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Original Article

Drying kinetics and physiological quality of *Solanum aethiopicum* seeds[1]

Cinética de secagem e qualidade fisiológica de sementes de jiló

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HIGHLIGHTS:
The Modified Midilli model can be used to estimate the drying curves of S. aethiopicum *seeds.*
S. aethiopicum *seeds dried at 35 and 38 °C show higher germination and vigor.*
Drying at 41 and 44 °C impairs the physiological quality of S. aethiopicum seeds.

ABSTRACT: The drying process is paramount for maintaining seed quality, where the temperature during this process directly influences germination and vigor, especially for vegetable species harvested with high moisture content. This research aimed to determine and model the drying curves of *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds at temperatures of 35, 38, 41, and 44 °C, as well as to evaluate the physiological quality of the seeds after drying. A completely randomized design was used, with four drying temperatures (35, 38, 41, and 44 °C) and four replicates. Nine mathematical models were fitted using the non-linear regression analysis by the Gauss-Newton method, and the goodness of fit was assessed based on the magnitude of the coefficient of determination (R^2), chi-square test (χ^2), relative mean error (P), and estimated mean error (SE). Seed quality was evaluated by germination test (G), electrical conductivity (EC), and accelerated aging (AA). The Modified Midilli model best represents the drying curves of *S. aethiopicum* seeds at the studied temperatures. Seeds with higher germination and vigor, meaning lower electrical conductivity values and higher germination rates after accelerated aging, are achieved through drying at 35 and 38 °C.

Key words: mathematical modeling, germination, vigor

RESUMO: O processo de secagem é de suma importância para a manutenção da qualidade das sementes, onde a temperatura de condução deste processo exerce influência direta sobre a germinação e vigor, sobretudo para as espécies olerícolas que são colhidas com alto teor de água. O objetivo desta pesquisa foi determinar e modelar as curvas de secagem de sementes de jiló (cultivar Tinguá-verde-claro) nas temperaturas de 35, 38, 41 e 44 °C, bem como avaliar a qualidade fisiológica das sementes após a secagem. Foi utilizado o delineamento inteiramente casualizado, sendo quatro temperaturas de secagem (35, 38, 41 e 44 °C) com quatro repetições. Nove modelos matemáticos foram ajustados por meio de análise de regressão não linear pelo método de Gauss-Newton, e o grau de ajuste foi avaliado com base na magnitude do coeficiente de determinação (R^2), teste qui-quadrado (χ^2), erro médio relativo (P) e erro médio estimado (SE). A qualidade das sementes foi avaliada pelo teste de germinação (G), condutividade elétrica (CE) e envelhecimento acelerado (EA). O modelo 'Midilli Modificado' é o que melhor representa as curvas de secagem das sementes de jiló nas temperaturas estudadas. Sementes com maior germinação e vigor, ou seja, com menores valores de CE e maiores taxas de germinação após EA, são alcançadas através da secagem a 35 e 38 °C.

Palavras-chave: modelagem matemática, germinação, vigor

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Introduction

Solanum aethiopicum, a member of the Solanaceae family, produces initially green fruits that ripen into an orange-red hue (Santos et al., 2020). In Brazil, its cultivation is predominantly concentrated in the southeastern states, with Rio de Janeiro notably leading as the primary producer, contributing 32% to the national yield (Pinheiro et al., 2015). Its fruits are nutrient-rich, including various vitamins (A, B, and C), minerals, and flavonoids (Alcântara & Porto, 2019).

Seeds of fleshy fruits, such as those of *S. aethiopicum*, exhibit high moisture levels, exceeding 40% post-physiological maturity, making them prone to deterioration, thus reducing their quality (Guragain et al., 2023). Hence, the drying process is pivotal for preserving seed quality, eliminating excess free water, curbing biological activity, and ensuring germination viability. Improper drying induces adverse physiological effects in seeds, including alterations in enzymatic activity, protein denaturation, and cellular damage, impairing germination (Rosa et al., 2023). This study hypothesizes that drying at high temperatures may reduce the physiological quality of *S. aethiopicum* seeds.

