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# Mathematical drying kinetics modeling of jackfruit seeds (*Artocarpus heterophyllus* Lam.)[1]

## Modelagem matemática da cinética de secagem das sementes germinadas de jaca (*Artocarpus heterophyllus* Lam.)

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**ABSTRACT -** Jackfruit (*Artocarpus heterophyllus* Lam.) is a fruit with pulp rich in carbohydrates, calcium, phosphorus, iron and B-complex vitamins. A large amount of waste is generated in the pulp processing, in which the seeds are included. Jackfruit seeds are often consumed after cooking, and may also undergo roasting, milling and incorporation into bakery products. The remaining jackfruit seeds can be germinated as a means to increase its utilization, constituting a process that confers positive biochemical modifications to the nutritional quality. Thus, the objective of this work was to dry the germinated seeds of the jackfruit tree in a convective drier at 55, 65 and 75 °C with drying air velocities of 1.0 and 1.3 m $s^{-1}$, and adjusting different mathematical models to the experimental data. The Two-Terms model presented the best adjustment parameters among the ten mathematical models tested, resulting in the most adequate model to represent the drying behavior. The effective diffusivity increased with the increase in temperature, being in the order of $10^{-7}$ $m^2$ $s^{-1}$.

**Key words:** Agricultural waste. Malting. Sustainability. Environment.

**RESUMO -** A jaca (*Artocarpus heterophyllus* Lam.) é uma fruta com polpa rica em carboidratos, cálcio, fósforo, ferro e vitaminas do complexo B. No processamento da polpa é gerada uma grande quantidade de resíduos, onde incluem-se as sementes. Consumidas após cozimento, podem também passar por torra, moagem e incorporação em produtos de panificação. Como meio de incrementar seu aproveitamento, as sementes residuais de jaca podem ser germinadas, processo que confere modificações bioquímicas positivas para a qualidade nutricional. Assim, este trabalho foi realizado com o objetivo de secar as sementes de jaca germinadas em secador convectivo, em temperaturas de 55, 65 e 75 °C com velocidades do ar de secagem de 1,0 e 1,3 m $s^{-1}$, ajustando diferentes modelos matemáticos aos dados experimentais. Dentre os dez modelos matemáticos testados, o de Dois Termos apresentou os melhores parâmetros de ajuste, resultando no mais adequado para representar o comportamento da secagem. Os coeficientes de difusão efetivos aumentaram com o incremento de temperatura, apresentando-se na ordem de $10^{-7}$ $m^2$ $s^{-1}$.

**Palavras-chave**: Resíduos agrícolas. Maltagem. Sustentabilidade. Meio ambiente.

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## INTRODUCTION

Jackfruit (*Artocarpus heterophyllus* Lam.) is a native fruit from India that is rich in nutrients, presenting food and agroindustrial potential due to its peculiar flavor and aromatic characteristics (BALIGA *et al*., 2011). Only the pulp is used in human food during jackfruit processing, while the seed is discarded. However, considering its nutritional value, this waste can be incorporated into food formulations such as cakes, breads, or cookies, providing an increase in nutritional value and promoting cost reduction in the food industry through adding an ingredient which has lower purchasing power.

The use of jackfruit seeds in the food industry can become more attractive through transformations caused by the germination process, in which endogenous enzymes are activated resulting in significant changes in the biochemical and physical properties of the seeds (HAO *et al*., 2016); for example, the reduction in the antinutrient levels in the seeds through enzymatic actions.

The high content of the remaining moisture requires immediate drying after germination in order to avoid rapid deterioration of the product. Drying is an essential process for the grain and by-products industry in order to preserve quality and stability by reducing the water activity obtained by decreasing the moisture content. In this perspective, convective drying is a widely used and suitable technology for by-products, as it is generally used with dehydration of agroindustrial residues (VEGA-GÁLVEZ *et al.*, 2010).

It is of great importance to monitor the physical phenomena that occur during the product dehydration. Drying kinetics studies deserve interest from researchers in the area in the most diverse products, considering the diversity of the biological structures involved in heat and mass transfer, and the effects observed in each product. Information about the conditions with which the product loses humidity is sought after, being an issue which can be solved incorporating widely used mathematical models.

Both moisture transfer from the product interior to the surface and from the surface to the drying air in the form of vapor occurs simultaneously during drying. To determine the effective diffusivity and the convective coefficient of mass transfer, often the solution of the diffusion equation is coupled to an optimizer that, in general, it is based on the inverse method (SILVA; SILVA; LINS, 2011).

Costa *et al.* (2011) and Faria *et al.* (2012) studied the mathematical modeling for drying crambe seeds (*Crambe abyssinica*); Sousa *et al.* (2011), drying kinetics of forage turnip seeds (*Raphanus sativus* L.), among others reported.

