

Infrared Drying of Bocaiuva (*Acrocomia Aculeata*) Slices: Drying Kinetics, Energy Consumption, and Quality Characteristics

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Abstract

Bocaiuva is the fruit of the palm tree *Acrocomia aculeata* (Jacq.) Lodd, native to various regions of Brazil, particularly in the Cerrado and Pantanal biomes. However, its commercialization is hindered by its fibrous nature and short shelf life, leading to post-harvest losses. This study aimed to obtain bocaiuva slices at different infrared drying temperatures (60, 70 and 80 °C). It was found that a shortening in the drying time at 80 °C caused an increase in the drying rate. Fick's second law and Page's equation were suitable for describing the process behavior. The thermodynamics and energetic analysis demonstrated higher energy efficiency at 80 °C. Lower temperature (60 °C) promoted lower total color difference and hygroscopicity, and higher volumetric shrinkage. The results suggested that IRD at 80 °C was able to produce bocaiuva slices with suitable physical characteristics. Furthermore, the production of dried bocaiuva contributes to the regional development of the Cerrado biome, thereby enhancing the bioeconomy.

1 INTRODUCTION

The state of Mato Grosso do Sul boasts a rich diversity of native species, necessitating techniques that promote the valorization and preservation of its biomes, notably the Cerrado and Pantanal. Among these species is the *Acrocomia aculeata* (Jacq.) Lodd, a native palm found predominantly in the central region of Brazil, particularly in the Cerrado and Pantanal. The economic significance of this plant stems from the commercialization of its fruits, renowned for their edibility and utility in oil extraction, while also holding cultural and environmental importance (Bortolotto et al., 2021; Munhoz et al., 2013).

Referred to as bocaiuva, *macaúba*, or *coco-de-espinho*, the fruits of this palm exhibit considerable nutritional potential, serving as a natural source of vitamins, minerals, fiber, and bioactive compounds. However, owing to their seasonality and perishable nature, it becomes imperative to employ techniques that prolong the shelf life of bocaiuva fruits while retaining their inherent characteristics. Processes aimed at reducing moisture content in the fruits can yield value-added products and enhance stability (Correia et al., 2022; V. M. da Silva et al., 2018).

Infrared drying (IRD) emerges as a viable method for preserving bocaiuva fruits. This technique offers faster drying rates, improved heat transfer coefficients, and enhanced energy efficiency, resulting in reduced processing times. In IRD, radiation energy within the wavelength range of 0.78 to 1000 µm is converted into heat, facilitating moisture removal from the fruits. Notably, infrared energy is selectively transferred from the heat source to the sample, expediting heating while minimizing heat dispersion to the surroundings (Delfiya et al., 2022; Sakare et al., 2020; Salehi, 2020).

In the literature, IRD has recently studied in foods and agricultural products such as: ginger (Osae et al., 2020), kiwifruit (Lyu et al., 2017), pears (Araujo et al., 2021), bitter melon (Akhoundzadeh Yamchi et al., 2023), okra (El-Mesery et al., 2023) among others. To our knowledge, no study was conducted for a native Cerrado fruit.

This technology yields promising results; nevertheless, its implementation is confined to pilot scale and laboratory settings, necessitating comprehensive energy and feasibility assessments for its viability on an industrial scale. In this sense, the objective of this study was to analyze the quality of bocaiuva slices submitted to IRD observing the influence of different temperatures with respect to drying kinetics, mathematical modeling, thermodynamics, energetic and physical analyses.

2 MATERIALS AND METHODS

2.1 Fruit characterization

The fruits of bocaiuva (*Acrocomia aculeata*) were obtained from a local producer (La Lima Village, Miranda, Campo Grande state, Brazil). The fruits were selected, washed, and sanitized, then removing the epicarp and endocarp manually. Samples were prepared with mesocarp slices, that were cut (2.50 ± 0.10 cm length $\times$ 1.00 ± 0.05 cm width $\times$ 0.25 ± 0.05 cm thick), with the aid of a stainless steel knife and stored under freezing ($-18\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$).

Prior the experiments, the samples were thawed under refrigeration ($4^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$) during 12 h, followed by room temperature until thermal balance ($25^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$). The initial moisture content was 0.622 ± 0.012 kg of water/kg sample (wet basis, w.b.), determined by drying in an oven at $105\text{ }^{\circ}\text{C}$ until constant weight (AOAC, 2016).