Silva et al. (2018) found that 'Cabacinha' pepper seeds dried at 35 and 38 °C exhibited higher germination and vigor, but drying at 42 °C reduced seed quality. Similar results were found for tomato seeds (Gomes et al., 2023). However, there are no studies on the ideal drying temperatures for *S. aethiopicum* seeds. Furthermore, studies related to mathematical modeling and kinetics of seed drying are highlighted to optimize drying processes, reduce costs, and enhance dryer design (Alves et al., 2022; Arsenoaia et al., 2023).

Therefore, this research aimed to determine and model the drying curves of *S. aethiopicum (*cultivar Tinguá-verde-claro) seeds at temperatures of 35, 38, 41, and 44 °C, as well as to evaluate the physiological quality of the seeds after drying.

Material and Methods

The study was conducted at the Seed Analysis Laboratory (LAS) of the Universidade Federal de Viçosa, located in Viçosa, Minas Gerais state, Brazil (20° 44' 35" S and 42° 52' 33" W), between March and July of 2023. The fruits of *S. aethiopicum,* cultivar Tinguá Verde-Claro, were harvested at full maturity (completely red), and their seeds were manually extracted. It is worth mentioning that, before extraction, the fruits were left to rest for seven days under laboratory conditions to standardize the ripening stage and facilitate seed extraction.

Following extraction, the seeds underwent natural pre-drying under laboratory conditions (mean values = 25.8 °C temperature and 68.8% relative air humidity) for 48 hours, reaching a moisture content of approximately 29% (wet basis). It should be emphasized that the moisture content was monitored using gravimetry and compared with the oven method at 105 °C for 24 hours (BRASIL, 2009).

Subsequently, the seeds were dried in a forced circulation oven at 35, 38, 41, and 44 °C. The seeds were dried until the appropriate moisture content (7% kg^{-1} of dry weight) for storage of vegetable seeds in airtight containers, as recommended by Melo et al. (2014). For this purpose, three replications of approximately 5 g of seeds were arranged in metal trays (7.30 × 2.00 cm) in a single layer. The moisture content of the seeds was monitored using gravimetry, weighing the seeds periodically on an analytical balance (precision of 0.0001 g).

The calculation of the moisture content ratio (RX) during the drying processes was performed using Eq. 1:

$$RX = \frac{X - Xe}{Xi - Xe} \quad (1)$$

Where:

RX - moisture content ratio, dimensionless;

X - seed moisture content, kg water kg^{-1} dry mass;

Xe - equilibrium moisture content of seeds, kg water kg^{-1} dry mass; and,

Xi - initial seed moisture content, kg water kg^{-1} dry mass.

The Modified Oswin model (Eq. 2) was used to calculate the equilibrium moisture content of the seeds under each drying condition, whose values were 6.73, 5.82, 4.77, and 4.00%, respectively, for temperatures of 35, 38, 41, and 44 °C and relative air humidity of 29.4, 26.7, 21.4, and 19.2%. This model was recommended by Santos et al. (2020) to estimate the hygroscopic equilibrium curves of *S. aethiopicum* seeds.

$$Xe = \frac{(18.7511^{**} - 0.2931^{**}T)}{\left[a_w (1 - a_w)\right]^{1/3.7745^{**}}} \quad (2)$$

Where:

Xe - equilibrium moisture content, % dry basis (d.b.);

a_w - water activity, decimal; and,

T - temperature, °C.

Nine mathematical models were fitted to the experimental moisture content ratio data (Silva et al., 2018; Oliveira et al., 2021), represented in Table 1.

The criteria initially used to assess the fitting quality of the models were the coefficient of determination (R^2), estimated mean error (SE), relative mean error (P), and the chi-square test (χ^2). The SE, P, and χ^2 values were calculated using Eqs. 12, 13, and 14, respectively.

