \{ - \frac{E_a}{R T} \} \quad (6)$$

where D_0 corresponds to the Arrhenius factor related to the collision factor in terms of absolute reaction speed, E_a is the activation energy (kJ·mol^{-1}), R is the universal gas constant (8.31447 J·mol^{-1}·K^{-1}), and T is the absolute temperature, K. By plotting, ln (D_{eff}) vs. $1/T$, D_0 and E_a coefficients were determined.

2.6. Selection of the Best Drying Condition

The best drying condition was selected for each cassava variety based on drying kinetics, considering the shortest time required to reach residual moisture. The cassava slices dried under optimal conditions were pulverized in a Wiley TE-650/1 mill (Tecnal, Piracicaba, Brazil) and sieved to obtain a flour with a particle size of less than 100 µm (ASTM 150 mesh). The flours obtained were packed in aluminum-coated polyethylene bags, hermetically sealed, and stored at room temperature (25 °C) until their nutritional characterization.

2.7. Physicochemical Analysis of Fresh Cassava and Cassava Flour

The characterization of fresh cassava roots and flour was determined by official AOAC (2012) methods: moisture (AOAC 925.10), total fat (AOAC 920.85), protein (AOAC 960.52, conversion factor 6.25), ash (AOAC 923.03), and crude fiber (AOAC 920.86). The total carbohydrate content (%) was calculated by difference (Equation (7)), based on the remaining percentage of the quantification of the main components [28].

$$\%Carbohydrates = 100 - (Moisture + Total\ fat + Protein + Ash + Crude\ fiber) \quad (7)$$

The color parameters of the cassava flours were determined using a colorimeter (CR-20 brand: Konica Minolta, Sydney, NSW, Australia) and the CIELab scale with a standard illuminant D65 (daylight) and an observation angle of 10° to obtain the parameters: L* (black (0) to white (100)), a* (green (−128) to red (+127)), and b* (blue (−128) to yellow (+127)).

2.8. Processing and Statistical Analysis

For drying kinetics, MATLAB software (version R2024a) was used to fit the drying kinetic data to different mathematical models. For the proximal analysis of fresh cassava and flours, the data were statistically analyzed using one-way ANOVA ($p \leq 0.05$) using Minitab® version 9. All analyses were performed in triplicate, and the data were expressed as mean ± SD. Once significant differences were verified, the Tukey test ($p \leq 0.05$) was performed.

3. Results and Discussion

3.1. Drying Kinetics

The initial moisture content of the cassava slices was 59.66 ± 0.62% for the *Blanca Mona* variety, 66.94 ± 0.81% for the *Ica Negrita* variety, and 58.60 ± 0.23% for the *Venezolana* variety. These values reflect the natural variability between varieties and form the basis for calculating the moisture fraction during the drying kinetics.

Figure 2 shows the influence of temperature and air velocity on the drying process of the three varieties of sweet cassava. The drying kinetics observed in the cassava samples are similar to those reported for other food raw materials such as sweet potato [29], yam [30] and pumpkin [31]. The increase in temperature reduces the time needed to reach equilibrium moisture content. In addition, the progressive reduction in slope shows a higher rate of moisture loss at the beginning of drying, followed by a slower phase. These curves are typical of food drying processes, in which the falling rate period is the predominant and, therefore, the most studied in food drying [32]. In the specific case of cassava samples, drying occurs exclusively during the falling rate period, in which internal diffusion phenomena predominate, caused by the movement of water from the interior of the plant tissue to the surface [33].

Statistical analysis showed that both temperature and air velocity significantly influenced drying time ($p < 0.05$). The temperature of 70 °C differed significantly from the temperatures of 50 and 60 °C, between which no significant differences were observed, demonstrating that the increase in temperature has a direct effect on reducing drying time. In terms of air velocity, an increase from 1 to 2 m/s significantly reduced drying time ($p < 0.05$), while there were no statistical differences between 2 and 3 m/s ($p > 0.05$). The absence of significant differences in drying time at higher air velocities can be attributed to the fact that the drying process occurred entirely in the falling rate period, where internal moisture diffusion governs mass transfer rather than external convective conditions. On the other hand, the three varieties (*Blanca Mona*, *ICA*, and *Venezolana*) showed no significant differences ($p > 0.05$), suggesting that under the conditions evaluated (50–70 °C and 1–3 m/s), structural or compositional differences between varieties do not substantially affect the drying rate.