Total soluble solids (Abbè refractometer, Tecnal RL3, Brazil) pH analysis (HANNA pHmeter pH21, Brazil), and total titratable acidity by volume potentiometric measurements were also performed for the fruit characterization (Instituto Adolfo Lutz, 2008). The soluble solids content was 0.032 ± 0.002 kg solid/kg product, and the pH was 6.45 ± 0.06 . The acidity total titratable was 0.313 ± 0.007 g of citric acid/ kg product.

2.2 Infrared drying experiments

The drying process took place using an infrared radiation dryer (Model IV 2500, Gehaka, São Paulo, Brazil). Each batch involved drying 0.020 kg of fresh fruits. The experiments continued until reaching an average final moisture content of 0.150 ± 0.01 kg of water/kg sample (w.b.).

During the drying, the mass of the samples was monitored using a digital balance coupled to the equipment (accuracy ± 0.01 g). The radiation source (infrared power of 300 W) was located at a fixed distance of approximately 0.10 m from the samples. The moisture content of the samples throughout the drying process was assessed gravimetrically by comparing the initial moisture content of the sample (before the drying) with its mass at each time interval.

2.3 Mathematical modeling

The experimental results obtained were fitted using drying equations. The moisture ratio (MR) of the samples was calculated using the Eq. 1.

$$MR = \frac{X_t - X_e}{X_0 - X_e}$$

1

where MR is the moisture ratio [dimensionless], X_t is the moisture content at a specific time [kg water/kg], X_0 is the initial moisture content [kg water/kg] and X_e is the moisture content under equilibrium conditions [kg water/kg].

The drying rate (DR) of the bocaiuva slices was calculated using Eq. 2

$$DR = \frac{X_{t+dt} - X_t}{dt}$$

2

where DR is drying rate [kg water/ (kg × min)], t is time [min] and dt is time increase [min].

The effective diffusivity (D_{eff}) was derived from the analytical solution of Fick's second law under unsteady-state conditions, as represented by Eq. 3:

$$\frac{\partial X_t}{\partial t} = D_{eff} \nabla^2 X_t$$

3

where D_{eff} is the effective diffusivity [m^2 /s].

The solution to Eq. 3 is obtained using the Fourier series, assuming: Uniform initial moisture content $X(z,0) = X_0$; moisture concentration symmetry $\left. \frac{\partial X_t}{\partial t} \right|_{z=0} = 0$; equilibrium content at the surface, $X(L, t) = X_e$; the samples are infinite slabs, and shrinkage and external resistance to mass transfer are neglected.

Considering an unidirectional moisture diffusion, the D_{eff} was calculated according to Eq. 4

$$MR = \left(\frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp \left(-(2i+1)^2 \pi^2 D_{eff} \frac{t}{4L^2} \right) \right)$$

4

where L is the characteristic length (half of the thickness).

The activation energy, governing the relationship between D_{eff} values and temperature dependence, is characterized by an Arrhenius-type correlation, as expressed by Eq. 5

$$D_{eff} = D_0 \times \exp \left(-\frac{E_a}{RT} \right) \quad (5)$$

where D_0 is the pre-exponential factor of the Arrhenius equation [m^2/s]; E_a is the activation energy [kJ/mol]; R is the universal gas constant [$8.314 \times 10^{-3} \text{ kJ} / (\text{mol} \times \text{K})$] and T is the IRD temperature [K].

The Eq. (5) can be linearized into the form of Eq. (6):

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT}$$

6

E_a can be calculated with the slope of the Eq. 6 by plotting $\ln D_{eff}$ as a function of $1/T$ (Oliveira et al., 2021).

The Page's equation (Eq. 7) was used describe the drying kinetics of agricultural products (Page, 1949).

$$MR = \exp(-kt^n)$$

7

Where k is the drying rate [$1 / \text{s}$]; n is the unit coefficient [dimensionless].

2.4 Thermodynamic parameters and Energetic Analysis

The E_a value allowed determination of different thermodynamic parameters such as the enthalpy (ΔH), the entropy (ΔS), and the free energy (ΔG), according to the Equations 8–10 (Jideani & Mpotokwana, 2009).

$$\Delta H = E_a - RT$$

8

$$\Delta S = R \left(\ln D_0 - \ln \left(\frac{k_B}{h_P} \right) - \ln T \right)$$

9

$$\Delta G = \Delta H - T\Delta S$$

10

where k_B indicates the Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$) and h_P represents the Planck constant ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$).