Table 1. Non-linear regression models used to estimate the drying phenomenon of *S. aethiopicum* seeds

Model designation	Model	Eq.
Approximation of Diffusion	$RX = a \exp(-k\,t) + (1 - a) \exp(-k\,b\,t)$	(3)
Two Terms	$RX = a \exp(-k\,t) + b \exp(-c\,t)$	(4)
Two Terms Exponential	$RX = a \exp(-k\,t) + (1-a) \exp(-k\,a\,t)$	(5)
Henderson and Pabis	$RX = a \exp(-k t)$	(6)
Logarithmic	$RX = a \exp(-k\,t) + b$	(7)
Midilli	$RX = a \exp(-k\,t^n) + b\,t$	(8)
Modified Midilli	$RX = \exp(-k\,t^n) + a\,t$	(9)
Newton	$RX = \exp(-k\,t)$	(10)
Page	$RX = \exp(-k\,t^n)$	(11)

RX - Seed moisture content ratio (dimensionless); t - Drying time (h); k - Drying coefficient; a, b, c, and n - Model parameters.

$$SE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y - \hat{Y}\right)^2}{DF}} \quad (12)$$

$$P = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{\left|Y - \hat{Y}\right|}{Y}\right) \quad (13)$$

$$\chi^2 = \sum_{i=1}^{n}\frac{\left(Y - \hat{Y}\right)^2}{DF} \quad (14)$$

Where:

n - number of experimental observations;

Y - experimental moisture content ratio;

$\hat{Y}$ - predicted moisture content ratio;

DF - degrees of freedom of the model.

Additional criteria were employed to select a single model that more accurately describes the drying process of *S. aethiopicum* seeds. For the models that showed the best fit according to the previously listed criteria, the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were calculated using Eqs. 15 and 16, respectively.

$$AIC = -2loglike + 2p \quad (15)$$

$$BIC = -2loglike + 2p\ln(n) \quad (16)$$

Where:

p - number of parameters of the model;

n - total number of observations;

loglike - value of the logarithm of the likelihood function considering the estimates of the parameters.

In choosing the best mathematical model, considerations were made for the R^2 closest to the magnitude, P values below 10%, standard error (SE), and χ^2 values closer to zero, in addition to the lowest values of AIC and BIC.

After drying at each temperature, the seeds were placed in airtight plastic containers and stored in a refrigerator (T = 9.9 °C and RH = 70%) for one day. The following tests were conducted to assess physiological quality:

Germination test: four replications of 50 seeds were placed in germination boxes (gerbox). The seeds were sown on two sheets of seed germination paper moistened with distilled water at 2.5 times the weight of the dry paper. The boxes were placed in a germinator at a constant temperature of 30 °C. Evaluations were conducted at 6 (first count) and 14 days (last count) after the test was set up, considering the normal seedlings and the results expressed in % (BRASIL, 2009).

Electrical conductivity test: four replications of 50 intact seeds were weighed on a precision scale. The seeds were placed in disposable cups with 25 mL of distilled water. The cups with the seeds and water were placed in a germination chamber (B.O.D.) at 25 °C for 24 hours. Subsequently, the electrical conductivity of the seed-soaking solution was measured using a conductivity meter, and the results were expressed in $\mu S\ cm^{-1}\ g^{-1}$ (Vieira & Krzyzanowski, 1999).

Accelerated aging: four replications of 3 g of seeds were used for each treatment. The seeds were laid out in a single layer and distributed over a plastic screen fixed inside a germination box containing 40 mL of sodium chloride (NaCl) solution at the bottom (40 g NaCl 100 mL^{-1} of water). The covered boxes were placed in a B.O.D. chamber at 41 °C for 48 hours (Alves et al., 2012). After this period, the seeds were allowed to germinate according to the methodology described for the germination test, and the number of normal seedlings was assessed six days after the test was set up, with the results expressed in percentage (%).