The shortest drying time to complete the process was recorded at the maximum temperature (70 °C) and maximum air velocity (3 m/s), with a value of 80 min, while the longest time was observed at the minimum temperature (50 °C) and minimum air velocity (1 m/s), reaching 160 min for the three varieties (*Blanca Mona*, *Ica Negrita*, *Venezolana*), showing that drying time decreases as temperature and air velocity increase. This behavior is due to the fact that higher temperatures provide more thermal energy for water evaporation [34]. Finally, because the temperature of 70 °C induced the shortest drying times in the three cassava varieties evaluated (Table 2), with reductions of up to 50% compared to the temperature of 50 °C, and given that no appreciable differences were detected between the air velocities of 2 m/s and 3 m/s, the combination of 70 °C and 3 m/s was selected as the preferred operating regime. This configuration emerges as a viable alternative for industrial scaling in the processing of tropical roots, enhancing overall efficiency by minimizing total operating time, improving mass transfer, and mitigating the associated energy load.

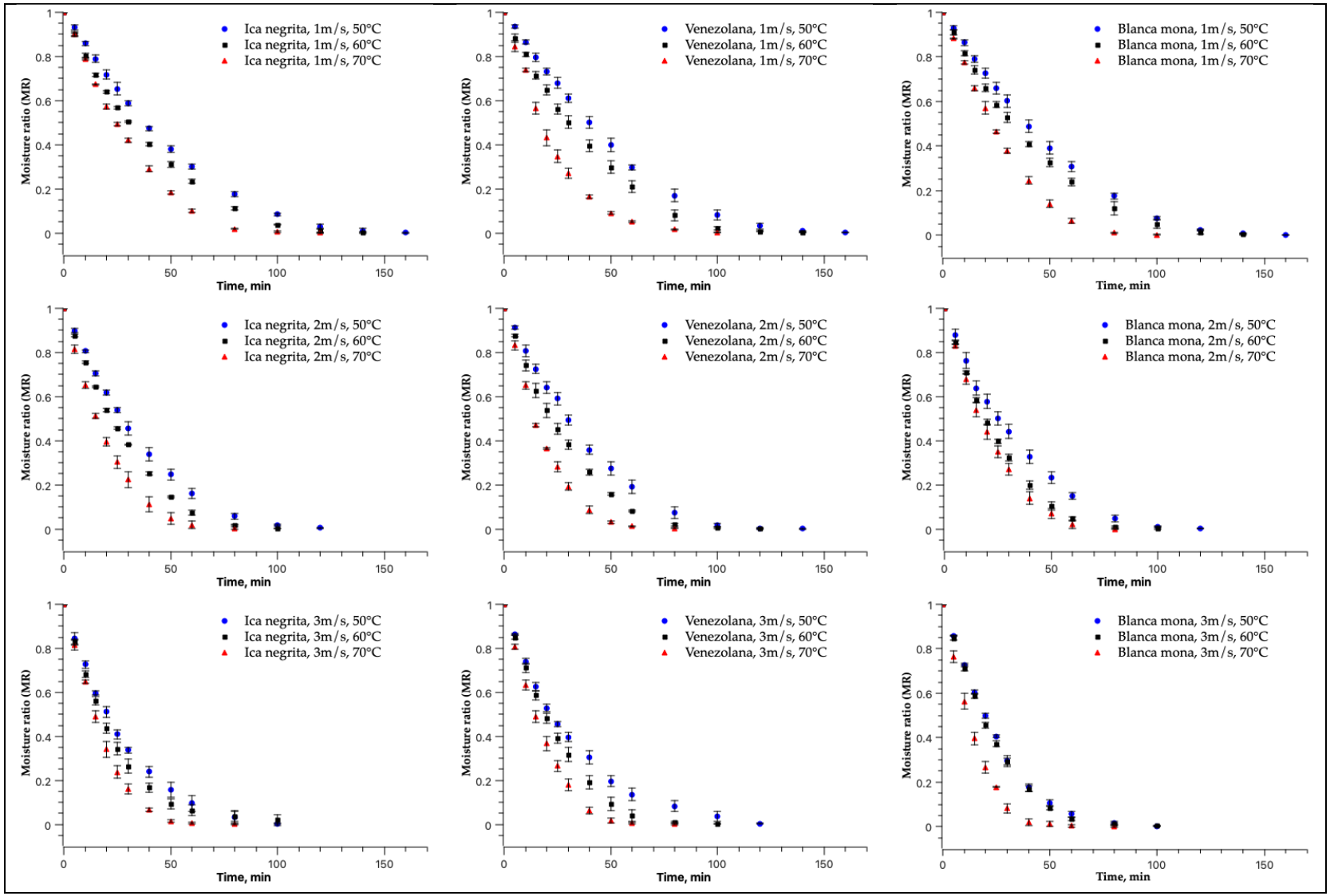


Figure 2. Drying curves of cassava varieties (*Ica negrita*, *Venezolana*, and *Blanca mona*) for different temperature and air velocity conditions.

Table 2. Drying time to reach the final moisture content in cassava slices according to variety, temperature, and air velocity.

Variety	Temperature (°C)	Air Velocity (m/s)	Time (min)
Blanca Mona	50	1	160
		2	120
		3	100
	60	1	140
		2	100
		3	100
	70	1	100
		2	80
		3	80
Ica Negrita	50	1	160
		2	120
		3	100
	60	1	140
		2	100
		3	100
	70	1	120
		2	80
		3	80
Venezolana	50	1	160
		2	140
		3	120
	60	1	140
		2	120
		3	100
	70	1	100
		2	80
		3	80

3.2. Mathematical Models

Table 3 shows the values for the adjustment parameters of the four models evaluated (Newton-Lewis, Page, Modified Page, Henderson-Pabis). All models described the experimental data with high accuracy, with an adjusted coefficient of determination (R^2_{adj}) very close to one, indicating a good fit for all variations in temperature and air velocity. The Page and Henderson–Pabis models performed best; however, the R^2_{adj} values for the Page model were the highest, ranging from 0.9943 to 0.9993 for all varieties, in addition to lower values of the residual sum of squares (RSS), which ranged from 0.0014 to 0.0085 for the *Blanca Mona* variety, 0.0012 to 0.0057 for the *Ica Negrita* variety, and 0.0018 to 0.0048 for the *Venezolana* variety. Similar results were reported with three varieties of industrial cassava in a tunnel dryer [35].

Table 3. Parameters of the Newton-Lewis, Page, Modified Page, and Henderson-Pabis models of drying kinetics for cassava varieties, temperature, and air velocities.