Assessing energy consumption contributes to the cost-effective operation and advancement of energy-efficient drying systems (Delfiya et al., 2022). The specific energy consumption (SEC) was obtained as the consumed energy [kJ] for the removal of 1.0 kg water from the sample, according to Eq. 11 (Zhang et al., 2021):

$$SEC = \frac{P \times t \times 10^{-6}}{m_{ev}}$$

11

where SEC is specific energy consumption [MJ/ kg_{water}], P is the infrared power [W] and m_{ev} is the total mass of water removal during the drying [kg].

2.6 Quality analyses

All the following analyses were performed in triplicate (at least), in either dried and fresh samples.

2.6.1 Color Parameters

Color parameters were measured using a colorimeter (CM-2600D model, Konica Minolta). The parameters recorded L*, a*, and b* were quantified for each sample. These color parameters were used to calculate the total color difference (ΔE) (Eq. 12). Six samples were evaluated for each treatment.

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2}$$

12

where L* indicates the lightness (100 for white to 0 for black), a* indicates red when positive and green when negative, and b* indicates yellow when positive and blue when negative. The subscript '0' denotes the color parameters of the fresh fruit.

2.6.2 Volumetric Shrinkage

The volume (V) of the bocaiuva samples was determined by averaging three measurements of the fruit dimensions along the corresponding coordinate axes, using a calibrated digital caliper (Western, DC-6 model, China). Five samples were assessed for each treatment during the drying process. Volumetric shrinkage was calculated as the ratio of the dried fruit volume (V_t) to the initial fruit volume (V₀) (Junqueira et al., 2018).

2.6.3 Rehydration

The dried fruits were submerged in distilled water at 25°C for 20 hours to determine their rehydration capacity (RC). After the drying, three dehydrated samples were submitted to rehydration (Badwaik et al., 2014). The RC was calculated as the ratio between the weight of the dried sample and the weight of the fresh samples.

2.6.4 Hygroscopicity

Approximately 1.0 g of the sample was placed in an airtight desiccator filled with saturated solution of NaCl (75% RH) and stored at 25 ± 1°C for seven days (Ng & Sulaiman, 2018). Subsequently, the samples

were weighed, and the absorbed moisture was expressed in grams per 100 grams of dry solids. The difference in weight of dried was calculated to determine its hygroscopicity.

2.7 Statistical analyses

The results were analyzed using Statistica software (Statistica 8.0, Statsoft Inc., Tulsa, UK). For the statistical evaluation of the mathematical modeling, the coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2), were used to determine the quality of the adjustment. Higher R^2 and lower RMSE and χ^2 values indicated better adjustment (Babu et al., 2018).

The quality analysis results underwent evaluation through one-way ANOVA at a 95% confidence level. If significant effects were observed ($p < 0.05$), mean comparisons were conducted using the Tukey test.

3 RESULTS AND DISCUSSION

3.1 Drying kinetics

Figure 1 shows the drying kinetics of bocaiuva slices during the IRD. The duration for the samples to attain a final moisture content of 0.150 ± 0.01 kg of water/kg sample (w.b.) ranged from 160 minutes at 80°C to 280 minutes at 60°C .

As expected, lower drying time was observed in the treatments at higher temperature (Fig. 1). As the drying temperature rises, both internal and external resistance to moisture removal diminishes. This phenomenon is associated with the augmentation of water molecule mobility, an increase in the driving force, and consequently, a heightened vapor pressure that facilitates the evaporation of moisture from the product's interior to its surface (Araújo et al., 2020; Elhussein & Şahin, 2018; Turan & Firatligil, 2019).

Similar reports were presented by Rodríguez-Ramos et al. (Rodríguez-Ramos et al., 2021) during the convective drying of *Salicornia fruticosa*. In this study, comparing the treatments at different temperatures, a reduction in drying time of approximately 50% was observed, comparing 70 and 50°C . Such a reduction in the drying period at higher temperatures were also reported by Ju et al. (Ju et al., 2020) during the convective drying of American ginseng root (*Panax quinquefolium*) at $45\text{--}60^\circ\text{C}$ and by Bakhara et al. (Bakhara et al., 2018) during osmo-convective of tender jackfruit slices at $50\text{--}70^\circ\text{C}$.

Figure 2 - The drying rate of bocaiuva slices *versus* moisture content in different IRD treatments

According to Fig. 2, maximum drying occurred at the initial stages of the process, characterized by high moisture content in the fruits, leading to elevated drying rates. As the process progressed, the treatments entered the falling rate period, indicating that diffusion mass transfer governs the drying process. During agricultural food drying, the absence of a constant drying rate period has been reported by several authors (Babu et al., 2018; Junqueira et al., 2021; Ovando-Medina, 2023).

