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Mathematical models and X-ray image analysis in the drying of cumbaru seeds

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Abstract

The cumbaru (*Dipteryx alata* Vog.) is a native species of the Cerrado. The species is of great economic expression for family farming. This study aimed to determine the drying curves and fit mathematical models to the experimental data obtained in the drying of cumbaru seeds. Furthermore, it aimed to define the best-fitted model and correlate the damage caused by the drying process through X-ray images. The *Dipteryx alata* Vog. seeds were obtained from fruits collected from 20 matrices in the municipality of Cáceres, in the state of Mato Grosso (MT), approximately 255 days after anthesis. The seeds were extracted and stored for 15 days until they reached hygroscopic equilibrium and a 14.5% water content. Drying was conducted in a continuous airflow dryer with an approximate temperature of 40° and a constant airflow velocity of 2.5 m/s. The experimental data were fitted to twelve mathematical models. The values of the coefficients of determination (R^2), the relative mean error (P), and the estimated mean error (SE) were used to check the models' fit degree. After drying, 40 seeds from each treatment were subjected to X-ray testing using the Faxitron MX-20 DC 12 equipment. The Midilli mathematical model was the best fit for the experimental data. The X-ray images showed no cracks or any other damage caused by the drying process.

Keywords: Dipteryx alata. Vog, drying kinetics, Midilli, quality, x-ray

Introduction

The Brazilian Cerrado brings together a large number of plants, including the cumbaru (*Dipteryx alata* Vog.). The cumbaru is a native species widely used by the regional population as an income source (Alvarenga et al., 2008).

Due to its importance and environmental concerns, it is necessary to produce seedlings for extractive use and recovery of degraded areas, demanding good quality materials (Freitas et al., 2017). However, in nature, there is no regular supply of forest seeds. Thus, processes must ensure seeds with good germination potential and the necessary quality and quantity in the desired periods.

For the seed to remain preserved in storage, the water inside it must be removed to a final water content that does not promote deterioration. Silveira et al. (2019) reported that these values are between 11 and 13% since seed respiration is reduced in this range.

When drying, directly removing water contributes to decreasing the seed's metabolism, allowing physiological quality preservation during storage. Moreover, this process promotes decreased losses, increased microbiological safety, stability of aromatic components, protection against enzymatic and oxidative degradation, and reduced seed weight, facilitating product preservation (Diogenes et al., 2013; Ullmann et al., 2018).

Drying can be natural or artificial. The latter comprises thermal processes, with a recommended drying air temperature of 40°C (Engelhardt & Arrieche, 2016; Silva et al., 2016). Despite being an advantage, this process has a high potential for damage. It depends on proper management regarding initial and final seed water content, airflow velocity and temperature, relative humidity of the air, and heating exposure time (Coradi et al., 2016).

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In order to detect changes in seed physiological quality after drying, germination and vigor tests should be performed (Marcos Filho, 1999). However, since they occur in environments with controlled conditions, the results may overestimate the material's real potential (Schuch et al., 2013; Nunes et al., 2014).

Currently, the analysis of seed images using X-rays has proven beneficial. Observing their internal structures makes it possible to quickly and non-destructively establish relationships between physical, morphological, and physiological integrity (Marcos Filho et al., 2010; Silva et al., 2013).

Even though some studies relate drying and image analysis in seeds, the literature lacks information on specific approaches to several species, such as cumbaru.

Thus, this study aimed to determine the drying curves of cumbaru seeds and fit mathematical models to the experimental data obtained. Furthermore, it aimed to define the best model fit and correlate the damage caused by drying using X-ray images.

Materials And Methods

The study was conducted in the Seed Laboratory of the Agronomy Department of the Universidade do Estado de Mato Grosso (UNEMAT), Caceres campus.

The *cumbaru* seeds were obtained from fruits collected from 20 matrices duly identified, georeferenced, and randomly distributed in the region of the municipality of Cáceres (MT). The collections took place between May and June 2019. The fruits were collected from the matrices approximately 255 days after anthesis. Their morphological characteristics were similar to those of Nascimento et al. (2021). The matrices' choice criterion was based on plant height and crown shape similarity.

In order to facilitate endocarp removal, the fruits were taken to the laboratory and placed into plastic boxes with lateral openings for air circulation. Then, for three weeks, they went through an ambient drying process, where they were moved every two days to ensure the uniformity of water removal from the fruit's mucilage and avoid the occurrence of any pathogens.

Seed removal involved breaking the endocarp, which was done using a manual seed breaker built specifically for breaking cumbaru fruits to avoid physically damaging the seeds. In order to obtain a more uniform and better quality material during the breaking process, the seeds were visually selected to eliminate deteriorated and/or damaged seeds.