	T (°C)	V (m/s)	*Blanca Mona*					*Ica Negrita*					*Venezolana*				
			k	***n***	***α***	R^2_{adj}	***RSS***	***k***	***n***	***α***	R^2_{adj}	***RSS***	***k***	***n***	***α***	R^2_{adj}	***RSS***
Newton- Lewis	50	1	0.0193			0.9904	0.0277	0.0194			0.9915	0.0239	0.0190			0.9885	0.0316
		2	0.0293			0.9938	0.0144	0.0267			0.9928	0.0168	0.0249			0.9937	0.0166
		3	0.0379			0.9936	0.0134	0.0352			0.9972	0.0053	0.0322			0.9954	0.0100
	60	1	0.0222			0.9961	0.0105	0.0243			0.9940	0.0145	0.0257			0.9939	0.0150
		2	0.0378			0.9949	0.0082	0.0338			0.9903	0.0171	0.0333			0.9942	0.0104
		3	0.0399			0.9947	0.0112	0.0420			0.9967	0.0057	0.0390			0.9940	0.0112
	70	1	0.0326			0.9902	0.0229	0.0303			0.9906	0.0203	0.0409			0.9927	0.0153
		2	0.0434			0.9940	0.0118	0.0478			0.9946	0.0091	0.0508			0.9931	0.0116
		3	0.0652			0.9879	0.0185	0.0539			0.9857	0.0204	0.0527			0.9906	0.0143
Page	50	1	0.0075	1.2489		0.9989	0.0031	0.0080	1.2344		0.9991	0.0023	0.0065	1.2757		0.9989	0.0027
		2	0.0212	1.1184		0.9968	0.0071	0.0126	1.2129		0.9989	0.0023	0.0120	1.2016		0.9988	0.0030
		3	0.0190	1.2134		0.9989	0.0022	0.0267	1.0851		0.9986	0.0026	0.0241	1.0944		0.9979	0.0044
	60	1	0.0132	1.1408		0.9990	0.0024	0.0141	1.1483		0.9976	0.0057	0.0134	1.1784		0.9983	0.0040
		2	0.0229	1.1526		0.9988	0.0019	0.0158	1.2353		0.9983	0.0029	0.0198	1.1605		0.9988	0.0021
		3	0.0212	1.1990		0.9993	0.0014	0.0301	1.1049		0.9985	0.0025	0.0211	1.1875		0.9988	0.0021
	70	1	0.0127	1.2825		0.9989	0.0024	0.0127	1.2525		0.9989	0.0021	0.0229	1.1948		0.9976	0.0048
		2	0.0236	1.1902		0.9985	0.0029	0.0286	1.1728		0.9992	0.0012	0.0265	1.2138		0.9988	0.0018
		3	0.0336	1.2367		0.9943	0.0085	0.0213	1.3095		0.9978	0.0030	0.0257	1.2380		0.9982	0.0026
Modified Page	50	1	0.1388	0.1388		0.9904	0.0277	0.1394	0.1394		0.9914	0.0239	0.1379	0.1379		0.9885	0.0316
		2	0.1707	0.1707		0.9938	0.0144	0.1634	0.1634		0.9928	0.0168	0.1577	0.1577		0.9937	0.0166
		3	0.1946	0.1946		0.9936	0.0134	0.1877	0.1877		0.9972	0.0053	0.1791	0.1791		0.9954	0.0100
	60	1	0.1491	0.1491		0.9961	0.0105	0.1558	0.1558		0.9940	0.0145	0.1601	0.1601		0.9939	0.0150
		2	0.1944	0.1944		0.9948	0.0082	0.1840	0.1840		0.9903	0.0171	0.1825	0.1825		0.9942	0.0104