It was also observed higher drying rates at 80 °C (Fig. 2). Babu et al. (Babu et al., 2018) pointed that an elevation in temperature leads to a decrease in drying time. Consequently, a greater gradient in both moisture and heat is achieved, resulting in an increased drying rate. Junqueira et al. (Junqueira et al., 2021) observed that taioba leaves dried at higher temperatures presented higher drying rates (lower drying periods).

3.2 Mathematical modeling

Table 1 presents the effective diffusivities (D_{eff}) of bocaiuva slices during IRD, calculated based on Fick’s diffusion theory. The D_{eff} values ranged from 4.53×10^{-11} to 9.38×10^{-11} m²/s. The results showed that R^2 values were greater than 0.97, and RMSE and χ^2 values were lower than 0.07 and 0.005, respectively. These values presented analogous magnitude orders than those observed for IRD (Delfiya et al., 2022).

Table 1
Effective diffusivity of bocaiuva slices during IRD at different temperatures

Temperature	D_{eff} [m ² /s] ×10 ¹¹	R^2	RMSE ×10 ²	χ^2 ×10 ³
60 °C	4.53	0.973	6.46	4.32
70 °C	6.95	0.971	6.98	5.13
80 °C	9.38	0.975	6.62	4.64

According to Table 1, an increase in the temperature process promoted an increase in the D_{eff} . Araujo et al. (Araujo et al., 2021) observed similar behavior during IRD of pear slices (50–100 °C) and pointed that the temperature enhancement leads to alterations in the physical properties of fluids, including viscosity and the molecular vibration of water and air molecules.

D_{eff} values of various food products during IRD are reported in many literatures, for example, $2.89\text{--}12.23 \times 10^{-10}$ m²/s for okra (El-Mesery et al., 2023), $1.14\text{--}3.08 \times 10^{-9}$ m²/s for black mulberry (Doymaz & Kipcak, 2019), $6.97\text{--}8.96 \times 10^{-9}$ m²/s for dill leaves (Tezcan et al., 2021), $1.53\text{--}3.23 \times 10^{-10}$ m²/s for piquin pepper (Ovando-Medina, 2023), and $1.15\text{--}8.96 \times 10^{-9}$ m²/s for pears (Araujo et al., 2021).

The disparities observed in D_{eff} values are attributed to factors such as material thickness and composition, IR power, drying temperature, distance between the IR heater and the sample, among others (Sakare et al., 2020).

The commencement of the moisture diffusion from the inside to the outside of bocaiuva slices requires energy, which is expressed as E_a . This parameter was calculated using the Arrhenius equation (Eq. 6) and was found as 35.69 kJ/mol. This value represents the energy required to achieve the D_{eff} (Balzarini et al., 2018; Kamble et al., 2022).

The determined values of activation energy present the range of many food products during the drying such as lemon basil leaves (32.35 kJ/mol) (Mbegbu et al., 2021), piquin pepper (38.81 kJ/mol) (Ovando-Medina, 2023), potato slices (25.35–36.17 kJ/mol) (Singh & Talukdar, 2019), yam slices (10.59–54.93 kJ/mol) (Ojediran et al., 2020) and orange slices (18.64–32.88 kJ/mol) (Bozkir, 2020) in different conditions.

The statistical results of the modeling with Page’s equation are presented in the Table 3.

Table 2

Effect of drying temperature on Page’ equation regression parameters

Temperature	k	n	R ²	RMSE ×10 ³	χ ² ×10 ⁵
60 °C	4.82 × 10 ⁻⁵	1.12	0.999	3.17	1.08
70 °C	5.84 × 10 ⁻⁵	1.17	0.999	5.59	3.09
80 °C	7.29 × 10 ⁻⁵	1.16	0.999	7.05	5.57

As indicated in Table 2, the drying constant “k” parameter exhibited an increase with the rise in IRD temperature. This finding aligns with the D_{eff} values, wherein faster drying (Fig. 1) corresponded to higher diffusivity (Table 1).

The adjustment parameter “n” ranged from 1.12 to 1.17, presenting similar values (Table 2). No trend was observed. The results showed statistical values of R² greater than 0.99 and lower RMSE and χ² values. This suggests the suitability of this equation for depicting the drying behavior. Recently, this model was successfully used for describing the IRD of black mulberry (Doymaz & Kipcak, 2019), ginger (Osae et al., 2020) and turmeric (Jeevarathinam et al., 2022).