The design used was completely randomized, with four treatments and four replicates. The data was assessed for normality and homogeneity of residuals using the Kolmogorov-Smirnov and Layard tests, respectively. The data was then subjected to analysis of variance using the F-test at $p \leq 0.01$. Variables with significant differences (p-value ≤ 0.01) were subjected to regression analysis. The models were selected based on the significance of the equation (t-test, p-value ≤ 0.01), the coefficient of determination (R^2), and knowledge of the evolution of the biological phenomenon. The statistical analyses were performed using the R® software.

Results and Discussion

After pre-drying, the moisture content of *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds was approximately 29% (Figure 1). The drying time required to reduce the moisture content to approximately 7% was 0.75, 0.66, 0.50, and 0.33 hours (45, 40, 30, and 20 min) at 35, 38, 41, and 44 °C, respectively. It can be seen that the drying time of *S. aethiopicum* seeds decreases with increasing air temperature due to the increase in the pressure gradient between the inside of the seed and the surrounding air. Similar results were found for pepper seeds (*Capsicum* spp) (Reis et al., 2015; Silva et al., 2018).

It is important, furthermore, to highlight that reducing drying time is crucial to preserving seed quality. The faster the

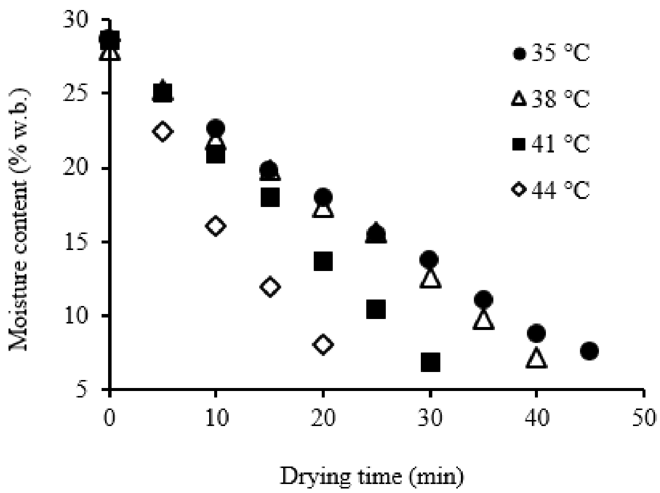


Figure 1. Moisture content during drying of *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds at different temperatures

seeds are dried, the shorter the exposure time to unfavorable conditions, such as the proliferation of microorganisms and the risk of fermentation. However, it is important to emphasize that high temperatures of the drying air can compromise the physiological quality of the seeds, as they may cause damage to membrane systems and protein denaturation (Rosa et al., 2023).

Table 2 shows the models used to predict the drying process of *S. aethiopicum* seeds. Among the various models, Logarithm, Midilli, and Modified Midilli showed a coefficient of determination (R^2) higher than 0.993 for all temperatures, which was not the case for the other models studied. According to Karizaki (2016), higher R^2 values indicate that the model had a better fit to the experimental data. However, it is worth highlighting that using this parameter alone is insufficient for the selection of non-linear models (Corrêa Filho et al., 2015). For this reason, the relative mean error (P), the estimated mean error (SE), and the chi-squared test (χ^2) were considered.

For a model to adequately represent any phenomenon, it must have a relative mean error lower than 10% (Piekutowska et al., 2021), a chi-squared test, and an estimated mean error as close to zero as possible (Silva et al., 2022). As a result, the Logarithm, Midilli, and Modified Midilli models exhibited low standard error (SE) and χ^2 values, with P-values below 10%, regardless of the temperature studied, and are recommended for representing the drying of *S. aethiopicum* seeds (Table 2). However, the Bayesian Information Criterion (BIC) and the Akaike Information Criterion (AIC) were utilized to select a single model.