		3	0.1996	0.1996		0.9947	0.0112	0.2049	0.2049		0.9967	0.0057	0.1974	0.1974		0.9939	0.0112
	70	1	0.1807	0.1807		0.9902	0.0229	0.1741	0.1742		0.9905	0.0203	0.2018	0.2019		0.9927	0.0153
		2	0.2079	0.2079		0.9940	0.0118	0.2185	0.2185		0.9945	0.0091	0.2253	0.2253		0.9931	0.0116
		3	−0.0895	−0.0895		0.9885	0.0176	0.2321	0.2321		0.9856	0.0204	0.2294	0.2294		0.9905	0.0143

Table 3. *Cont.*

	T (°C)	V (m/s)	*Blanca Mona*					*Ica Negrita*					*Venezolana*				
			k	***n***	***α***	R^2_{adj}	***RSS***	***k***	***n***	***α***	R^2_{adj}	***RSS***	***k***	***n***	***α***	R^2_{adj}	***RSS***
Henderson- Pabis	50	1	0.0206		1.0534	0.9932	0.0196	0.0207		1.0517	0.9941	0.0165	0.0205		1.0590	0.9921	0.0218
		2	0.0301		1.0238	0.9944	0.0128	0.0282		1.0453	0.9948	0.0121	0.0263		1.0435	0.9954	0.0122
		3	0.0397		1.0410	0.9951	0.0104	0.0360		1.0176	0.9976	0.0045	0.0328		1.0164	0.9961	0.0086
	60	1	0.0232		1.0318	0.9971	0.0078	0.0253		1.0323	0.9951	0.0120	0.0268		1.0352	0.9951	0.0120
		2	0.0390		1.0289	0.9958	0.0068	0.0356		1.0444	0.9924	0.0134	0.0346		1.0322	0.9954	0.0082
		3	0.0416		1.0380	0.9959	0.0086	0.0431		1.0215	0.9971	0.0049	0.0406		1.0349	0.9951	0.0090
	70	1	0.0346		1.0524	0.9925	0.0175	0.0323		1.0539	0.9932	0.0144	0.0427		1.0400	0.9943	0.0119
		2	0.0450		1.0326	0.9949	0.0099	0.0493		1.0291	0.9956	0.0074	0.0530		1.0421	0.9947	0.0088
		3	0.0674		1.0353	0.9890	0.0167	0.0566		1.0485	0.9881	0.0168	0.0548		1.0375	0.9920	0.0122

It was observed that the drying constant k (min^{-1}) of Page's model showed an increasing trend with increasing temperature and air velocity, reflecting an acceleration in the mass transfer process. Higher temperatures increase the water vapor pressure inside the product and favor diffusion toward the surface, while higher air velocities decrease the external resistance to water vapor transport [36]. Although the three varieties exhibited similar behavior, differences in k values were observed through nonlinear adjustments of the experimental moisture ratio (MR) data as a function of drying time, which are possibly attributable to the composition of cassava (starch content, fibers, cell structure). Similar results were obtained in slices of yacon [18] and taro [37].

