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Drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds in natural and artificial methods[1]

Cinética de secagem de sementes de *Amaranthus cruentus* 'BRS Alegria' nos métodos natural e artificial

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HIGHLIGHTS:
The drying of amaranth seeds can be easily modeled.
Amaranth seeds can be dried quickly at high temperatures.
Artificial drying of amaranth seeds can reduce the water concentration by half in the first two hours.

ABSTRACT: The seeds of most crops are often harvested with water concentrations above the recommended levels; for instance, amaranth crops can be harvested under water contents up to 40%. Therefore, drying of the harvest is essential to preserve its post-harvest quality. Thus, the objective of this study was to investigate the drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds dried via natural and artificial methods. Drying experiments were conducted in laboratory under natural methods, in shaded and open sun conditions, and also under artificial drying at temperatures of 60, 80 and 100 °C. The average temperatures of the seed mass were 30, 40, 50, 60, and 70 °C for the natural drying methods, shaded and open sun, and under the artificial drying at temperatures of 60, 80, and 100 °C. The modified Midilli equation proved to be the best model for describing the drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds. For the artificial drying method at temperatures of 60, 80, and 100 °C, durations of 2.5, 3.5, and 7 hours were respectively required to reduce the water content from 21.1% to 11.5%; and, 4.25, 4.75, and 10 hours to reduce concentration 21.1% to 8.5%. For natural drying under open sun, a drying time of 15 hours was required; for shaded conditions, a drying time of 164 hours was required until the water concentration reduced to 13% which was the equilibrium moisture.

Key words: drying time, temperature, artificial drying, open sun, shade drying

RESUMO: As sementes da maioria das culturas são frequentemente colhidas com um teor de água acima do recomendado; por exemplo, a cultura do amaranto pode ser colhida com teores de água até 40%. Portanto, a secagem da colheita é necessária para preservar a qualidade pós-colheita. Assim, objetivou-se estudar a cinética de secagem de sementes de *Amaranthus cruentus* 'BRS Alegria' secas por métodos naturais e artificiais. Os experimentos foram conduzidos em laboratório utilizando os métodos de secagem natural, sombra e pleno sol, e, secagem artificial nas temperaturas de 60, 80 e 100 °C. As médias das temperaturas da massa de sementes foram de 30, 40, 50, 60 e 70 °C respectivamente para os métodos de secagem natural, sombra e pleno sol, e, secagem artificial nas temperaturas de 60, 80 e 100 °C. A equação de Midilli modificada foi o melhor modelo para descrever a cinética de secagem de sementes de *Amaranthus cruentus* 'BRS Alegria'. Para o método de secagem artificial nas temperaturas de 60, 80 e 100 °C, durações de 2,5, 3,5 e 7 horas foram necessárias, respectivamente, para reduzir o teor de água de 21,1% para 11,5%; e 4,25, 4,75 e 10 horas, para reduzir o teor de água de 21,1% para 8,5%. Para secagem natural a pleno sol, foi necessário um tempo de secagem de 15 horas; para condições de sombra, um tempo de secagem de 164 horas foi necessário até o teor de água ser reduzido para 13%, a umidade de equilíbrio.

Palavras-chave: tempo de secagem, temperatura, secagem artificial, pleno sol, secagem à sombra

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Introduction

Amaranth (*Amaranthus cruentus*) seeds can be naturally dried on a small scale by exposing them to ambient air (Abalone et al., 2006; Ronoh et al., 2009). This natural drying method mostly contributes to maintaining the original qualities of seeds and is the most suitable method for drying such seeds (Silva, 2008).

In addition, the natural drying method is simple and incurs low investment costs for the producer. This method is advantageous in that it involves the germicidal action of the sun's rays and causes no pollution. However, it is a slow process and depends entirely on climatic conditions (Silva, 2008).

On a large scale, amaranth seeds are often harvested under a higher water content, i.e., approximately 40%. Here, artificial drying methods are required to rapidly reduce the seed water concentration and guarantee good preservation of the harvest (Silva, 2008). Therefore, the drying kinetics of the seeds must be analyzed.

The drying systems, their dimensions, optimization, and determination of the viability of their commercial application, can be studied through a mathematical simulation. The principle thereof is based on the drying of thin layers of the harvest. The simulation involves a mathematical model that satisfactorily represents the water loss (Resende et al., 2007).

In existing studies, mathematical models have been investigated and adjusted to predict the drying kinetics of various grains (Costa et al., 2011; Morais et al., 2013; Mendonça et al., 2015; Coradi et al., 2016; Goneli et al., 2017; Smaniotto et al., 2017).