The next step comprised homogenizing the seeds of all matrices. They were stored in glass jars in an acclimatized environment (25°C and 40% R.H.) for 15 days to ensure seeds reached hygroscopic equilibrium.

In order to obtain the initial water content, four repetitions of three seeds were taken from the main sample (Nascimento et al., 2021). Determination occurred using the oven method at 105 ± 3 °C for 24 hours (BRASIL, 2009). Then, the samples were removed from the oven, placed in a desiccator, and weighed on a precision balance. The results were expressed on a wet basis percentage (wb).

For the drying test, the seed samples showed an initial water content of approximately 14.5% (wb). The experiment comprised a randomized block design (in a subdivided plot) with two types of drying (continuous and 1:1 intermittent), three levels of final water content (approximately 12%, 10%, and 8.5%), four repetitions, and 100 seeds per repetition, totaling 400 seeds per treatment.

In the 1:1 intermittent treatment, the seeds went through the same drying time as the continuous treatment, but with a 5-minute rest, after the predetermined periods specified in the paragraph above.

The drying tests were performed in the continuous airflow dryer, with temperature and airflow control supplied by an axial fan at approximately 40°C to ensure the product's initial quality. The drying air was heated using electrical resistances, and the temperature was controlled through a variable voltage transformer from 0 to 140 volts connected in series with the electrical resistances.

The constant airflow velocity of 2.5 $m.s^{-1}$ conducted the air to the plenum, where distribution flowed into three steel trays with screened and removable bottoms containing the seed samples. The temperature and airflow were determined through tests performed prior to the experiment installation. The airflow value was verified using a rotating blade anemometer adapted to the fan air inlet for all drying treatments.

A psychrometer inside the drying chamber monitored the drying air's relative humidity and dry-bulb temperature. In addition, data were recorded by sensors connected to two datalogger systems, one commercial and the other comprising an Arduino UNO board with an SD shield for data storage.

During the drying operation, the amount of water removed was determined by a gravimetric process, where periodic weighing of the samples is done using a semi-analytical balance. Weighings were performed every 5 minutes for the first 35 minutes, every 15 minutes until 140 minutes, and every half hour until 320 minutes. Then, weighings were performed every hour, with a one-hour addition after four weighing periods. Drying ceased when the seeds reached the pre-established final water content.

Seed final water content was determined using the oven method at 105 ±3°C for 24 h, with three repetitions of three seeds according to the Rules for Seed Analysis (BRASIL, 2009).

The drying curves were obtained by converting the data related to water loss into the "humidity ratio" parameter (adimensional). This parameter is important for describing the thin-layer drying models. Under specific drying conditions, the water content is correlated with the initial and equilibrium water content. Thus, there was a fit of the humidity ratio for all mathematical models tested here. Therefore, it allowed describing the drying kinetics (Mendonça et al., 2015).

For calculating the humidity ratios (HR), the hygroscopic equilibrium humidity was calculated using the Henderson equation:

$$HR = \frac{(X - Xe)}{(Xi - Xe)}$$

Where:

X - the water content of the product, decimal (db);

Xe - the equilibrium water content of the product, decimal (db);

Xi - the initial water content of the product, decimal (db).

In order to fit the mathematical models described in (**Table 1**) to the drying curve experimental data, nonlinear regression analysis was performed following the Quasi-Newton method using the Statistica software, version 7.0. The parameter values of the models were estimated as a function of the independent variables of drying air temperature and equilibrium water content of the product.

The relative mean error (P) and the estimated mean error (SE) for each model were calculated as follows:

$$P = \frac{100}{n} \cdot \sum \frac{|Y - \hat{}Y|}{Y}$$

$$SE = \sqrt{\sum \frac{(Y - \hat{}Y)2}{DFM}}$$

Where:

n – number of observations;

Y - experimentally observed value;

^Y - value calculated by the model;

DFM - degrees of freedom of the model (number of observations (n) minus the number of model parameters).

Criteria for determining the best fit of the models to the experimental data comprised the magnitude of the values of the coefficient of determination (R^2), the significance of the regression coefficients, the magnitude of the relative mean error (P) and the estimated mean error (SE), and the tendency of the distribution of the residuals (random or biased). The residual refers to the difference between the experimentally observed value and the value estimated by the model.

After the drying step, four repetitions of 10 seeds from the continuous drying and 1:1 intermittent drying treatments were subjected to an X-ray test. The test was conducted in the Seed Laboratory of the Universidade Federal de Lavras, Minas Gerais. The seeds were fixed with double-sided tape on transparent slides and numbered according to the position occupied so that they could be identified for later determination. The images were generated using the Faxitron MX-20 DC 12 equipment. The adjustment of the exposure time and radiation intensity was automatic. After developing the radiographic images, the seeds underwent visual analysis to verify any damage during the drying process.