3.3 Thermodynamic properties and Energetic Analysis

Table 5 shows the thermodynamic functions including enthalpy, entropy, Gibbs free energy, and specific energy consumption under various IRD temperatures.

Table 3

Thermodynamic properties and energetic consumption of bocaiuva slices during IRD

Temperature	ΔH [kJ/mol]	ΔS [kJ/mol×K]	ΔG [kJ/mol]	SEC [MJ/kg _{water}]
60 °C	32.93	-336.56	145.05	448.79
70 °C	32.84	-336.80	148.42	311.42
80 °C	32.76	-337.04	151.79	243.24

According to Table 3, minor differences were noted in the thermodynamic properties. Furthermore, enthalpy and entropy decreased with increasing IRD temperature, while the Gibbs free energy showed an

increase.

The higher enthalpy change (ΔH) value, the stronger the water is attached to the product, and more energy are required to separate water from the product over the course of the drying process (Akhoundzadeh Yamchi et al., 2023). Positive enthalpy values indicate endergonic reactions, implying that drying at a higher temperature requires less energy to separate the water attached to the product. Similar magnitude order values were observed during the IRD of bitter melon (28.83–36.06 kJ/mol), without pretreatments (Akhoundzadeh Yamchi et al., 2023).

The ΔS presented similar behavior of ΔH , with values being reduced with the increase in IRD temperature (Table 3). The reduction in the moisture content throughout the drying process, hinders the movement of water molecules. Enhancing the IRD temperature results in an increase in the partial pressure of water vapor within the product, consequently elevating the excitation of water molecules. This, in turn, accelerates the diffusion process rate (El-Mesery et al., 2023).

According to Silva et al. (E. K. Silva et al., 2014), negative ΔS values are attributed to the presence of chemical adsorption and/or structural modifications of the adsorbent occurring during the process. Studying the drying (40–80 °C) of *azuki* beans, Almeida et al. (Almeida et al., 2020) obtained ΔS ranging from – 339 kJ/mol $\times$ K to -340 kJ/mol $\times$ K.

ΔG showed positive values for all treatments, and increased with increasing IRD temperature, ranging from 145.05 (60°C) to 151.79 kJ/mol (80°C), indicating a non-spontaneous process. Hence, it is essential to supply thermal energy for these processes to occur.

The SEC reduced with an increase in IRD temperature (Table 3). Such a results are related to the higher temperature gradient, which reduces the total drying time (Fig. 1) and favors the energy save, since the energy spent on the evaporation process decreases. According to the Eq. 9, the higher time process, the higher energy consumption (Çelen, 2019; Junqueira et al., 2022).

The findings of this study was in agreement with Sa-Adchom (Sa-Adchom, 2023). He investigated the impact of far-infrared radiation in conjunction with a belt conveyor system during the drying of tamarind foam-mats and observed a decrease in the specific energy consumption (SEC) in treatments with higher power levels (resulting in shorter drying periods).

During *Mentha spicata* IRD, Hazervazifeh et al. (Hazervazifeh & A. Moghaddam, 2024) observed that increasing the drying temperature reduces the SEC. The lowest (42.23 MJ/g_{water}) and the highest (67.19 MJ/g_{water}) values of SEC were observed at 70 and 50 °C, respectively.

3.5 Quality parameters

The color characteristics of bocaiuva slices during IRD are presented in the Table 4

Table 4
– Color parameters of bociuiva slices during IRD at different temperatures

Temperature	L*	a*	b*	ΔE
60 °C	39.14 ± 2.66 ^a	11.67 ± 1.58 ^a	41.23 ± 1.35 ^a	3.71 ± 0.29 ^a
70 °C	48.87 ± 2.46 ^c	11.27 ± 0.78 ^a	47.78 ± 1.15 ^b	9.66 ± 0.39 ^b
80 °C	43.70 ± 1.50 ^b	11.98 ± 1.63 ^a	47.62 ± 1.78 ^b	11.09 ± 0.56 ^b

Average value ± standard deviation. Mean followed by different letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

The fresh bociuiva presented the color characteristics: $L^* = 41.76 \pm 1.93$; $a^* = 10.16 \pm 1.78$; and $b^* = 46.56 \pm 2.86$. The parameters L^* and b^* were significantly affected by the IRD temperature (Table 4) ($p \leq 0.05$). We observed an increase in L^* , b^* and ΔE , at higher drying temperature.