Owing to the importance of the drying kinetics of *Amaranthus cruentus* seeds, this aspect has gained global research interest (Abalone et al., 2006; Ronoh et al., 2009). However, little is known about the 'BRS Alegria' cultivar.

The objective of this study was therefore to investigate the drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds under natural, in shaded and open sun conditions, and artificial methods at temperatures of 60, 80, and 100 °C.

Material and Methods

This study was conducted at the Laboratory of Machines and Motors, Federal University of Mato Grosso, Cuiabá city, Mato Grosso State, Brazil (15° 35' 56" S; 56° 5' 42" W, altitude 180 m). *Amaranthus cruentus* seeds, cultivar BRS Alegria, from the 2018 harvest were used, as described by Silva (2019). Harvesting was performed 90 days after the seeds were sown.

Under 37% water concentration, the panicles were manually harvested immediately after they attained physiological maturation, which was identified by a change in the panicle color from green to reddish (Mendes, 2014; Silva, 2019). This harvest was conducted to reduce possible dehiscence losses.

The panicles were placed under open sun on black plastic canvases for two hours under the following climatic conditions: temperature of 28.6 °C and relative air humidity of 70.8% (INMET, 2020). This was to facilitate the release of the seeds and reduce dent damage during the trail. The panicles were tracked in an adapted grain thresher and transported to the laboratory where they were handled.

The seeds were cleaned in a forced counterflow blower (non-patented and designed by us) at a speed of 4.5 ms^{-1} and an air temperature of 30 °C; further, 4.5% of impurities were removed from the seeds, which consisted of straw, light, and withered seeds. During preparation of the seeds for the drying test, they were stored under laboratory conditions (temperature of 26.8 °C and relative air humidity of 56.4%).

Representative samples were collected during the post-harvest processes to determine the seed water concentration; the concentration was determined at 105 ± 3 °C for 24 hours using the oven method (Brasil, 2009).

Drying was performed for a static seed mass with an average thickness of 25 ± 2 mm on stainless-steel sieves with a diameter of 200 mm and a mesh size of less than 1 mm. The average mass of each sample was 620 g.

The water loss in the seeds occurred owing to the weight difference. The sieves were weighed on a semi-analytical scale (Shimadzu AUW220D model, Brazil) with a resolution of 1 mg.

The final drying point under the artificial drying method was considered as that at which the product water content was reduced to 8.5%. Owing to the rainy weather conditions during the period of the experiment, a water concentration of 11.5% was considered as the final point under the natural drying method.

The experiments were conducted under natural ventilation, in shaded and open sun drying conditions, and using artificial drying methods controlled electronically at air temperatures of 60 ± 2 °C, 80 ± 3 °C, and 100 ± 2 °C. During drying, the corresponding temperature of the seed mass was also monitored using a mercury bulb thermometer.

For the artificial methods, an oven-dryer was used with forced air circulation and electronic temperature control (Logen Scientific Drying Oven, Brazil). The air circulation in the dryer is aided by a fan, with electrical resistors used to heat the incoming air, and the temperature is controlled using a PT-100 type sensor.

In addition, during the drying process, the variables measured included drying temperature (°C), relative air humidity (%), average wind speed, and air flow in the kiln-dryer (ms^{-1}). These variables were determined using a portable thermo-hygroanemometer (Icel WN-1800 model).

For drying under open sun, the insolation data were also observed and computed at 5.9 and 7.1 h for the 6th and 7th of October 2018, respectively (INMET, 2020).

For the artificial method, measurements were read for the temperatures of 100 and 80 °C every 15 min (0.25 h) and subsequently every 30 min until the end of the process. At 60 °C, the first four readings were taken every 30 min, followed by four more readings of 1 hours and the subsequent readings every 2 hours until the end of the process.

For the natural method, the seeds were dried under open sun. The first readings were recorded every 1 hours, followed by two readings recorded every 1.5 hours, and the remaining readings recorded every 3 hours until the end of drying. The drying was performed for 15 hours, divided into periods of 7.5 hours each (for two days), owing to cloudy conditions during the test.

Between the periods of interruption in the open sun drying, the seeds were kept in a desiccator without silica gel to maintain the water content, the period of time for which was not considered.

For shade drying, readings were recorded every 1 hour on the first day, while they were recorded every 12 hours during the second to the fifteenth days of the experiment; further, the readings were recorded once a day until equilibrium between the environment was attained, which was considered as the end point of the experiment.

The time required to obtain each reading ranged from 5 to 15 min; this duration was considered as a part of the drying process and was not discounted from the total drying time.