3.3. Effective Moisture Diffusivity

Table 4 shows the effective diffusivity values (D_{eff}) for the different cassava samples. For the *Blanca Mona* variety, the effective diffusivity values ranged from 5.58×10^{-10} to 1.58×10^{-9} m^2/s, *Ica Negrita* from 5.24×10^{-10} to 1.32×10^{-9} m^2/s and *Venezolana* from 5.38×10^{-10} to 1.32×10^{-9} m^2/s. These values are similar to those reported for cassava slices at 70 °C and an air velocity of 2 m/s (10^{-10} m^2/s) [38], for carrots in a hybrid infrared dryer at 45, 70, and 75 °C (10^{-10} to 10^{-9} m^2/s) [39], for potato slices applying four levels of microwave power (10^{-8} m^2/s) [40], and for thin-layer drying of sweet potato slices (10^{-10} to 10^{-9} m^2/s) [41].

Table 4. Effective diffusivity (D_{eff}), activation energy E_a and Arrhenius factor D_0, from the *Blanca Mona*, *Ica Negrita*, and *Venezolana* varieties.

Variety	Velocity Air (m/s)	Temperature (°C)	D_{eff} (m^2/s) × 10^{-10}	E_a (kJ/mol)	D_0 (m^2/s) × 10^{-6}
Blanca Mona	1	50	5.58 ± 0.29	22.27 ± 0.26	2.11 ± 0.62
		60	6.15 ± 0.71		
		70	9.07 ± 0.20		
	2	50	6.77 ± 0.46	23.35 ± 0.25	4.01 ± 1.34
		60	8.64 ± 0.69		
		70	11.20 ± 1.66		
	3	50	8.79 ± 0.48	26.93 ± 0.33	18.1 ± 0.93
		60	9.12 ± 0.39		
		70	15.80 ± 4.60		
Ica Negrita	1	50	5.24 ± 0.54	20.34 ± 0.26	0.99 ± 0.17
		60	6.02 ± 0.49		
		70	8.16 ± 0.41		
	2	50	6.61 ± 0.24	28.32 ± 0.25	24.76 ± 1.53
		60	8.78 ± 0.46		
		70	12.20 ± 3.01		
	3	50	8.12 ± 1.03	22.23 ± 0.29	3.02 ± 0.95
		60	8.84 ± 1.89		
		70	13.20 ± 1.61		
Venezolana	1	50	5.38 ± 0.28	23.91 ± 0.23	3.89 ± 0.29
		60	6.77 ± 0.54		
		70	9.05 ± 0.48		

Table 4. *Cont.*

Variety	Velocity Air (m/s)	Temperature (°C)	D_{eff} (m^2/s) × 10^{-10}	E_a (kJ/mol)	D_0 (m^2/s) × 10^{-6}
Venezolana	2	50	7.37 ± 0.57	21.62 ± 0.31	2.20 ± 0.61
		60	8.13 ± 0.67		
		70	11.80 ± 1.16		
	3	50	7.37 ± 1.09	26.89 ± 0.26	16.32 ± 0.52
		60	9.79 ± 0.69		
		70	13.20 ± 2.66		

ANOVA showed that temperature and air velocity significantly affected the effective moisture diffusivity ($p < 0.05$), while the variety did not affect this parameter ($p > 0.05$). Temperature and air velocity had a directly proportional influence on diffusivity, i.e., an increase in temperature caused an increase in the effective diffusivity values in the cassava samples. The decrease in resistance observed in the samples is the result of the effect caused by the increase in temperature on the solid matrix, as this increase reduced the internal resistance of the material to moisture movement due to the resulting structural changes [42]. This thermal effect increases the porosity of the cassava tissue, facilitating greater water mobility towards the surface and, therefore, more efficient diffusion [43] and consequently causing greater elimination of free water [42]. Compared to liquid or more open-structured products, dense, starch-rich tissues such as those found in cassava offered greater resistance to moisture movement. Furthermore, due to their hygroscopic nature, they retained water bound to their structural components [44]. This bound water is not free but associated with macromolecules such as starches or fibers, which reduces the internal vapor pressure of the material compared to that of free water. As a result, the movement of moisture to the surface was slower and required more energy, which was reflected in lower effective diffusivity (D_{eff}) values and the need to use higher temperatures to facilitate water release during drying [45].