Results And Discussion

The initial water content of the cumbaru seeds was 14.5% (wb) at the beginning of the drying process. Then, they were dried to the pre-established final water contents of 12, 10, and 8.5% (wb). (**Figure 1**) and (**Figure 2**) show the drying curves of the respective values in the continuous and 1:1 intermittent drying treatments. In these curves, we can see that in the continuous drying, there was a higher water removal rate at the beginning

Table 1. Mathematical models used to predict the drying phenomenon of cumbaru (*Dipteryx alata* Vog.) seeds

Mathematical Models	Equation
Newton	HR= exp(-k*t)
Henderson and Pabis	HR= a*exp(-k*t)
Modified Henderson and Pabis	HR= a*exp(-k*t)+b*exp(-k0*t)+c*exp (- k1*t)
Two terms	HR= a*exp(-k0*t)+b*exp(-k1*t)
Two-Term Exponential	HR = a*exp(-k*t)+(1-a)exp(-k*a*t)
Logarithmic	HR= a*exp(-k*t)+c
Page	HR= exp(-k*t^n)
Thompson	HR = exp((-a-(a^2 + 4*b*t)^0,5))/2*b
Verma	HR = a*exp (-k*t) + (1 - a)*exp (-k1*t)
Diffusion Approximation	HR= a*exp(-k*t)+(1-a)*exp(-k*b*t)
Wang and Sing	HR= 1+a*t+b*t^2
Midilli	HR= a*exp(-k*t^n)+b*t

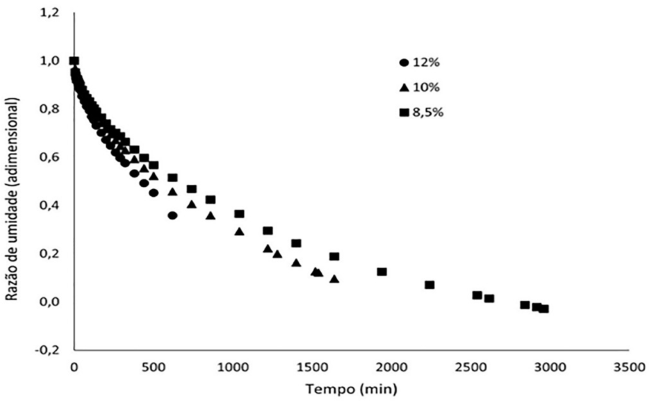

Figure 1. Drying curves of Cumbaru (*Dipteryx alata*) at final water contents of 12, 10, and 8.5% on a dry basis (db) with continuous drying.

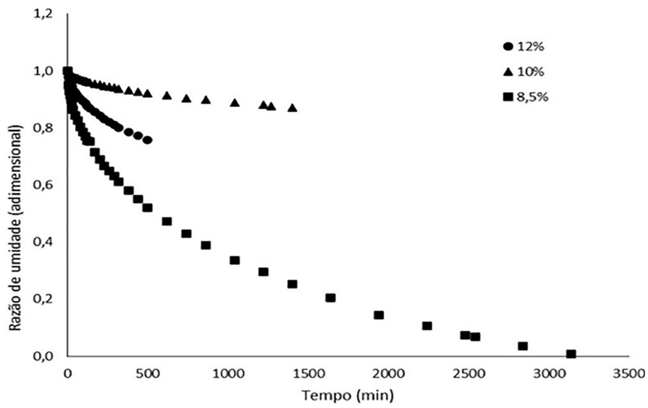

Figure 2. Drying curves of Cumbaru (*Dipteryx alata*) at final water contents of 12, 10, and 8.5% on a dry basis (db) with 1:1 intermittent drying.

of the process compared to the 1:1 intermittent drying. At the end of the process, the water is strongly bound, resulting in higher energy demand for its evaporation and a longer time to remove lower water rate values. These results coincide with Mendonça et al. (2015), who, while working with seeds of *Carapa guianenssis* in a solar dryer, also observed this pattern in the water removal behavior in their material.

Furthermore, the absolute time of the continuous treatment was 5.73% or 180 minutes shorter at the end of the total drying period (8.5%) compared to the treatment with a purposeful equalization between the material's drying and the resting period. In other words, when there was no intermittent relationship, the product's higher water removal rate was inversely proportional to the time. Meneghetti et al. (2012) also observed these results.

(Table 1) shows the analyzed drying models with the respective values of the statistical parameters relating to the coefficients of determination (R^2), chi-square (x^2), estimated mean error (SE), and relative mean error (P) for the fitted models for drying cumbaru seeds at final water contents of 12, 10, and 8.5% in continuous and 1:1 intermittent drying.