The equilibrium moisture (We) was obtained using the modified Henderson equation (Eq. 1), described by Pagano & Mascheroni (2005) as the equation that best represents the phenomenon of desorption in *Amaranthus cruentus* seeds for a wide range of temperatures and humidity; it was also recommended by Abalone et al. (2006).

$$We = \left[\frac{\ln(1 - RH)}{-1.1499 \cdot (T + 24.2105)} \right]^{\frac{1}{1.9639}} \qquad (1)$$

where:

T - temperature of the drying air, °C; and,

RH - relative air humidity measured at the dryer outlet, decimal.

The moisture ratio (MR) under different air conditions was determined using Eq. 2:

$$MR = \frac{W - We}{Wi - We} \qquad (2)$$

where:

W - water concentration of the product at time T, decimal; and,

Wi - initial water concentration of the product, decimal.

The drying curves were obtained by converting the water loss data into a dimensionless MR parameter. For each drying time, the water concentration was correlated with the initial water concentration and equilibrium moisture for specific drying conditions.

The values of moisture ratio as a function of drying time were adjusted to the models to describe the drying kinetics, the equations for which are presented in Table 1.

The criteria used to determine the best fit of the models to the experimental data were based on the statistical indices: coefficient of determination (R^2), standard deviation of the estimate (SE), and magnitude of the relative mean error (P). The SE and P for each of the models were calculated according to Eqs. 17 and 18.

$$SE = \sqrt{\frac{\sum_{i=1}^{N} (Y - Y_0)^2}{N - 2}} \qquad (17)$$

$$P = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{|Y - Y_0|}{Y} \right) \qquad (18)$$

where:

Y - value observed;

Y_0 - value calculated by the model; and,

N - number of data observed.

In addition, the residual distribution tendency (random or tendentious) was used, which was the difference between the observed values and those estimated by the models (Mendonça et al., 2015). This distribution has been used to select mathematical drying models (Costa et al., 2011; Mendonça et al., 2015; Coradi et al., 2016; Goneli et al., 2017).

The CurveExpert Professional 2.4.0 software was used to adjust the non-linear regression models to the experimental drying data.

Results and Discussion

The water concentration of the amaranth seeds decreased from 37% to 26.8% after the panicles had been exposed to the sun for 2 hours. This rapid reduction was due to free water; the seeds have low energy retention of free water (Silva, 2008).

The water concentration of the seeds further reduced to 23.1% after the trial and different handling processes. The removal of impurities with a blow-dryer at 30 °C reduced the concentration to an average of 22%.

Table 1. Non-linear regression models used to describe drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds

Model name	Model equation*	Eq.
Diffusion approximation	$MR = a\exp(-kt) + (1 - A)\exp(-kbt)$	(3)
Two-terms	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	(4)
Two-terms exponential	$MR = a\exp(-kt) + (1 - a)\exp(-kat)$	(5)
Henderson and Pabis	$MR = a\exp(-kt)$	(6)
Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-k_0 t) + c\exp(-k_1 t)$	(7)
Logarithmic	$MR = a\exp(-kt) + b$	(8)
Midilli	$MR = a\exp(-kt^C) + bt$	(9)
Modified Midilli	$MR = \exp(-kt^C) + bt$	(10)
Newton	$MR = \exp(-kt)$	(11)
Page	$MR = \exp(-kt^C)$	(12)
Modified Page	$MR = \exp[-(kt)^C]$	(13)
Thompson	$MR = \exp\{[-a - (a^2 + 4bt)^{0,5}]/2b\}$	(14)
Verna	$MR = a\exp(-kt) + (1 - a)\exp(-k_1 t)$	(15)
Wang-Singh	$MR = kt^2 + at + 1$	(16)

*a, b, and c: drying coefficients, t: drying time (h), and k, k_0, and k_1: drying parameters (h^{-1})

Most of the water evaporated during drying is free water. It can be easily removed by air with a low relative humidity involving low loss of water when the water concentration in the seed is low (Silva, 2008). This is observed in the form of rapid loss of water, which occurred initially in the processes after the seed harvest.

While drying amaranth seeds using a solar convection dryer with natural convection under open sun at 22.6-30.4 °C and 25-52% relative air humidity, Ronoh et al. (2009) observed a reduction in the water concentration from 39.1% to values close to 25.9% after 30 min.

This difference in the time of exposure to the sun with respect to the loss of water is related to the seeds being protected by the panicles with higher moisture than that of the seeds.