3.4. Activation Energy

Activation energy (E_a) is a fundamental thermodynamic parameter that describes the minimum amount of energy required for moisture to diffuse from the interior of the material to its surface during drying. The E_a values for drying the three cassava varieties ranged from 20.34 to 28.32 kJ/mol (Table 4). These values were within the lower range (12–110 kJ/mol) reported for agricultural products. These results indicate that the movement of water molecules from the interior to the surface of the material requires relatively little energy, confirming that the cassava drying process is highly temperature-dependent and proceeds easily under the applied thermal parameters [46]. These characteristics are mainly typical of food raw materials with compact structures and high starch content and are similar to alternative kinetic studies with other products such as yams 22.38 kJ/mol [47], 28.576 kJ/mol for cassava noodles [48], and 22.70 kJ/mol for sweet potato slices [41]. On the other hand, the variations observed between the activation energy values reported in different studies can be attributed to factors such as the variety used, the degree of maturity of the material, the size and thickness of the samples, the previous treatments applied, as well as the specific drying conditions and structural composition of the food matrix [49].

3.5. Physicochemical Analysis of Fresh Cassava and Cassava Flour

Table 5 shows the physicochemical characterization of fresh cassava roots and flours obtained from the *Blanca Mona*, *Ica Negrita*, and *Venezolana* varieties, allowing for an evaluation of the influence of drying on their nutritional composition.

Table 5. Physicochemical characterization of fresh cassava and its flours (g/100 g, dry basis).

Parameters	Fresh			Flour		
	Blaca Mona	***Ica Negrita***	***Venezolana***	***Blaca Mona***	***Ica Negrita***	***Venezolana***
Total fat	0.73 ± 0.03^{b}	0.91 ± 0.03^{a}	0.61 ± 0.02^{c}	0.40 ± 0.04^{a}	0.22 ± 0.01^{b}	0.30 ± 0.08^{ab}
Ash	0.90 ± 0.07^{a}	0.74 ± 0.04^{b}	0.62 ± 0.04^{b}	1.72 ± 0.07^{a}	1.81 ± 0.05^{a}	1.12 ± 0.06^{b}
Crude protein	2.68 ± 0.05^{a}	1.52 ± 0.05^{c}	2.14 ± 0.03^{b}	3.51 ± 0.13^{b}	3.32 ± 0.05^{b}	3.86 ± 0.04^{a}
Crude fiber	1.09 ± 0.07^{a}	0.83 ± 0.03^{b}	0.67 ± 0.02^{c}	1.47 ± 0.07^{b}	1.63 ± 0.04^{a}	1.39 ± 0.04^{b}
Carbohydrates	94.60 ± 0.03^{b}	96.00 ± 0.02^{a}	95.96 ± 0.10^{a}	92.9 ± 0.13^{a}	93.02 ± 0.76^{a}	94.13 ± 0.12^{a}
L*				92.39 ± 0.18^{a}	90.50 ± 0.23^{b}	93.68 ± 0.47^{a}
a*				-0.08 ± 0.07^{a}	-0.06 ± 0.04^{a}	-0.38 ± 0.17^{a}
b*				10.53 ± 0.44^{a}	10.17 ± 0.18^{a}	9.20 ± 0.15^{b}

Different letters in the same row indicate significant differences according to Tukey's test ($p < 0.05$). Comparisons were made independently between fresh cassava varieties and separately between flours.