The R^2 of all fitted models in continuous drying, regardless of the pre-established final water content, was greater than 96.9%. Meanwhile, in 1:1 intermittent drying, the lowest observed value was 86.42%. These results are statistically considered competent. However, Silva et al. (2018) report that when analyzed in isolation, the coefficient of determination does not establish a reliability parameter for exponential model selection. Therefore, the estimated mean error (SE) and relative mean error (P) values were also used to affirm the results' credibility.

According to Kashaninejad et al. (2007), analyzing the values of (P) is important to observe the deviation of the observed values from the curve plotted by the model. Thus, values lower than 10% should be used when choosing models, as it adequately represents the Mohapatra and Rao (2005) phenomenon. Furthermore, according to Draper and Smith (1998), the smaller the values of (x^2), (SE), and (P), the more accurate the fitting to the mathematical model (**Table 2**).

Thus, the Midilli model was the one that presented the best fit to the experimental data for all final water contents in both types of drying. It showed a coefficient of determination values (R^2) above 99.97% and with (R^2) of 100% for the 10% final water content treatment in continuous drying. The values of (x^2), (SE), and (P) for this model were also within the parameters considered ideal.

When working with drying cumari pepper seeds from Pará, Reis et al. (2011) also found a better fit to the experimental data with the Midilli model. So did authors who worked with andiroba seeds (Mendonça et al., 2015) and paddy rice (Meneghetii et al., 2012).

(Table 2) shows the values of the coefficients of the fitted Midilli model as a function of the drying type and the final water content values. It is possible to observe that within the final water contents, the constants a, k, b, and n presented values close to each other. Moreover, between the continuous and the 1:1 intermittent drying, lower values of k and b were observed in 10% in the 1:1 intermittent drying, however, with values very close to the other treatments. In other words, the drying types did not influence any behavior regarding changes in the absolute values of the coefficients (**Table 3**).

According to Madamba et al. (1996), the constant k is related to the drying air temperature and effective diffusivity in the drying process throughout the process. This study found no changes in the drying temperature, which explains the approximate values for all treatments. Thus, it differs from Reis et al. (2011), who noted an increase in k values and a decrease in b values according to different drying treatments in pepper.

After the cumbaru seeds drying process, the

Table 2. Parameters obtained from the models fitted to cumbaru seed drying data

Mathematical Models	H_2O content (%) (wb)	R^2 (%)	X^2	SE	P
		Continuous Drying			
Newton	12	96.90%	0.0397	0.0429	5.3662
	10	99.08%	0.0349	0.0390	6.2230
	8.5	98.91%	0.0455	0.0494	7.4765
Henderson and Pabis	12	99.39%	0.0160	0.0195	2.0234
	10	99.76%	0.0173	0.0203	4.2789
	8.5	99.60%	0.0238	0.0305	12.1202
Modified Henderson and Pabis	12	99.92%	0.0069	0.0076	0.7912
	10	99.74%	0.0205	0.0227	4.7709
	8.5	99.67%	0.0216	0.0293	12.7684
Two terms	12	99.92%	0.0065	0.0073	0.8519
	10	99.76%	0.0183	0.0208	4.5272
	8.5	99.60%	0.0252	0.0314	12.1212
Two-Term Exponential	12	99.14%	0.0190	0.0222	2.5273
	10	99.76%	0.0171	0.0195	4.6235
	8.5	99.44%	0.0299	0.0349	11.1519
Logarithmic	12	99.60%	0.0131	0.0162	1.7493
	10	99.76%	0.0179	0.0206	4.2122
	8.5	99.78%	0.0195	0.0228	2.5441
Page	12	99.75%	0.0095	0.0124	1.4098
	10	99.68%	0.0200	0.0234	6.5911
	8.5	99.27%	0.0400	0.0409	12.4222
Thompson	12	99.39%	0.0160	0.0195	2.0190
	10	99.76%	0.0173	0.0203	4.2904
	8.5	99.60%	0.0237	0.0306	12.1404
Verma	12	96.90%	0.0433	0.0448	5.3683
	10	99.08%	0.0371	0.0402	6.1102
	8.5	98.90%	0.0485	0.0510	7.7845
Diffusion Approximation	12	99.91%	0.0068	0.0077	0.9173
	10	99.89%	0.0105	0.0137	3.9695
	8.5	99.67%	0.0196	0.0280	12.9087
Wang and Sing	12	97.51%	0.0372	0.0394	4.9125
	10	98.35%	0.0498	0.0529	11.1132
	8.5	97.60%	0.0703	0.0740	1.9009
Midilli	12	99.97%	0.0038	0.0043	0.5186
	10	100.00%	0.0022	0.0026	0.4877
	8.5	99.98%	0.0060	0.0076	1.0628
		1:1 Intermittent Drying			
Newton	12	87.84%	0.0306	0.0334	3.3415
	10	86.43%	0.0176	0.0189	1.8089
	8.5	97.33%	0.0635	0.4172	19.7475
Henderson and Pabis	12	97.07%	0.0148	0.0172	1.5449
	10	96.53%	0.0091	0.0100	0.9013
	8.5	99.41%	0.0279	0.0333	17.3305
Modified Henderson and Pabis	12	97.14%	0.0182	0.0188	1.5327
	10	95.85%	0.0109	0.0117	0.9177
	8.5	99.91%	0.0122	0.0141	20.7377
Two terms	12	99.39%	0.0068	0.0083	0.6243
	10	99.20%	0.0045	0.0050	0.4137
	8.5	99.91%	0.0115	0.0138	20.1451
Two-Term Exponential	12	94.63%	0.0214	0.0231	2.2253
	10	93.60%	0.0128	0.0134	1.2711
	8.5	98.90%	0.0408	0.0454	18.2491
Logarithmic	12	99.56%	0.0054	0.0069	0.5271
	10	99.58%	0.0030	0.0036	0.2892
	8.5	99.43%	0.0286	0.0331	26.9619
Page	12	99.99%	0.0010	0.0012	0.1085
	10	99.98%	0.0007	0.0008	0.0670
	8.5	99.58%	0.0243	0.0282	39.6173
Thompson	12	97.07%	0.0148	0.0172	1.5450
	10	96.54%	0.0091	0.0099	0.8958
	8.5	99.41%	0.0279	0.0333	17.3746
Verma	12	87.84%	0.0335	0.0350	3.3409
	10	86.42%	0.0188	0.0195	1.8054
	8.5	97.31%	0.0675	0.0717	19.8655
Diffusion Approximation	12	99.77%	0.0045	0.0050	0.4543
	10	99.72%	0.0026	0.0029	0.2505
	8.5	99.89%	0.0121	0.0144	20.3042
Wang and Sing	12	96.56%	0.0171	0.0186	1.7627
	10	96.65%	0.0092	0.0098	0.9057
	8.5	93.87%	0.0997	0.1058	88.6378
Midilli	12	99.99%	0.0008	0.0009	0.0782
	10	99.99%	0.0004	0.0006	0.0387
	8.5	99.99%	0.0039	0.0052	5.2451