In light of the above, this work was carried out with the objective of drying germinated jackfruit seeds in a convective dryer at 55, 65 and 75 °C, with drying air velocities of 1.0 and 1.3 m $s^{-1}$ and to adjust mathematical models to the experimental kinetic drying data.

## MATERIAL AND METHODS

The raw material used were jackfruit seeds (*Artocarpus heterophyllus* Lam.) of the soft variety from the 2016 crop obtained from the local fruit and vegetables trade.

The jackfruits were transported in wooden crates to the laboratory, where the mature specimens without mechanical and/or physical injuries were selected. The seeds were washed in running water and placed in trays to evaporate the surface water for approximately 2 h.

The procedure performed for the germination process was based on Silva *et al*. (2007) with adaptations, under conditions of good laboratory ventilation, in the shade, with natural temperature and relative humidity. The seeds were placed in trays with vermiculite substrate (approximately 700 g) and were irrigated with distilled water every 2 days (using 400 mL for each tray). The radicle was obtained after 15 days of germination with a standard length of 2.5 cm.

The germinated jackfruit seeds were scattered in screened baskets and dried in convective drier by varying the air velocity (1.0 and 1.3 m $s^{-1}$) and the temperature (55, 65 and 75 °C). The drying kinetics were determined by weighing the baskets with the samples at regular intervals of 5, 10, 20, 30, 60 and 120 min until equilibrium was reached, and then the oven dried mass was determined at 105 °C, according to the Adolfo Lutz Institute (INSTITUTO ADOLFO LUTZ, 2008). The moisture ratios of the samples were calculated with the experimental drying kinetics data according to Equation 1:

$$RX = \frac{X - X_e}{X_i - X_e} \quad (1)$$

In which:

$RX$ - moisture ratio of the sample (dimensionless);

$X$ - moisture content of the sample in a given drying time (d.b.);

$X_i$ - initial moisture content of the sample (d.b.);

$X_e$ - equilibrium moisture content of the sample (d.b.).

The results were obtained by using the following equations: (1) the kinetic curves and the Thompson, Lewis, Modified Page, Page, Henderson and Pabis, the Two-Term Exponential, Logarithmic, Diffusion

Approximation, Two-Terms, Midilli, and the Wang and Singh mathematical models (Table 1) were fitted to the experimental data using the non-linear regression analysis by the Quasi-Newton method through the STATISTICA 7.7® computational program.

To evaluate which model produced the best fit, the coefficient of determination ($R^2$), the distribution of the residuals (random - A and biased - B) and the mean squared deviation (MSD) were used as parameters, with the latter according to Equation 13:

$$MSD = \left[\frac{1}{n}\sum_{i=1}^{n}\left(RX_{pred,i} - RX_{\exp,i}\right)^2\right]^{\frac{1}{2}} \quad (13)$$

In which:

*MSD* - mean squared deviation;

$RX_{pred}$ - moisture ratio predicted by the model;

$RX_{exp}$ - experimental moisture ratio;

*n* - number of observations made during the experiment.

The drying rates were then calculated with the moisture content data (d.b.) of the germinated jackfruit seeds at each dehydration time according to Equation 14:

$$DR = X_{t+dt} - X_t/dt \quad (14)$$

In which:

*DR* - drying rate (kg $kg^{-1}$ $min^{-1}$);

$X_{t+dt}$ - moisture content in t + dt (kg water kg dry $matter^{-1}$);

$X_t$ - moisture content at a specific time (d.b.);

*t* - drying time (min).

The effective diffusivity was determined by adjusting the mathematical model that represents the analytical solution for Fick's second law (Equation 15) to the experimental drying kinetics data of germinated jackfruit seeds at different drying temperatures and air velocities. The average diameter adopted for the seeds was 0.0205 m, considering the approximation of its geometric shape to that of a sphere.

$$RX = \frac{X - X_e}{X_i - X_e} = 6\sum_{n=1}^{\infty}\frac{1}{n^2\pi^2}\exp\left(-n^2\pi^2\frac{D_{eff}t}{r^2}\right) \quad (15)$$

In which:

*RX* - moisture ratio of the sample (dimensionless);

*X* - mean moisture content in time;

$X_e$ - equilibrium moisture content;

$X_i$ - initial moisture content of the sample;

$D_{eff}$ - effective diffusivity ($m^2$ $s^{-1}$);

*t* - time (s);

*r* - seed radius (m);

*n* - number of terms in the series.