In fresh roots, the fat content was less than 1 g/100 g in all varieties, which differed significantly ($p \leq 0.05$), confirming that the lipid fraction of the root is intrinsically low and is modulated by genotypic and environmental factors [50]. Comparable values have been reported for varieties from the Bahamas (0.20–0.41 g/100 g) [51] and traditional cultivars from West Africa (0.74–1.49 g/100 g) [52]. After drying, the lipid content decreased further, and the flours had final values below 0.40 g/100 g. Statistically, the flour from the *Blanca Mona* variety differs significantly from *Ica Negrita* ($p \leq 0.05$), while *Venezolana* does not differ from either of the two ($p \geq 0.05$). This pattern is consistent with that reported for cassava dehydrated at 50–60 °C under similar conditions [53,54]. This loss may be associated with thermal oxidation processes or interactions with other components when drying is carried out without a controlled atmosphere [55]. In addition, the low tendency of cassava flour to form amylose-lipid complexes [56], which have lower swelling and solubility [57], supports its technological suitability for formulations with a reduced fat profile [56].

The ash content in fresh roots remained within the ranges reported for other Nigerian cassava varieties (0.4–1.5 g/100 g) [58] and was lower than the values described for six cultivars from the Bahamas (2.0–3.0 g/100 g). Among the varieties evaluated, *Blanca Mona* showed slightly higher values compared to *Ica Negrita* and *Venezolana*. According to statistical analysis, *Blanca Mona* had a significantly higher ash content ($p \leq 0.05$), while *Ica Negrita* and *Venezolana* showed no differences between them ($p \geq 0.05$). This behavior could reflect variations in mineral absorption and accumulation capacity, as well as inherent differences in fertility and nutrient availability in the soils of origin, as has been proposed in previous research [51,59]. After the drying process, the expected increase in ash content in the flours was observed, attributable to the concentration effect resulting from moisture reduction [60]. The values obtained were within the ranges described for cassava flours (1.06–2.20 g/100 g) [56], confirming the consistency of the hygrothermal behavior of these matrices. Likewise, a trend was identified in which the varieties with the highest fiber fraction also had a higher ash content, a pattern that is consistent with that reported for other starchy matrices, such as wheat flour, where fiber is associated with the retention and concentration of minerals [61]. In this context, the *Venezolana* variety maintained the lowest ash level and differed significantly from *Blanca Mona* and *Ica Negrita* ($p \leq 0.05$), reinforcing the idea of genotypic and structural variability among the cultivars evaluated.

In terms of crude protein, fresh roots had low contents (1.52–2.68 g/100 g), but consistent with the ranges previously described for various cassava genetic materials in both the Caribbean (1.2–2.1 g/100 g) and Africa (0.01–1.45 g/100 g) [51,62]. In this study, signifi-

cant differences were observed between the three varieties ($p \leq 0.05$), in line with reports highlighting the marked genetic influence on the protein content of cassava roots [63].

After the drying process, the *Venezolana* variety had the highest protein content in flour, surpassing *Blanca Mona* and *Ica Negrita*. This behavior suggests greater thermal stability of the protein fractions in *Venezolana* flour, which could favor lower loss due to denaturation during dehydration. From a statistical point of view, *Venezolana* flour differed significantly from the other two ($p \leq 0.05$), while *Blanca Mona* and *Ica Negrita* showed no differences ($p \geq 0.05$). This result could be attributed to similarities in amino acid composition, as well as in the conformation of their structural proteins, which determine thermal resistance and susceptibility to denaturation [64].

The values reported here are comparable to those obtained for cassava flours dried at 60–70 °C (3.73–4.75 g/100 g) [65], confirming the consistency of the effects of drying on protein concentration. Previous studies have indicated that protein stability in starchy matrices, such as cassava, can be modulated by protein–starch interaction and by the presence of phenolic compounds, which act by restricting thermal denaturation and favoring the preservation of the protein fraction [66]. These findings suggest that the observed differences between the varieties evaluated are not only due to genetic and structural factors, but also to the physicochemical dynamics that occur during drying.

The crude fiber content in fresh roots ranged from 0.67 to 1.09 g/100 g, values that are at the lower end of those reported for white and yellow/cream-fleshed cassava (0.62–4.92 g/100 g), where harvest age and genetic material explain much of the observed variability [23]. Consistently, other studies in different genetic contexts have reported values between 1.14 and 3.00 g/100 g, confirming that this trait is inherently variable and highly sensitive to biological and environmental factors [50]. In the present study, significant differences were found between the three varieties evaluated ($p \leq 0.05$), supporting the influence of genotype on the proportion of structural components present in the root.