The values obtained for BIC and AIC for the Logarithm, Midilli, and Modified Midilli models are described in Table 3. Lower values for these criteria indicate a better fit of the model

Table 3. Akaike Information Criterion (AIC) and Schwartz Bayesian Information Criterion (BIC) values for the Logarithm, Midilli, and Modified Midilli models adjusted to the drying curves of *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds at different temperatures

Model	Temperature (°C)	AIC	BIC
Midilli	35	-6.0803	-5.9592
	38	-5.5268	-5.4391
	41	-4.2550	-4.2859
	44	-6.6175	-6.9299
Modified Midilli	35	-6.0812	-5.9601
	38	-5.5296	-5.4420
	41	-7.0770	-7.1079
	44	-6,6189	-6.9314
Logarithmic	35	-5.3272	-5.2062
	38	-5.0801	-4.9924
	41	-6.3165	-6.3475
	44	-6.0159	-6.3284

Table 2. Coefficients of determination (R^2), relative mean error (P, %), estimated mean error (SE, decimal), and chi-squared test (χ^2, decimal) for the models fitted to the experimental data for drying *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds

Mathematical model	Temperature (°C)	(R^2)	SE	χ^2	P
Approximation of Diffusion	35	0.980	0.119	0.0142	30.811
	38	0.998	0.029	0.0009	3.535
	41	0.998	0.020	0.0004	2.075
	44	0.999	0.017	0.0003	1.673
Two Terms	35	0.998	0.039	0.0016	6.953
	38	0.975	0.115	0.0133	25.693
	41	0.978	0.104	0.0109	22.987
	44	0.999	0.016	0.0003	2.865
Two-Terms Exponential	35	0.987	0.089	0.0081	23.564
	38	0.983	0.097	0.0095	20.870
	41	0.992	0.061	0.0037	10.101
	44	0.999	0.016	0.0003	3.004
Henderson and Pabis	35	0.978	0.129	0.0167	33.512
	38	0.978	0.107	0.0116	15.675
	41	0.969	0.130	0.0171	28.021
	44	0.993	0.049	0.0025	7.519
Logarithmic	35	0.997	0.041	0.0017	4.467
	38	0.996	0.040	0.0016	4.736
	41	0.999	0.020	0.0004	1.777
	44	0.998	0.019	0.0004	1.749
Newton	35	0.977	0.121	0.0147	34.719
	38	0.966	0.139	0.0194	31.170
	41	0.965	0.129	0.0168	29.591
	44	0.992	0.046	0.0021	7.941
Midilli	35	0.998	0.030	0.0009	6.667
	38	0.997	0.032	0.0011	2.821
	41	0.993	0.060	0.0037	8.838
	44	0.999	0.015	0.0002	2.116
Modified Midilli	35	0.998	0.030	0.0009	6.686
	38	0.997	0.031	0.0010	2.796
	41	0.999	0.013	0.0002	1.680
	44	0.999	0.015	0.0002	2.106
Page	35	0.987	0.090	0.0082	21.838
	38	0.984	0.095	0.0092	18.885
	41	0.988	0.072	0.0052	14.572
	44	0.992	0.015	0.0002	7.941

to the drying data (Ferreira Júnior et al., 2020). Therefore, it is observed that the Modified Midilli model showed lower AIC and BIC values, thus being chosen to represent the drying of *S. aethiopicum* seeds. The regression coefficients of the Modified Midilli model adjusted for temperatures of 35, 38, 41, and 44 °C are shown in Eqs. 17, 18, 19, and 20, respectively.

$$RX_{35} = \exp\left(-(1.1879^{**})t^{0.7779^{**}}\right) + (-0.4766^{**})t \quad (17)$$

$$RX_{38} = \exp\left(-(0.6773^{**})t^{0.7213^{**}}\right) + (-0.8101^{**})t \quad (18)$$

$$RX_{41} = \exp\left(-(0.8988^{**})t^{0.7775^{**}}\right) + (-1.047^{**})t \quad (19)$$

$$RX_{44} = \exp\left(-(6.2704^{**})t^{1.1410^{**}}\right) + (-0.0943^{**})t \quad (20)$$