Under the artificial method, the air temperatures in the drying chamber were electronically controlled and carefully monitored using a portable thermo-hygroanemometer. They were maintained at 60 ± 2 °C, 80 ± 3 °C, and 100 ± 2 °C and the obtained temperatures in the seed mass were 50 ± 3 °C, 60 ± 5 °C, and 70 ± 5 °C, respectively. Thus, average differences of 10, 20, and 30 °C were observed between the temperature of the drying air and that of the seed mass for the treatments of 60, 80, and 100 °C, respectively.

Under the natural method, temperatures changed by 29 and 37 °C in air, while they changed by 40 ± 4 °C and 30 ± 3 °C for the seed mass under open sun and shade drying, respectively.

The lower the drying air temperature, the greater its amplitude (variation between maximum and minimum). Thus, for drying air temperatures, the range was 4, 6, 4, 12 and 14 °C for artificial drying at 100, 80 and 60 °C and for natural drying methods, in full sun and drying in the shade, in order, and for the seed mass temperatures, the differences between the maximum and minimum temperatures were 11, 10, 5, 7 and 7 °C.

This difference is mainly because during the initiation of drying, the temperature was low and gradually increased. Therefore, under the artificial method, the drying air temperature control was greater; however, a low temperature in the seed mass was maintained. This was possible owing to the shorter exposure time of the seeds in the drying chamber and frequent readings of water loss.

Under the natural method, the temperature of the seed mass tended to equilibrium, having an amplitude lower than that of the surrounding environment (Silva, 2008). The temperature in the case of shade drying in air involved an amplitude greater than that of the seed mass, although, on average, the values were equal.

The average relative humidity of the drying air was 20.3, 22.8, 33.4, 66.6, and 70.2% for artificial drying, 100, 80, and 60 °C, and for natural drying, open sun and shade, treatments, respectively.

During open sun drying, the insolation was 6.5 h day^{-1} (INMET, 2020), with cloudy periods of approximately 1 hour. The insolation effect increased the air mass temperature with respect to the drying temperature. Another important factor was the high relative air humidity that influenced the natural method and increased the drying time.

The average air flow speed was 0.7 m s^{-1} for the artificial method. In the natural method, it was 1.1 m s^{-1} for open sun and 0 for shade drying.

The objective of the drying test was to partially remove the water from the *A. cruentus* 'BRS Alegria' seeds. Under different temperatures and methods, water concentration (%) as a function of the drying time (h) was considered, and the drying test was performed. The results are shown in Figure 1.

Under the artificial method, the drying times required for the amaranth water concentration to reduce from 21.1% to