After the drying process, the crude fiber remained relatively stable in the three flours, which was expected given the low thermolability of the structural components, mainly cellulose, hemicellulose, and lignin, when moderate temperatures are used [67]. In the flours, the *Ica Negrita* variety had the highest crude fiber content, differing significantly from *Blanca Mona* and *Venezolana* ($p \leq 0.05$), while the latter two showed no differences between each other ($p \geq 0.05$). This slight superiority in *Ica Negrita* suggests a higher proportion of insoluble fraction, a characteristic that could enhance functional properties such as water retention capacity and starch digestibility modulation [68].

This pattern is consistent with previous reports describing an association between a higher proportion of insoluble fiber in cassava flours and improvements in technological functionality, as well as in the final structure of food products based on starchy matrices [69]. Taken together, these results reflect the importance of genotype in fiber composition and suggest opportunities for selecting materials with specific functional characteristics according to their industrial application.

Finally, the total carbohydrate content in fresh roots remained around 95 g/100 g, confirming the predominance of starch in the composition of cassava, in which carbohydrates usually range between 80 and 95 g/100 g depending on different genetic profiles and agroecological conditions [70]. Among the varieties evaluated, *Blanca Mona* had the lowest value and differed significantly from *Ica Negrita* and *Venezolana* ($p \leq 0.05$), while the latter two showed no statistical differences ($p \geq 0.05$), suggesting more similar starch profiles between *Ica Negrita* and *Venezolana*.

In flours, total carbohydrate values were slightly lower than those observed in roots, although there were no significant differences between varieties ($p \geq 0.05$). This behavior indicates that drying promoted a homogeneous concentration of the starchy fraction,

without differentially affecting the composition of each cultivar [71]. The contents obtained are consistent with the ranges reported for cassava flours (90–94 g/100 g) [56,72], and reaffirm that, regardless of the cultivar, the resulting flour is a highly concentrated source of carbohydrates, a characteristic that supports its importance as an energy ingredient in food and industrial applications.

Table 4 shows the color parameters of the flours from three cassava varieties. All flours exhibited high lightness values (L* > 90), a critical aspect of flour quality and processing efficiency. ANOVA indicates a statistically significant difference in the lightness (L*) of the samples, with the highest values recorded in the cassava flour from the *Venezolana* and *Blanca Mona* varieties. These L* values are consistent with previous reports on cassava flours [69]. With respect to chromatic parameters, all varieties exhibited negative a* values (greenish tones) and positive b* values (yellowish tones). The cassava flours showed similar values for the a* parameter, with cassava flour from the *Venezolana* variety exhibiting the lowest values for the b* parameter. This finding suggests a tendency toward a less yellow flour. These color differences are of particular relevance for industrial applications, as color is a critical quality attribute for consumer acceptance and determines potential use in products such as baked goods, snacks, and as a wheat flour substitute [23,69].

4. Conclusions

The drying curves of the cassava slices showed behavior typical of materials with high moisture content, in which the falling rate period is predominant. Among the mathematical models evaluated, Page's model best described the drying kinetics, showing the highest values of adjusted coefficient of determination and the lowest values of residual sum of squares, highlighting its suitability for predicting moisture loss dynamics under the conditions studied. Likewise, the increase in temperature and drying air velocity favored an increase in effective diffusivity, accelerating the process and reducing both drying times and the time required to reach hygroscopic equilibrium.

The drying process influenced the concentration and stability of the nutritional components of the obtained flours. The ash, protein, and crude fiber contents remained stable or concentrated compared to fresh cassava, while total carbohydrates and crude fat decreased slightly in the three varieties. *Blanca Mona* showed the highest mineral content, whereas *Ica Negrita* presented the greatest crude fiber fraction, favoring water retention and starch digestibility modulation. Among the cultivars evaluated, *Venezolana* flour had the best nutritional profile, with the highest protein content and a significant amount of crude fiber, which provides advantages in terms of added value and suitability for food formulations.

Finally, the thermal stability observed in the nutritional components suggests that drying at 70 °C is an appropriate procedure for the preservation of essential nutrients in cassava, especially in matrices with low fat content. This behavior supports the use of this temperature as an efficient strategy for obtaining functional flours with a longer shelf life and suitable for the development of healthy food products.

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