** - Significant at $p \leq 0.01$ by t-test.

Figure 2 shows the drying curves of *S. aethiopicum* seeds at temperatures of 35, 38, 41, and 44 °C, with the values estimated by the Modified Midilli model. It should be noted that the Modified Midilli model has been used to represent the drying of various agricultural products such as *Aztec amaranth* seeds (Costa et al., 2021), corn seeds (Silva et al., 2022), and jackfruit almond (Santos et al., 2021).

Table 4 shows the analysis of variance for the variables relating to the physiological quality of the *S. aethiopicum* (Tinguá-verde-claro) seeds, which were subjected to different drying temperatures. It can be seen that the first germination count, electrical conductivity, and accelerated aging were significantly influenced by the treatments ($p \leq 0.01$). The germination, on the other hand, was not influenced ($p > 0.01$).

The different drying temperatures did not influence germination, with a mean value of 92.93% (Figure 3B). However, for the first germination count, the detrimental effect of the drying temperature of 44 °C on the seeds is noticeable, with an average of 58.0% of normal seedlings (Figure 3A). On the other hand, the drying temperature of 38 °C produced superior results, with an average of 84.0%, followed by 41 and 35 °C, with averages of 75.5 and 70.5%, respectively. It is important to emphasize that the first germination count is a vigor test, based on the germination speed, where more vigorous seeds germinate more quickly and take better advantage of the environmental conditions (Guedes et al., 2015). Therefore, although no difference was observed between treatments in the final germination count, it is evident that drying at 44 °C impairs seed vigor, resulting in slower germination compared to other temperatures.

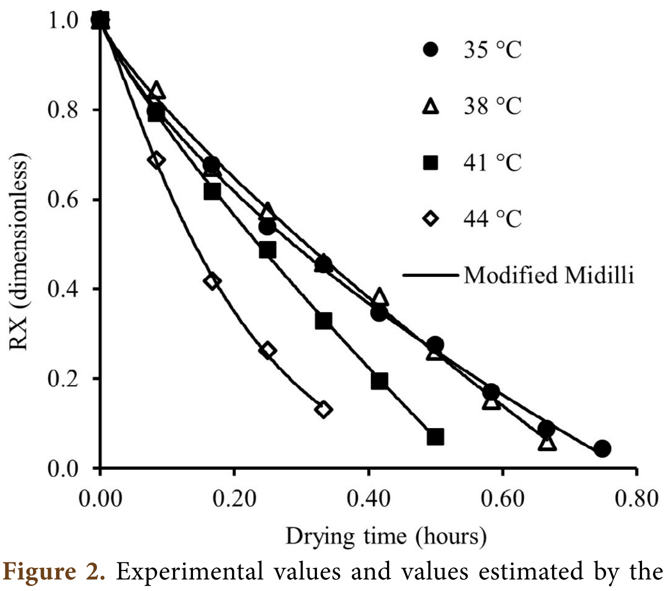
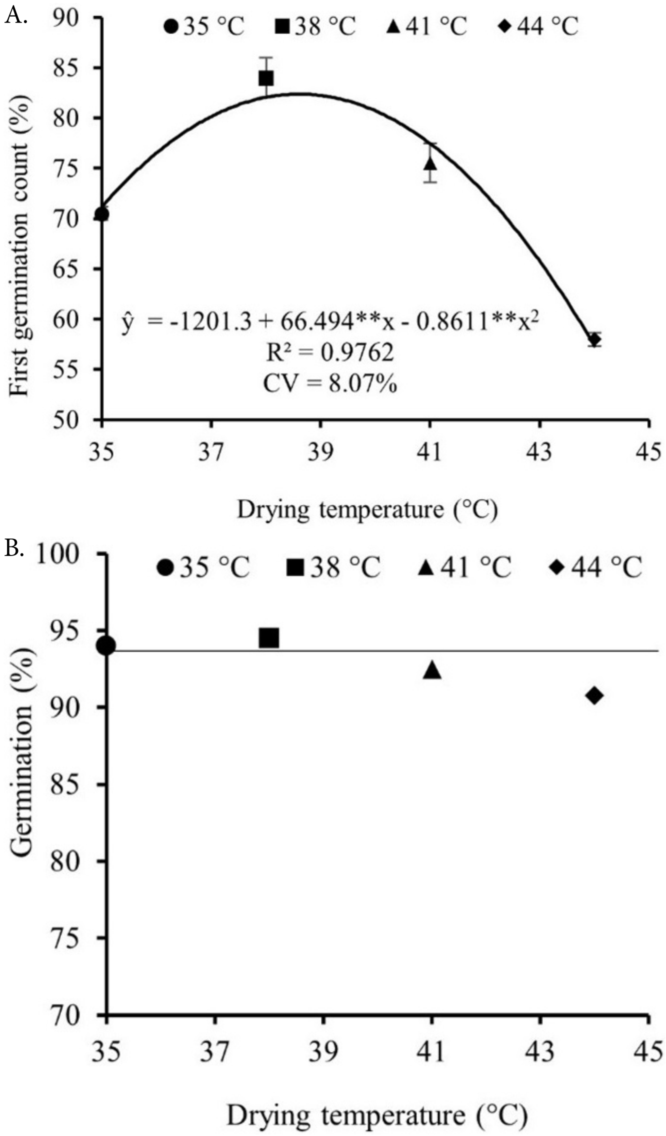