Table 3. Coefficients of the Midilli model in the continuous and 1:1 intermittent drying treatments on cumbaru seeds for final water contents of 12, 10, and 8.5%

Parameters				
Continuous Drying				
H_2O Content (%) (wb)	a	k	b	n
12	0.998934	0.016555	-0.000347	0.541591
10	0.997779	0.009621	-0.000143	0.641790
8.5	0.972779	0.005811	-0.000071	0.711367
Intermittent drying				
12	0.999712	0.008496	0.000048	0.578153
10	1.000	0.00257	0.000015	0.57045
8.5	0.98674	0.014481	-0.00005	0.59653

times spent for the seeds to reach the pre-established final water content value were 620, 1640, and 2690 minutes in continuous drying and 500, 1400, and 3140 in 1:1 intermittent drying for 12, 10, and 8.5% (wb) respectively.

(**Figure 3**) and (**Figure 4**) show the proper fit of the Midilli model in describing the experimental results and calculating the humidity ratio as a function of drying time in the treatments involving the pre-established final water contents in the continuous and 1:1 intermittent drying types.

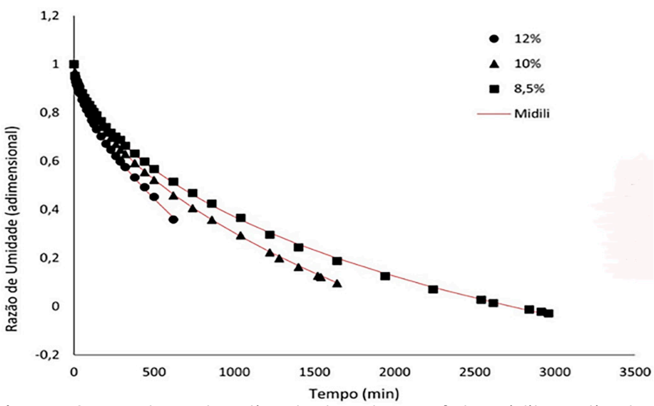

Figure 3. Real and estimated values of humidity ratio by estimating the parameters of the Midilli model at final water contents of 12, 10, and 8.5% on a dry basis (db) with continuous drying.