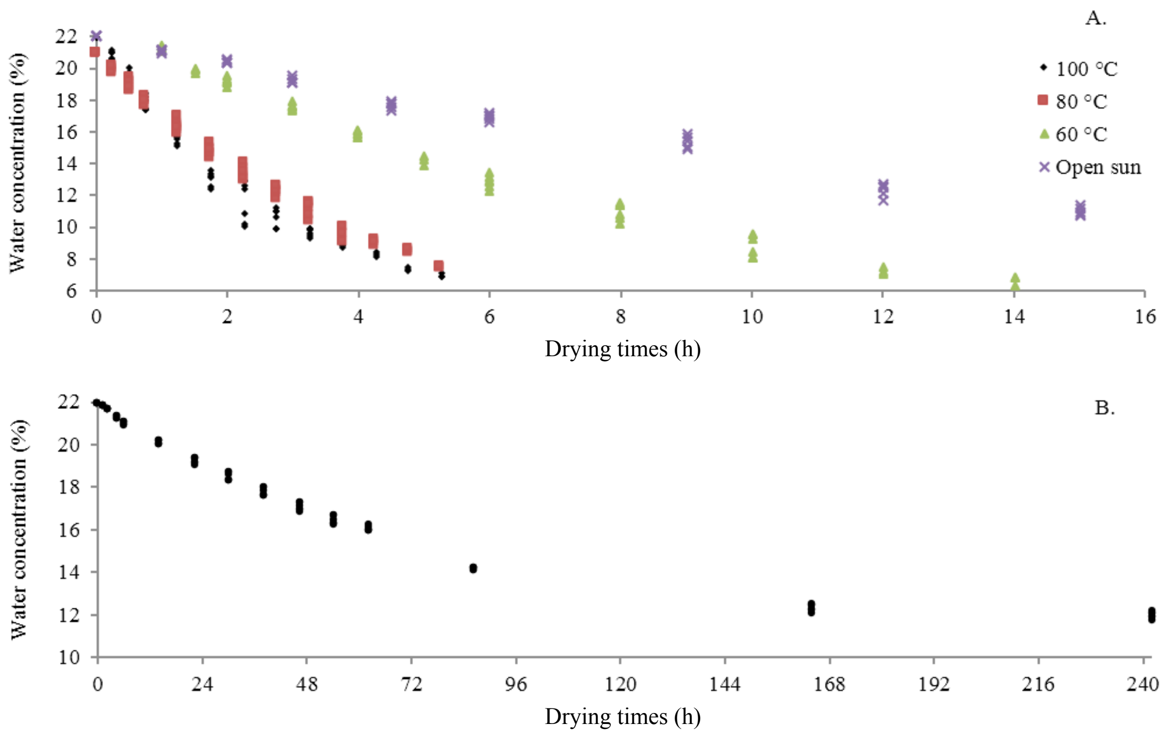


Figure 1. Drying curves of *Amaranthus cruentus* 'BRS Alegria' for temperatures of 100, 80 and 60 °C, under open sun (A) and shade drying treatments (B)

11.5% were 2.5, 3.5, and 7 hours; for reduction to 8.5%, the times required were 4.25, 4.75, and 10.0 hours at temperatures of 100, 80, and 60 °C, respectively (Figure 1A).

Under the natural method, for open sun drying, the corrected time required was 15 hours for water concentration reduction from 21.1% to 11.5% (Figure 1A).

For shade drying, the time required for reduction of the water concentrations from 22% to 13% was 164 hours when the equilibrium moisture was attained according to the relative air humidity. This was confirmed by the reading of 242 hours under moisture maintained at 12.3% (Figure 1B).

The natural method involved a greater amount of time for drying amaranth seeds and was influenced by the higher relative air humidity. This effect was more intense for shade drying, in which case the desired moisture of 11.5% was not attained even under prolonged time.

However, the desired value of water concentration suitable for storage of amaranthus seeds (13%) can be attained in the case of family farming or small-scale production in shade drying; the desired level could also be obtained with natural drying, whereby low investments and costs were required (Silva, 2008).

The artificial drying time was higher than that reported by Abalone et al. (2006) to dry *A. cruentus* seeds in 30-60% relative air humidity condition; for an air temperature of 60 ºC, it was a duration of 30 min, and 1.5 hours, to 30 °C. The initial water concentrations of 13, 17, 20 and 24% were used until equilibrium moisture (6-7%).

Ronoh et al. (2009) dried the *A. cruentus* seeds using solar energy (22.6-30.4 °C and 25-52% of relative air humidity); the drying time required was 3.5 h to reduce water concentration from 39% to the equilibrium moisture, i.e., approximately 9%. The study observed similar equilibrium moistures for drying using solar energy with longer drying times.

However, the study found that the drying time under open sun was shorter than that in the solar dryer (33.6 °C and 51.1% of relative air humidity) for andiroba seeds. The species *Carapa surinamensis* required 14 days for moisture reduction from 30.5% to 12.3% while *C. guianensis* required 20 days for moisture reduction from 30.5% to 13.9% (Mendonça et al., 2015).

The crambe (*Crambe abyssinica*) seeds were dried in an oven; the required dehydration times were 20.5, 8.5, 5.0, 5.0 and 2.75 h for temperatures of 30, 40, 50, 60 and 70 °C, respectively (Costa et al., 2011), which were approximately equal to the drying times required under the artificial method in this study.

Despite demonstrating a higher lipid concentration (38%), *Crambe abyssinica* seeds show diameters similar to those of the amaranth seeds, i.e., 0.8-2.6 mm (Desai et al., 1997). However, the drying time is function of the temperature in the chamber and the water concentration of the seeds, also size of the seeds and layer used in the dryer.

Thus, for comparison between the same species and different species, further information is required. Data on seed mass thickness of *Amaranthus cruentus* were not found in the literature.

The interaction between time and temperature is closely related to the drying process. This was further verified by Abalone et al. (2006) and Ronoh et al. (2009) for amaranth seeds. All curves for each criterion represented characteristic curves with similar water concentrations, varying widely with absolute temperature values. Therefore, the highest temperature resulted in the shortest drying time.

The increase in temperature decreased water concentration in a shorter time for several species, such as andiroba (Mendonça et al., 2015), soybeans (Coradi et al., 2016), peanut (Goneli et al., 2017), and sunflower (Smaniotto et al., 2017) seeds.

With the continuous drying process, through a decrease in the water concentration, the behavior of the curves was similar, differing only in terms of time and rate of drying. The curves were well defined without fluctuations in the points, indicating a condition of homogeneity in the dryer; an outlier was observed only for drying under open sun owing to the interruption in the process.