The Arrhenius equation parameters were obtained by linearizing Equation 15 with the logarithm application, according to Equation 16:

$$\text{Ln } D_{eff} = \text{Ln } D_o - \frac{E_a}{R}.\frac{1}{T} \quad (16)$$

In which:

$Ln\ D_o$ - pre-exponential factor ($m^2$ $s^{-1}$);

$E_a$ - activation energy (KJ $mol^{-1}$);

*R* - universal gas constant (0.008314 KJ $mol^{-1}$ $K^{-1}$);

*T* - temperature (K).

**Table 1** - Mathematical models used to adjust drying kinetics data

| Name of the model | Model | Reference | Eq. |
|---|---|---|---|
| Thompson | $RX = exp(-a-(a^2 +4bt)^{0,5})/2b$ | Sousa *et al*. (2011) | (2) |
| Lewis | $RX = exp(-k.t)$ | Kaleta and Górnicki (2010) | (3) |
| Modified Page | $RX = exp[-(k.t)^n]$ | Arslan and Özcan (2010) | (4) |
| Page | $RX = exp(-k.t^n)$ | Galdino *et al.* (2016) | (5) |
| Henderson and Pabis | $RX = a\ exp(-k.t)$ | Galdino *et al.* (2016) | (6) |
| Two-term exponential | $RX = a.exp(-k.t)+(1-a)exp(-k.a.t)$ | Ferreira *et al*. (2012) | (7) |
| Logarithmic | $RX = a\ exp(-k.t)+c$ | Diógenes *et al*. (2013) | (8) |
| Diffusion approximation | $RX = a.exp(-k.t)+(1-a).exp(-k.b.t)$ | Faria *et al*. (2012) | (9) |
| Two-terms | $RX = a.exp(-k_0.t)+b.exp(-k_1.t)$ | Jittanit (2011) | (10) |
| Midilli | $RX = a.exp(-k.t^n)+b.t$ | Galdino *et al.* (2016) | (11) |
| Wang and Singh | $RX = 1+a.t+b.t^2$ | Costa *et al*. (2015) | (12) |

Where: RX - moisture ratio, dimensionless; a, b, k, n, q - model parameters; t - drying time, min

## RESULTS AND DISCUSSION

The parameters of the Thompson, Lewis, Modified Page, Page, Henderson and Pabis, Two-Term Exponential, Logarithmic, Diffusion Approximation, Two-Terms, Midilli, Wang and Singh mathematical models adjusted to the experimental drying kinetics data results for the germinated jackfruit seeds at temperatures of 55, 65 and 75 °C and air velocities of 1.0 and 1.3 m $s^{-1}$ are presented in Tables 2 and 3 with respective coefficients of determination ($R^2$), mean squared deviations (MSD) and residuals distribution (RD).

According to Goneli *et al.* (2011), the residuals constitute the difference between the values observed experimentally and the values estimated by the models, being plotted as a function of the estimated values of equilibrium moisture content. A model is considered acceptable if the residual values are close to the horizontal range around zero, indicating no bias in the results. It is observed that the Two-Terms and Diffusion Approximation models presented random distribution of the residuals for the studied conditions, resulting in better adjustments for the experimental drying kinetics data and confirming the analysis done through $R^2$ and MSD (Tables 2 and 3). Faria *et al*. (2012) observed random behavior for the Diffusion Approximation model when studying the drying of crambe seeds for the temperature range of 40 to 70 °C.

It can be observed that all tested models fit well to the experimental drying data, presenting $R^2 > 0.9000$ and MSD < 0.12, which can be used to predict the drying kinetic curves of germinated jackfruit seeds. However, the Two-Terms model was considered the best to estimate the drying kinetic curves of the seeds among the models, presenting the highest $R^2$ and lower MSD. Santos *et al.* (2013) also indicated that the Two-Terms mathematical model was the one that best fit the experimental drying data of the residual grains of urucum with oil, presenting the highest $R^2$ values (higher than 0.99), and some of the smaller MSD values (drying at temperatures of 40 and 50 °C).

The k parameter of the Midili model, which represents the drying rate constant, increased with the increase in temperature, however it reduced at the temperature of 65 °C. Furthermore, the parameter n increased with increasing temperature, except at the temperature of 75 °C. In relation to the n constant of the Midilli and Page models, which is related to the internal resistance of the material to the drying (PEREZ *et al*., 2013), it was observed that there was no defined behavior with the increase in drying temperatures.