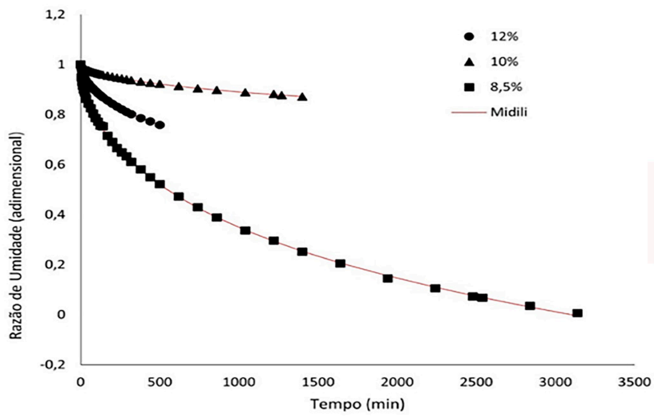

Figure 4. Real and estimated humidity ratio values by estimating the parameters of the Midilli (2002) model at final water contents of 12, 10, and 8.5% on a dry basis (db) with 1:1 intermittent drying.

In the curves obtained in the Midilli model, there is a good correlation between the experimental and estimated values for all treatments. In addition, there is satisfactory behavior in the distribution of the values along the curve. Thus, the reading in the Midilli model also indicates that the water content is reduced over time and that the highest water removal rate occurs in the first 500 minutes.After this period, the water goes to more intrinsic regions of the seed, slowing down the drying process and resulting in lower drying rate values (Martins et al., 2014). These results are in agreement with several studies conducted with different agricultural products, such as Cavalcante et al. (2020) with algaroba grains, Moscon et al. (2017) with Quinoa seeds, and Vieira et al. (2019) with pumpkin seeds. Regarding the visual analysis of seed damage using radiographic images, Menezes et al. (2005) report that most cracks occur within 48 hours after drying for rice seeds, a starchy plant. However, no information was found for cumbaru seeds, an oleaginous plant, regarding the minimum time the material begins to present physical damage due to drying. In this study, the radiographic analyses were performed 15 days after drying. These analyses showed that in all treatments, the seeds did not present cracks or any physical damage due to the drying process.

Possibly, such a fact is due to the adequacy of the drying air temperature and velocity, which were 40°C and 2.5 m/s^{-1}, respectively. According to Quequeto (2018) and Hartmann Filho et al. (2016), the quick water removal from the product, which combines high temperature and drying air values, creates a high-pressure gradient between the inner and outer seed parts. Thus, it results in cracks in the tegument and micro-cracks in the cotyledon, reducing their quality. Several studies point out that temperatures above 50°C promote greater damage to seeds (Bissaro, 2018; Quequeto, 2018) (**Figure 5**).

The association of the analysis of radiographic images in studies on drying kinetics is interesting. As a fast and non-destructive method, it allows the detection of different types of damage, such as mechanical damage, damage caused by insects, and damage resulting from a poorly conducted drying process. Samboni (2018), when working with coffee seeds, Amaral et al. (2020) with gabiroba seeds, and Silva et al. (2014) with pumpkin seeds, reported that using radiographic images is effective in evaluating, beyond internal morphology, damage caused by tissue deterioration. Thus, it enables establishing a relationship between damage and cause, contributing to other analyses aimed at evaluating seed germination performance.

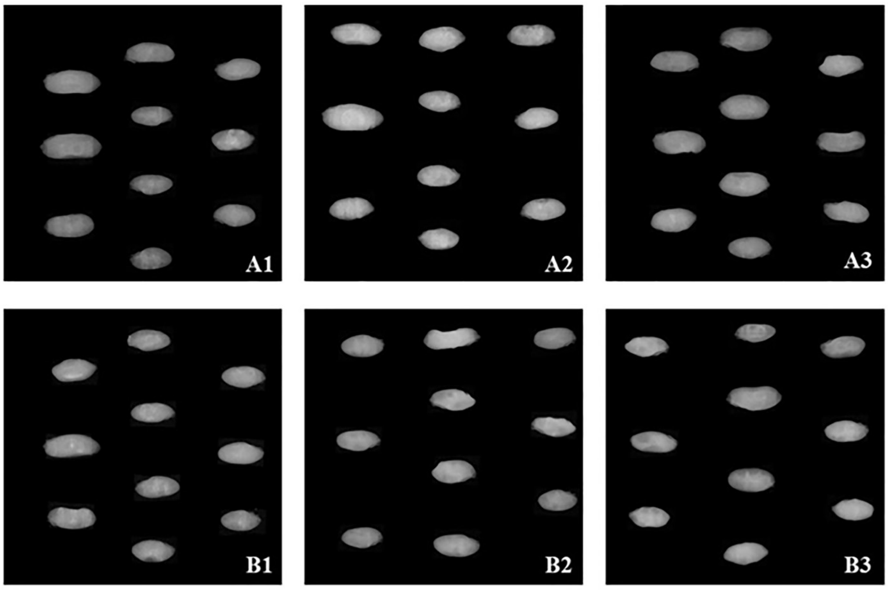

Figure 5. Radiographic images of cumbaru (*Dipteryx alata* Vog.) seeds in the continuous (A) and 1:1 intermittent (B) dryings at water contents of 12 (1), 10 (2), and 8.5% (3), respectively.