The loss of water was faster at the beginning of the drying process, corresponding to a slightly linear region. However, a polynomial trend was observed for all the temperatures considered for the study. Santos et al. (2013) further reported polynomial behavior in the drying kinetics of annatto seed flour.

Table 2 shows the coefficients of the mathematical models of the drying kinetics of *A. cruentus* 'BRS Alegria' seeds with the corresponding statistical indices.

The coefficients of determination (R^2) values were greater than 0.98, indicating a satisfactory representation of the drying process, except for the two-term exponential model (Eq. 4) for the highest temperature (100 °C), and modified Page (Eq. 13) for the natural method. Furthermore, evaluating R^2 in isolation is not an appropriate criterion for the selection of non-linear models, and therefore it is necessary to evaluate other essential indices.

Considering that the ability of a model to accurately describe a physical process is inversely proportional to the SE value, the Midilli (Eq. 9) and modified Midilli (Eq. 10) models had the lowest SE values for all conditions and the one that best fitted the data (Table 2).

Through analysis of the values of the relative mean error (P), the equations used were adjusted accordingly, as they present low deviations, except for the modified Page model (Eq. 13), for 60 °C owing to the relative average error being greater than 10% (Mohapatra & Rao, 2005).

The modified Page model was not suitable for the natural method possibly owing to the trend of the model wherein an expected sharp drop did not occur at the beginning of the drying process. It was also observed that the c parameter could not be calculated following the same principle.

Considering the high values of the R^2 and minimum values for SE, the best models could be chosen using the lowest magnitudes for relative mean error, which was then used to select the most appropriate model. The Midilli and modified Midilli models demonstrated the least errors for the artificial and natural methods at all the temperatures considered for the study.

In addition, for the distribution of residues, the two models showed a random distribution when adjusted to the drying data at 80 and 60 °C, indicating better adjustments.

The values of similar statistical parameters for the Midilli and modified Midilli models are owing to parameter a, which is very close to 1.0, whereby identical results of the two equations are obtained. Therefore, the modified Midilli model was used, as shown in Figure 2, as it is simpler with fewer parameters.

Several researchers have reported that the Midilli model demonstrated a good fit with the experimental data for drying

Table 2. Adjustment of non-linear regression models to drying kinetics data of *Amaranthus cruentus* 'BRS Alegria' and their corresponding statistical indices for temperatures of 100, 80 and 60 °C, for open sun and shade drying treatments