Figure 2. Experimental values and values estimated by the Modified Midilli model for moisture ratio (RX) according to the drying time of *S. aethiopicum* (cultivar Tinguá-verde-claro) seeds

Table 4. Summary of the analysis of variance for the first germination count (FGG), germination (G), electrical conductivity (EC), and accelerated aging (AA) of *S. aethiopicum* (Tinguá-verde-claro) seeds subjected to different drying temperatures

Source of Variation	FGG	G	CE	AA
Drying temperatures	53.83 **	11.896 ns	2.575 **	13.75 **
CV (%)	10.19	3.71	4.15	4.72

** and ns - Significant and not significant at $p \leq 0.01$ by F test, respectively; CV - Coefficient of variation



** - Significant at $p \leq 0.01$ by the t-test. Vertical bars represent the standard deviation of the mean

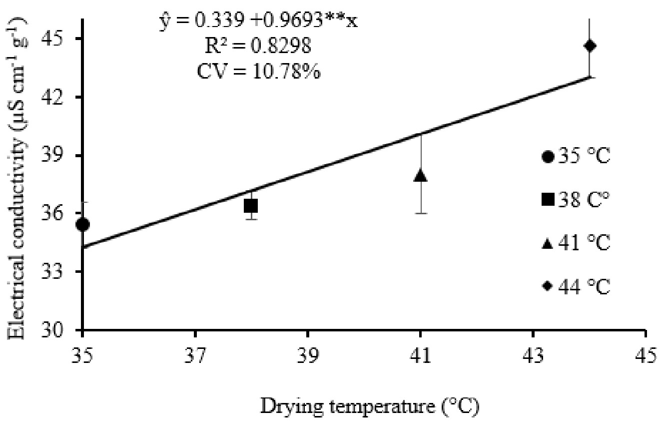
Figure 3. First germination count (A) and germination (B) of 'Tinguá-verde-claro' *S. aethiopicum* seeds as a function of drying temperature

The increase in temperature resulted in a higher electrical conductivity of the solution (Figure 4). Higher electrical conductivity values are associated with a greater release of exudates into the external environment through the cell membrane, indicating that the seeds are more deteriorated and less vigorous (Haesbaert et al., 2017). Therefore, it can be observed that drying at 44 °C had a detrimental effect on the quality of *S. aethiopicum* seeds. This may be associated with the oxidation of cell membranes resulting from the production of free radicals induced by exposure to high temperatures. On the other hand, low electrical conductivity was observed during the drying process at lower temperatures (35 and 38 °C). It is relevant to highlight that slow drying enables a gradual reduction in moisture content and, consequently, the functioning of desiccation tolerance mechanisms, allowing for the obtainment of more vigorous seed lots (Marcos Filho, 2015).