The samples dried at 60 °C, presented color characteristics darker and “less yellowness”, which may indicate browning reactions. The higher drying process time (40% higher than 70 °C and 75% higher than 80 °C) at this temperature, intensified contact of the sensible compounds, such as pigments (carotenoids), with oxygen and heat occurs, thereby promoting oxidation, which ultimately results in color changes (Macedo et al., 2021).

As presented in the Table 4, significative difference ($p \leq 0.05$) was observed for the ΔE .

Color differences can be categorized as follows: small differences ($\Delta E < 1.5$), distinct differences ($1.5 < \Delta E < 3$), and very distinct differences ($\Delta E > 3$) (Pathare et al., 2013). According to this assessment, all treatments exhibit very distinct color characteristics compared to the fresh fruit. During vacuum drying of yacon, Oliveira et al. (Oliveira et al., 2021) observed higher ΔE at higher temperatures. Similar findings were reported during of kiwifruit with/without osmotic dehydration under IRD (Lyu et al., 2017).

Table 5 shows physical analyses of the bociuiva slices during IRD.

Table 5
– Physical analyses of bociuiva slices during IRD at different temperatures

Temperature	Shrinkage [-]	Rehydration [%]	Hygroscopicity [g/100 g ⁻¹]
60 °C	0.620 ± 0.065 ^a	279 ± 23 ^a	13.807 ± 0.236 ^a
70 °C	0.533 ± 0.055 ^{ab}	281 ± 41 ^a	15.977 ± 1.576 ^a
80 °C	0.460 ± 0.010 ^b	289 ± 43 ^a	19.407 ± 1.427 ^b

Average value $\pm$ standard deviation. Mean followed by different letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

According to Table 5, it was observed significant difference between the treatments on the shrinkage parameter ($p \leq 0.05$). The closer the value is to unity, the greater the sample shrinkage, resulting in lower preservation of the physical and structural characteristics of the dried bocaiuva. This phenomenon is associated with changes in cell shape (Junqueira et al., 2017).

Lower shrinkage was observed at higher temperatures (Table 5). IRD induces a reduction in moisture content, thereby decreasing the tension exerted by liquid (water) against the cell wall. This can lead to a pressure imbalance between the interior and exterior of the tissues. It is pressure difference can cause ruptures and collapses to the structure of the material, and, therefore, shrinkage is observed (Rojas & Augusto, 2018).

Akbarian et al. (Akbarian et al., 2014) concluded that shrinkage is increased with increasing drying time. During the convective drying of hawthorn fruit, Aral and Beşe (Aral & Beşe, 2016) observed that the shrinkage decreased with increasing air temperature.

The ANOVA revealed no significant differences ($p > 0.05$) in the rehydration of the dried bocaiuva (Table 5). The removal of water during IRD results in cell damage, leading to a gradual breakdown in tissue organization. This affects the ability of semi-permeable membranes to act as a barrier to water diffusion (Junqueira et al., 2017).

The reduced process leads to the creation of a porous structure which increases the ability to absorb the water during the rehydration (Taghian Dinani & Havet, 2015). However, in this study, such a difference was not observed for this parameter. Probable the fibrous structure of the bocaiuva (Munhoz et al., 2013) aided the water absorption, regardless the temperature treatment.

During the drying of lettuce in different drying treatments (hot air, infrared, microwave-assisted hot air and hot air-assisted radio frequency), Roknul et al. (Roknul et al., 2014) observed rehydration capacity values ranging from 14.85–18.89%. Those authors reported slight differences in this parameter, although there was a significant difference in the duration of the process.

According to Russo et al. (Russo et al., 2013), several factors affect the structure of the dried samples, thereby influencing water uptake during rehydration. During the drying of eggplants, those authors observed that samples dried at 40, 50 and 60°C show similar rehydration kinetics with a weight gain of about 500%.

Table 5 presents the hygroscopicity of the samples, and a significant difference ($p \leq 0.05$) was observed between the treatments. The bocaiuva slices dried at 60 and 70 °C, presented lower hygroscopicity values ($p \leq 0.05$). It is desirable for dried fruits to exhibit low hygroscopicity, indicating minimal water absorption from the environment. (Macedo et al., 2021).

During the drying of soursop pulp, Cavalcante et al. (Cavalcante et al., 2017) observed that higher drying temperatures resulted in powders that exhibited greater ease in adsorbing water. This phenomenon is associated with the increased concentration gradient of water between the samples and the air. During the drying of kinui (mango), in different drying methods, Shuen et al. (Shuen et al., 2021) obtained hygroscopicity ranging from 18.66% (convective drying) to 22.41% (spray dryer).