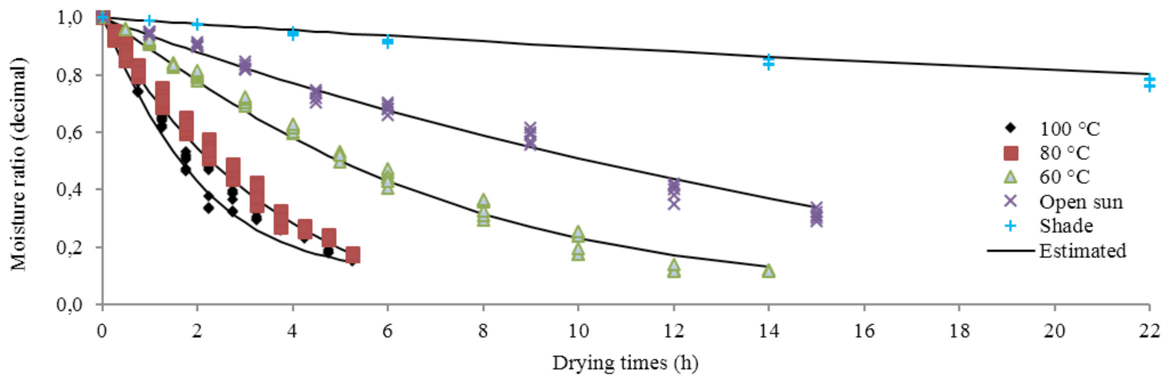
Equation	a	b	c	k	k_0	k_1	R^2	SE	P	Residual
100 °C										
(3)	1.00	1.00	-	0.41	-	-	0.99	0.02	5.84	T
(4)	0.98	0.03	-	-	0.46	-0.09	0.99	0.02	3.89	T
(5)	1.00	-	-	1.00	-	-	0.43	0.22	61.69	T
(6)	1.00	-	-	0.41	-	-	0.99	0.02	6.00	T
(7)	10.04	-24.98	15.96	0.22	0.26	0.29	0.99	0.02	3.94	T
(8)	0.95	0.06	-	0.48	-	-	0.99	0.02	3.84	T
(9)	1.01	0.01	1.05	0.44	-	-	0.99	0.02	4.09	T
(10)	-	0.01	1.07	0.44	-	-	0.99	0.02	4.12	T
(11)	-	-	-	0.42	-	-	0.99	0.02	5.84	T
(12)	-	-	0.97	0.42	-	-	0.99	0.02	5.01	T
(13)	-	-	0.97	0.41	-	-	0.99	0.02	6.26	T
(14)	-8.32	1.91	-	-	-	-	0.99	0.02	4.09	T
(15)	0.01	-	-	-0.35	-	0.43	0.99	0.02	3.87	T
(16)	-0.35	-	-	0.04	-	-	0.99	0.03	7.38	T
80 °C										
(3)	1.00	1.00	-	0.31	-	-	0.99	0.03	3.92	T
(4)	0.42	0.58	-	-	0.31	0.31	0.99	0.02	3.88	T
(5)	1.46	-	-	0.36	-	-	0.99	0.02	3.51	A
(6)	1.01	-	-	0.31	-	-	0.99	0.02	3.88	T
(7)	0.32	0.36	0.32	0.31	0.31	0.31	0.99	0.02	3.88	T
(8)	1.07	-0.07	-	0.27	-	-	0.99	0.02	3.35	A
(9)	1.00	-0.01	0.98	0.28	-	-	0.99	0.02	3.32	A
(10)	-	-0.01	0.98	0.28	-	-	0.99	0.02	3.32	A
(11)	-	-	-	0.31	-	-	0.99	0.02	3.92	T
(12)	-	-	1.03	0.29	-	-	0.99	0.02	3.59	A
(13)	-	-	1.03	0.31	-	-	0.99	0.02	5.08	A
(14)	-1020.31	17.78	-	-	-	-	0.99	0.02	3.92	T
(15)	5.41	-	-	0.41	-	0.43	0.99	0.02	3.50	A
(16)	-0.27	-	-	0.02	-	-	0.99	0.02	4.03	T
60 °C										
(3)	1.00	1.00	-	0.14	-	-	0.99	0.02	4.88	T
(4)	0.51	0.51	-	-	0.15	0.15	0.99	0.01	4.09	A
(5)	1.53	-	-	0.17	-	-	0.99	0.01	3.28	A
(6)	1.02	-	-	0.15	-	-	0.99	0.01	4.09	T
(7)	7.92	8.56	-15.48	0.19	0.19	0.19	0.99	0.01	3.35	A
(8)	1.03	-0.01	-	0.14	-	-	0.99	0.01	3.96	A
(9)	1.00	0.01	1.11	0.12	-	-	0.99	0.01	3.12	A
(10)	-	0.01	1.12	0.12	-	-	0.99	0.01	3.09	A
(11)	-	-	-	0.14	-	-	0.99	0.02	4.88	T
(12)	-	-	1.07	0.12	-	-	0.99	0.01	3.25	A
(13)	-	-	1.07	0.14	-	-	0.99	0.01	10.94	A
(14)	-1534.10	14.72	-	-	-	-	0.99	0.02	4.88	A
(15)	1.06	-	-	0.15	-	1.25	0.99	0.01	3.39	A
(16)	-0.11	-	-	0.00	-	-	0.99	0.02	5.75	T
Open sun										
(3)	1.00	1.00	-	0.07	-	-	0.98	0.02	3.22	T
(4)	0.51	0.49	-	-	0.07	0.07	0.98	0.02	3.16	T
(5)	1.56	-	-	0.09	-	-	0.98	0.02	2.75	T
(6)	1.01	-	-	0.07	-	-	0.98	0.02	3.16	T
(7)	0.34	0.34	0.34	0.07	0.07	0.07	0.98	0.02	3.16	T
(8)	1.26	-0.25	-	0.05	-	-	0.99	0.02	2.67	T
(9)	1.00	-0.01	0.94	0.06	-	-	0.99	0.02	2.71	T
(10)	-	-0.01	0.96	0.06	-	-	0.99	0.02	2.68	T
(11)	-	-	-	0.07	-	-	0.98	0.02	3.22	T
(12)	-	-	1.06	0.06	-	-	0.98	0.02	2.80	T
(13)	-	-	0.00	0.43	-	-	0.00	0.35	7.80	T
(14)	-1047.54	8.45	-	-	-	-	0.98	0.02	3.22	T
(15)	5.55	-	-	0.10	-	0.11	0.98	0.02	2.72	T
(16)	-0.06	-	-	0.00	-	-	0.99	0.02	2.66	T