The percentages of normal seedlings for each drying temperature after the accelerated aging test are shown in Figure 5. It can be seen that the increase in temperature led to a reduction in germination, especially at temperatures of 41 and 44 °C, with averages of 76.5 and 71.5%, respectively. On the other hand, drying the seeds at 35 and 38 °C obtained better results (averages of 87 and 79.5%, respectively), corroborating the electrical conductivity test (Figure 4). It is known that the accelerated aging test was introduced to evaluate the storage potential of seeds (Marcos Filho, 2015), and it is, therefore, an excellent method for differentiating seed lots with varying levels of vigor.

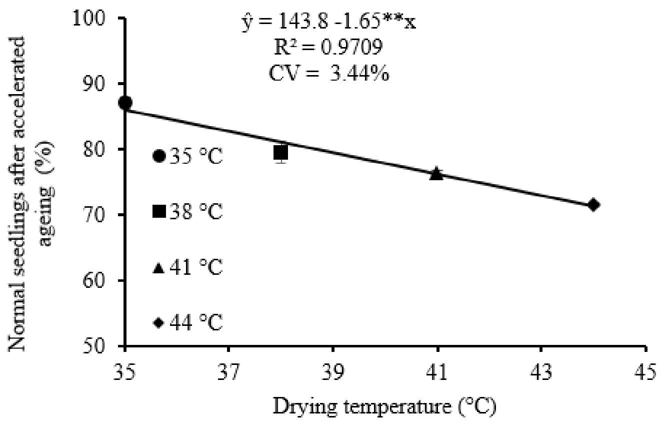
In general, drying vegetable seeds at 35 and 38 °C has produced seed lots with improved physiological quality. Similar outcomes were observed in 'dedo de moça' pepper seeds by Silva et al. (2018), where drying at these temperatures ensured the obtention of high-vigor seeds. These results have also been observed in eggplant seeds (Weber et al., 2013; Zamariola et al., 2014; Çelik & Kenanoğlu, 2023).

Ultimately, it is crucial to conduct additional research exploring different drying methods in vegetables, such as intermittent drying, and to investigate the effects of this process during seed storage, especially concerning *S. aethiopicum*, where there is a notable lack of information on the production and technology of its seeds in the literature.



** - Significant at $p \leq 0.01$ by the t-test. Vertical bars represent the standard deviation of the mean

Figure 4. Electrical conductivity of *S. aethiopicum* (Tinguá-verde-claro) seeds according to the drying temperature



** - Significant at $p \leq 0.01$ by the t-test. Vertical bars represent the standard deviation of the mean

Figure 5. Percentage of normal seedlings after accelerated aging of *S. aethiopicum* (cultivar 'Tinguá-verde-claro) seeds according to the drying temperature

Conclusions

1. The drying process of *S. aethiopicum* (Tinguá-verde-clara) seeds at temperatures of 35, 38, 41, and 44 °C is represented the best by the Modified Midilli model.
2. Drying *S. aethiopicum* seeds at 35 and 38 °C resulted in better physiological quality.

Contribution of authors: S. G. F. dos Santos, D. F. de Paula, and A. M. B. de Souza conducted the experiment, statistical analysis, and manuscript writing. A. P. F. Coelho and I. J. Silva participated in creating the graphs and finalizing the manuscript. L. J. da Silva, D. C. F. S. Dias, and E. F. Araújo were responsible for defining the main objectives of the research and contributed to the revision and final version of the manuscript.

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