Conclusions

The drying mathematical model proposed by Midilli is the one that best fits the experimental data for drying cumbaru seeds.

The drying air temperature and velocity provide a good water content removal from the product. In addition, they do not result in physical damage to the seeds.

The drying type interferes with the grains' drying time rate during the process. The continuous drying shows a shorter operating time.

Finally, x-ray images are efficient when analyzing damage related to the drying of cumbaru seeds.

References

Alvarenga, C., Jorge, M.H.A. Cumbaru no Pantanal. 2008. Disponível em: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/790287/1/ADM127.pdf<Acesso em 27 jan. 2022>

Amaral, E.V.E.J., Sales, J.F., Zuchi, J., Neves, J.M.G., Oliveira, J.A. 2020.

Analysis of radiographic images and germination of *Campomanesia pubescens* (mart. Ex dc.) O. Berg (*Myrtaceae juss*.) Seeds under drying. *Brazilian journal of biology* 80: 777-782.

Bissaro, C.A. 2018. *Avaliação da qualidade e do consumo energético no processo de secagem intermitente em sementes de soja*. 79 f. (Dissertação de Mestrado) – Universidade Estadual de Maringá, Maringá, Brasil.

Brasil. 2009. *Regras para análise de sementes*. Ministério da Agricultura, Pecuária e Abastecimento, Brasília, Brasil. 398 p.

Cavalcante, A.M.M., Almeida, R.D., Melo, A.M., Morais, B.A., Silva, I.R., Ribeiro, N.L., Silva, O.S. 2020. Modelos de predição da cinética de secagem dos grãos da algaroba. *Brazilian Journal of Development* 6: 11192-11209.

Coradi, P.C., Milane, L.V., Andrade, M.G.O., Camilo, L.J., Souza, A.H.S. 2016. Secagem de grãos de milho do cerrado em um secador comercial de fluxos mistos. *Revista Brasileira de Engenharia de Biossistemas* 10: 14-26.

Diogenes, A.D.M.G., QUEIROZ, A.J.D.M., Figueirêdo, R.M.F., Santos, D.D.C. 2013. Cinética de secagem de grãos de abóbora. *Revista Caatinga* 26: 71-80.

Draper, N.R., Smith, H. 1998. *Applied regression analysis*. John Wiley & Sons, New York, EUA. 326 p.

Engelhardt, B.A.S., Arrieche, L.S. 2016. Análise da secagem de amêndoas de cacau por convecção forçada a partir de diferentes secadores. *Brazilian Journal of Production Engineering-BJPE* 2: 18-26.

Freitas, E.C.S.D., Paiva, H.N.D., Leite, H.G., Oliveira, S.N.D. 2017. Crescimento e qualidade de mudas de *Cassia grandis* Linnaeus f. em resposta à adubação fosfatada e calagem. *Ciência Florestal* 27: 509-519.

Hartmann Filho, C.P., Goneli, A.L.D., Masetto, T.E., Martins, E.A.S., Oba, G.C. 2016. The effect of drying temperatures and storage of seeds on the growth of soybean seedlings. *Journal of Seed Science* 38: 287-295.

Kashaninejad, M., Mortazavi, A., Safekordi, A., Tabil, L.G. 2007. Thin-layer drying characteristics and modeling of pistachio nuts. *Journal of food engineering* 78: 98-108.

Madamba, P.S., Driscoll, R.H., Buckle, K.A. 1996. The thin-layer drying characteristics of garlic slices. *Journal of food* *engineering* 29: 75-97.

Marcos Filho, J. 1999. *Testes de vigor: importância e utilização*. In: Krzyzanowski, F.C., Vieira, R.D., França NETO, J.B. *Vigor de sementes: conceitos e testes*. ABRATES, Londrina, Brasil. 9 p.

Marcos Filho, J., Gomes Junior, F.G., Bennett, M.A., Wells, A.A., Stieve, S. 2010. Using tomato analyzer software to determine embryo size in x-rayed seeds. *Revista Brasileira de Sementes* 32: 146-153.

Martins, J.J.A., Marques, J.I., Costa Santos, D., Rocha, A.P.T. 2014. Modelagem matemática da secagem de cascas de mulungu. *Bioscience Journal* 30: 1652-1660.

Mendonça, A.P., Sampaio, P.D.T., Almeida, F.D.A., Ferreira, R.F., Novais, J.M. 2015. Determinação das curvas de secagem das sementes de andiroba em secador solar. *Revista Brasileira de Engenharia Agrícola e Ambiental* 19: 382-387.