4 CONCLUSION

The production and consumption of native fruits from the Cerrado have been experiencing significant growth, contributing to the social development of the State of Mato Grosso do Sul. In this study, we investigated the effects of different IRD temperatures on the drying kinetics, mathematical modeling, thermodynamics, energetic, and physical analyses of dried bocaiuva slices. Higher temperature (80 °C) leads to shorter drying times, higher drying rate, and effective diffusivity. The Page's model described the process behavior ($R^2 > 0.999$) accurately. Slight differences were observed in the thermodynamics properties. At 80 °C, higher total color difference and hygroscopicity were observed. At 60 °C, higher specific energy consumption and shrinkage was obtained. Interest in native fruits has surged due to their economic potential for use in various products, thereby adding value and fostering the development of new goods. This supports the advancement of the bioeconomy.

Declarations

CRedit authorship contribution statement

João Renato de Jesus Junqueira: Writing – original draft, Methodology, Investigation, Conceptualization. Juliana Rodrigues do Carmo: Writing – review & editing, Data curation, Investigation. Luciana Miyagusku: Methodology, Data curation. Thaisa Carvalho Volpe Balbinoti: Methodology, Data curation. Reinaldo Farias Paiva de Lucena: Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Conflict of interest: The authors confirm that this article content has no conflict of interest.