Continues on the next page

Continuation of Table 2

Equation	a	b	c	k	k_0	k_1	R^2	SE	P	Residual
					Shade					
(3)	1.00	1.00	-	0.01	-	-	0.98	0.01	0.73	T
(4)	0.97	0.03	-	-	0.01	0.18	0.99	0.01	0.55	T
(5)	0.08	-	-	0.08	-	-	0.99	0.01	0.53	T
(6)	0.99	-	-	0.01	-	-	0.98	0.01	0.78	T
(7)	0.44	0.52	0.03	0.01	0.01	0.18	0.99	0.01	0.55	T
(8)	0.40	0.59	-	0.02	-	-	0.99	0.01	0.56	T
(9)	1.00	0.01	0.88	0.01	-	-	0.99	0.01	0.57	T
(10)	-	-0.01	1.27	-0.00	-	-	0.99	0.01	0.56	T
(11)	-	-	-	0.01	-	-	0.98	0.01	0.73	T
(12)	-	-	0.86	0.01	-	-	0.99	0.01	0.58	T
(13)	-	-	0.00	0.50	-	-	0.00	0.52	6.63	T
(14)	-3.41	0.19	-	-	-	-	0.99	0.01	0.54	T
(15)	0.04	-	-	0.14	-	0.01	0.99	0.01	0.55	T
(16)	-0.01	-	-	0.00	-	-	0.99	0.01	0.57	T

*a, b, and c - drying coefficients (dimensionless), k, k_0 and k_1 - drying parameters (h^{-1}), R^2 - coefficient of determination, SE - standard deviation of the estimate, P - relative mean error, and residual distribution trend (A - random; T - tendentious)



Note: For comparison, drying time was used up to 22 h for shade drying treatment

Figure 2. Moisture ratio of *Amaranthus cruentus* 'BRS Alegria' seeds, observed and estimated by the Modified Midilli model at temperatures of 100, 80 and 60 °C, for open sun and shade drying treatments

andiroba seeds using solar dryer (Mendonça et al., 2015), peanut seeds under drying temperatures of 40, 50, 60, and 70 °C (Goneli et al., 2017), and cowpea at temperatures of 45 °C and 55 °C (Morais et al., 2013).

For *A. cruentus* seeds under other drying conditions, the Page model was the most suitable for artificial (Abalone et al., 2006) and natural (Ronoh et al., 2009) drying methods.

Regarding the k parameter, it is possible to perceive, in general, that values are lower with decrease in the drying temperature. This is because the increase in drying temperatures decreases the relative humidity, which leads to an increase in the drying rate, which is represented by "k", reaching the equilibrium moisture in the shortest time. The same occurs with k_0 and k_1.

Thus, the drying kinetics of amaranth occurred during the period of decreasing rate and was strongly influenced by temperature. Thus, for the same time, the higher was the temperature, the higher was the rate or speed of drying of the *A. cruentus* 'BRS Alegria' seeds.

The opposite behavior was verified by Santos et al. (2013) that, when adjusting the Page and Midilli models to the data of annatto flour drying, observed a decrease in the value of "k" with the increase in temperature.

For the parameter k, similar linearity was observed in the modified Henderson and Pabis models (Eq. 7); similar behaviors were observed for the parameters a, b, and c, except for 100 °C. This was further observed in the natural method, where these parameters are identical. This is because the behavior of the sun drying kinetics was similar to the first-degree polynomial function.

Furthermore, the a and b parameters of the diffusion approximation model (Eq. 3) transforms the equation as that of the Newton model (Eq. 11); therefore, the two models obtained equal values of k.

As they are empirical in nature, these equations can only be used to predict drying data with the conditions of temperatures and speeds of the drying air considered in this study.

Conclusions

1. The average temperatures of the seed mass were 30, 40, 50, 60, and 70 °C for the natural drying, shade and open sun methods, and artificial drying at temperatures of 60, 80, and 100 °C.

2. The drying kinetics of *Amaranthus cruentus* 'BRS Alegria' seeds occurs during the drying period at a decreasing rate.

3. The modified Midilli model equation is the most appropriate model for describing the drying kinetics of *A. cruentus* 'BRS Alegria' seeds.

4. For the artificial methods, the time required to reduce the water concentration from 21.1% to 11.5% was 2.5, 3.5, and 7 h, and for up to 8.5%, it was 4.25, 4.75, and 10 h for 100, 80, and 60 °C air temperatures, respectively in artificial drying method.

5. For the natural methods, under open sun, the drying time was 15 hours. The shade drying time was 164 hours until the water concentration was 13%, which was the equilibrium moisture.

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