Meneghetti, V.L., Aosani, E., Rocha, J.C.D., Oliveira, M.D., Elias, M.C., Pohndorf, R.S. 2012. Modelos matemáticos para a secagem intermitente de arroz em casca. *Revista Brasileira de Engenharia Agrícola e Ambiental* 16: 1115-1120.

Menezes, N.L.D., Cícero, S.M., Villela, F.A. 2005. Identificação de fissuras em sementes de arroz após a secagem artificial, por meio de raios-x. *Ciência rural* 35: 1194-1196.

Mohapatra, D., Rao, P.S. 2005. A thin layer drying model of parboiled wheat. *Journal of food engineering* 66: 513-518.

Moscon, E.S., Martin, S., Spehar, C.R., Devilla, I.A., Junior, F.R. 2017. Cinética de secagem de grãos de quinoa (*Chenopodium quinoa* W.). *Revista engenharia na agricultura* 25: 318-325.

Nascimento, J.C., Vilarinho, M.K.C., Caldeira, D.S.A., Antoniacomi, L.A.M., Oliveira, A.J., Oliveira, T.C., Luz, P.B. 2021. Maturação e qualidade fisiológica das sementes de cumbaru em função do período de coleta dos frutos. *Research, Society and Development* 10: e21610111589.

Nunes, R.T.C., Souza, U.O., Morais, O.M., Lourenço, C.M.S. 2014. Análise de imagens na avaliação da qualidade fisiológica de sementes. *Revista Verde de Agroecologia e Desenvolvimento Sustentável* 27: 9-18.

Quequeto, W.D. 2018. *Qualidade fisiológica e perfil de ácidos graxos do óleo bruto de sementes de niger após a secagem*. 41 f. (Dissertação de Mestrado) – Universidade Federal da Grande Dourados, Dourados, Brasil.

Reis, R.C., Barbosa, L.S., Lima, M.D.L., Reis, J.D.S., Devilla, I.A., Ascheri, D.P. 2011. Modelagem matemática da secagem da pimenta Cumari do Pará. *Revista Brasileira de Engenharia Agrícola e Ambiental* 15: 347-353.

Samboni, H.A.T. 2018. *Análise radiográfica associada com o desempenho germinativo e determinação do vigor de sementes de café utilizando imagens digitalizadas de plântulas*. 77 f. (Dissertação de Mestrado) – Universidade de São Paulo, Piracicaba, Brasil.

Schuch, L.O.B., Vieira, J.F.V., Rufino, C.A., Júnior, J.S.A. 2013. *Sementes: Produção, qualidade e inovações tecnológicas*. Scientia Plena, Pelotas, Brasil. 571 p.

Silva, É.C.C., Rufini, J.C.M., Parrella, N.N.L.D., Campos, A.S., Neves, F.F. 2016. Comportamento fisiológico de sementes de *Eugenia dysenterica* DC submetidas à secagem artificial. *Global Science And Technology* 9: 7-14.

Silva, I.L., Silva, H.W., Camargo, F.R., Farias, H.F.F.M., Freitas, E. 2018. Secagem e difusividade de sementes de melão. *Revista de Ciências Agrárias* 41: 309-315.

Silva, P.P., Freitas, R.A., Cícero, S.M., Marcos-Filho, J., Nascimento, W.M. 2014. Análise de imagens no estudo morfológico e fisiológico de sementes de abóbora. *Horticultura brasileira* 32: 210-214.

Silva, V.N., Sarmento, M.B., Silveira, A.C., Silva, C.S., Cicero, S.M. 2013. Avaliação da morfologia interna de sementes de *Acca sellowiana* O. Berg por meio de análise de imagens. *Revista Brasileira de Fruticultura* 35: 1158-1169.

Silveira, D.C., Leite, A.C.N., Santos, N.C., Gomes, J.P. 2019. Características físicas de grãos de feijão-fava rajada, *Phaseolus lunatus* L. *Revista Verde de Agroecologia e Desenvolvimento Sustentável* 14: 518-523.

Ullmann, R., Resende, O., Rodrigues, G.B., Chaves, T.H., Oliveira, D.E.C. 2018. Qualidade fisiológica das sementes de sorgo sacarino submetidas à secagem e ao armazenamento. *Revista Engenharia na Agricultura* 26: 313-321.

Vieira, D.M., Barros, S.L., Alcântara Silva, V.M., Santos, NC., Nascimento, A.P.S., Melo, M.O.P. 2019. Cinética de secagem e sua influência nas dimensões de sementes de abóbora sem casca. *Revista Verde de Agroecologia e Desenvolvimento Sustentável* 14: 665-670.

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