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Figures

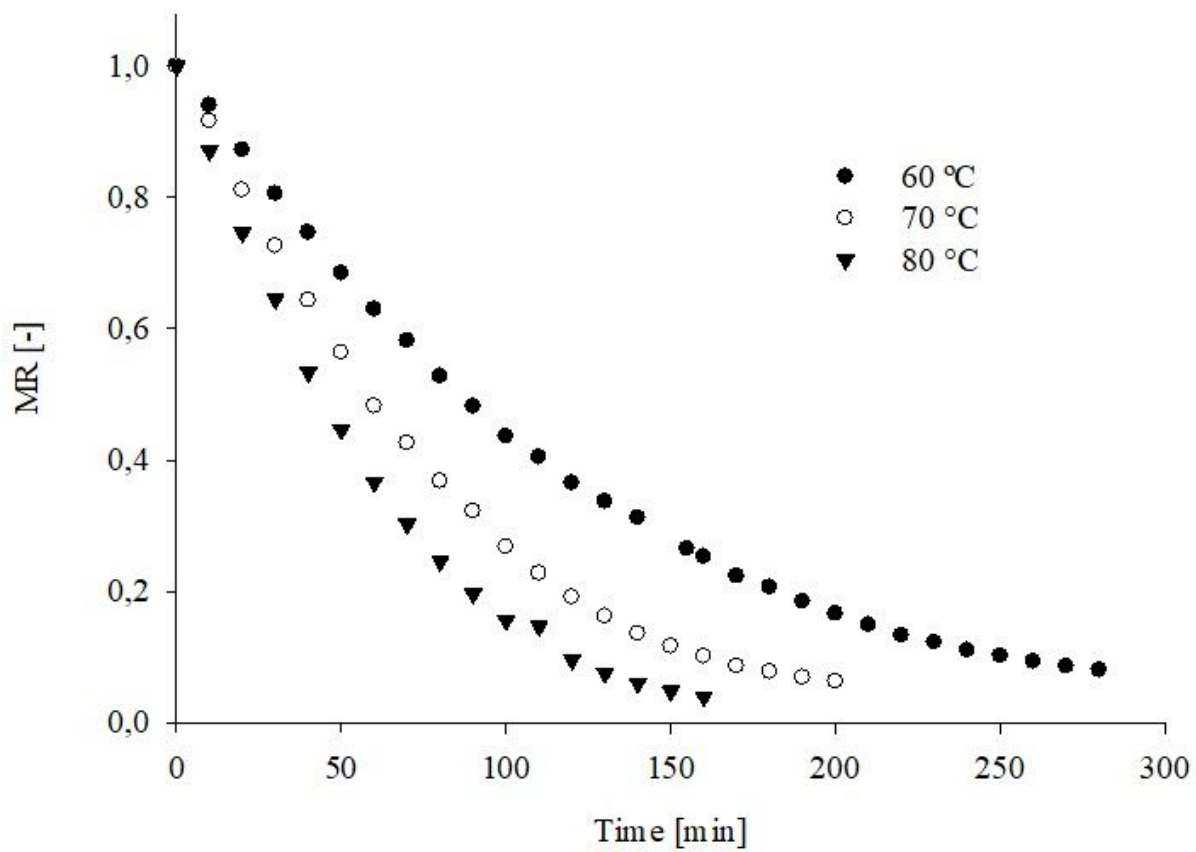


Figure 1

Drying kinetics of bocaiuva slices at different temperatures

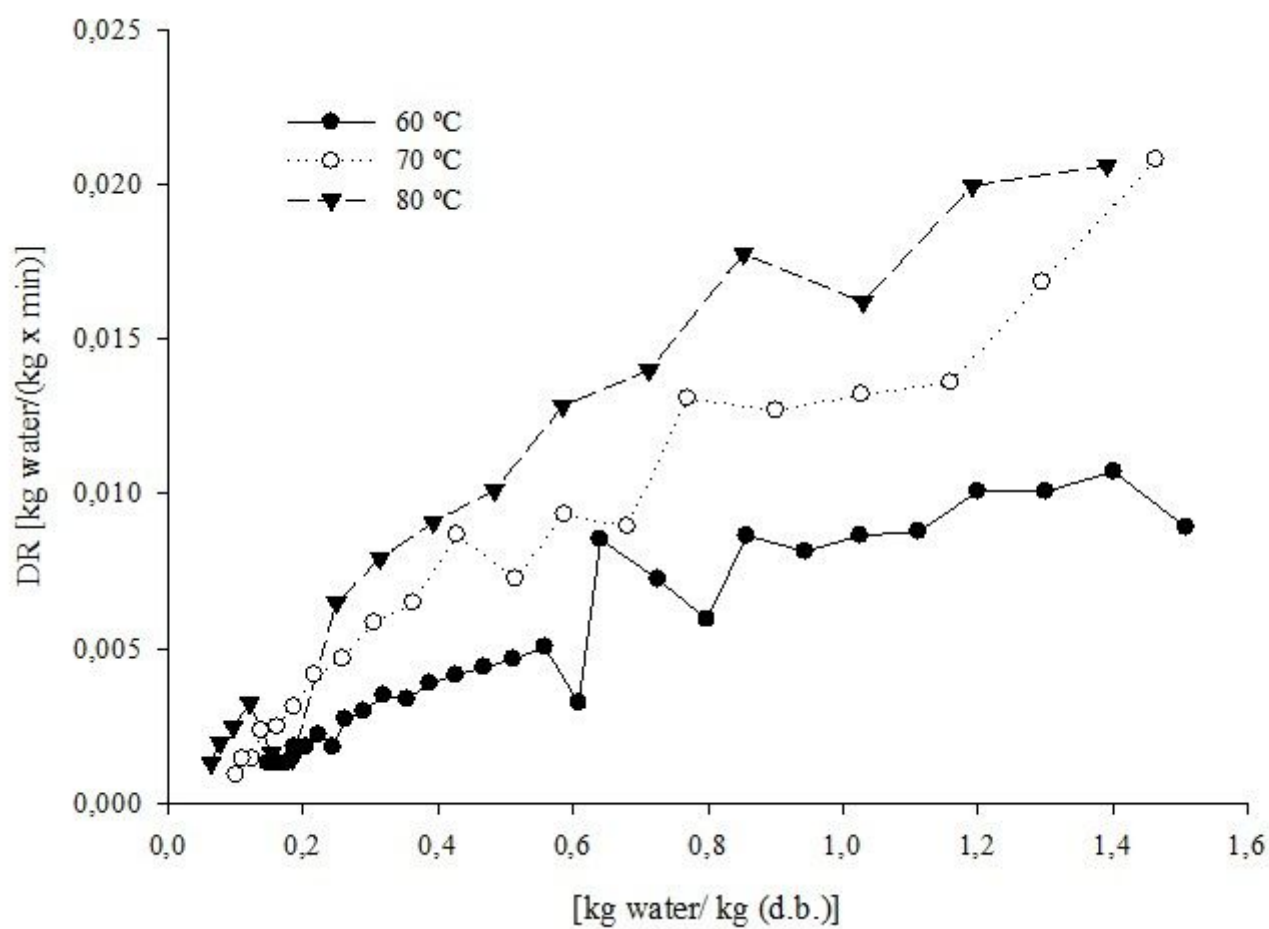


Figure 2

The drying rate of bocaiuva slices *versus* moisture content in different IRD treatments