It can be observed that the k and $k_0$ parameters (drying constants) of the Page, Diffusion Approximation and the Two-Terms models increased with the increase in drying temperature for the air velocity drying adjustments of 1.0 m $s^{-1}$ (Table 2), since higher temperatures lead to higher drying rates. The n constant in the Page and Midilli models increased with the temperature increase, suggesting that the external conditions have no influence on drying germinated jackfruit seeds; while in the air velocity dryings of 1.3 m $s^{-1}$ (Table 3), k and $k_1$ parameters of the Page, Midilli and the Two-Terms models also increased. Giraldo-Zuñiga *et al.* (2006) also verified that the k parameter of the Page model increased with increased temperature by drying the pulp of the dried fruit in trays with natural convection at temperatures of 50, 60 and 70 °C. The k parameter tends to increase with the increase in the drying temperature, which corresponds to the higher drying rates, reaching the equilibrium moisture content in less time of the product being submitted to the drying air (CORRÊA *et al.*, 2010).

Diógenes *et al.* (2013) also observed good adjustments of the Diffusion Approximation and Page models to kinetic drying data of pumpkin grains at temperatures of 40, 50, 60, 70 and 80 °C, and drying air velocity of approximately 1.0 m $s^{-1}$, with $R^2 \geq 0.9880$ and MSD < 0.03.

Figure 1 (a and b) shows the drying rates of germinated jackfruit seeds at temperatures of 55, 65 and 75 °C and air velocities of 1.0 and 1.3 m $s^{-1}$. It was verified that a higher moisture removal rate of the product was observed with the increase in drying temperature and air velocities as a consequence of the increase in the drying rate; similar results are reported by other researchers for numerous agricultural products, such as Goneli *et al.* (2009), Pessoa *et al.* (2011) and Resende *et al.* (2008).

The dehydrations were processed under a regimen of decreasing moisture removal rate in all drying conditions, constituting similar results to those found by Diógenes *et al.* (2013) and Santos *et al.* (2013) in pumpkin grains and residual urucum grains, respectively. Agricultural products with high initial moisture content (RESENDE; FERREIRA; ALMEIDA, 2010) easily lose moisture through diffusion to the environment due to the large pressure difference of water vapor between product and air. Depending on the evaporative demand for drying air, the moisture loss rate contributes to a marked reduction in moisture content, material size, and consequently volume (OLIVEIRA *et al.*, 2011).

The values of effective diffusivity and coefficients of determination ($R^2$) obtained in the drying experiments of the germinated jackfruit seeds at temperatures of 55, 65 and 75 °C and air velocities of 1.0 and 1.3 m $s^{-1}$ are presented in Table 4.

**Table 2** - Obtained parameters, coefficients of determination ($R^2$), mean squared deviations (MSD) and residual distribution (RD) of the adjusted mathematic models to the drying data of the germinated jackfruit seeds at three temperatures and air velocity of 1.0 m $s^{-1}$

| Model | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | T (°C) | k | | | | R² | MSD | RD |
| Lewis | 55 | 0.003360 | | | | 0.9915 | 0.0326 | B |
| | 65 | 0.005394 | | | | 0.9985 | 0.0129 | B |
| | 75 | 0.006860 | | | | 0.9905 | 0.0306 | B |
| | T (°C) | a | | b | | R² | MSD | RD |
| Thompson | 55 | 0.000096 | | 0.000185 | | 0.9330 | 0.0922 | B |
| | 65 | 0.000000 | | 0.000003 | | 0.9270 | 0.0918 | B |
| | 75 | 0.000428 | | 0.000658 | | 0.9475 | 0.0722 | B |
| | T (°C) | k | | n | | R² | MSD | RD |
| Modified Page | 55 | 0.003320 | | 0.993605 | | 0.9915 | 0.0325 | B |
| | 65 | 0.005346 | | 0.994465 | | 0.9985 | 0.0128 | B |
| | 75 | 0.006383 | | 0.957310 | | 0.9923 | 0.0276 | B |
| | T (°C) | k | | n | | R² | MSD | RD |
| Page | 55 | 0.005929 | | 0.893761 | | 0.9931 | 0.0295 | B |
| | 65 | 0.006622 | | 0.959053 | | 0.9988 | 0.0117 | B |
| | 75 | 0.015755 | | 0.826526 | | 0.9970 | 0.0172 | B |
| | T (°C) | a | | k | | R² | MSD | RD |
| Henderson and Pabis | 55 | 0.993605 | | 0.003320 | | 0.9916 | 0.0325 | B |
| | 65 | 0.994465 | | 0.005346 | | 0.9985 | 0.0127 | B |
| | 75 | 0.957311 | | 0.006383 | | 0.9923 | 0.0275 | B |
| | T (°C) | a | k | | | R² | MSD | RD |
| Two-Terms Exponential | 55 | 0.007571 | 0.437528 | | | 0.9915 | 0.0325 | B |
| | 65 | 0.006568 | 0.812613 | | | 0.9985 | 0.0128 | B |
| | 75 | 0.280098 | 0.017521 | | | 0.9973 | 0.0161 | B |
| | T (°C) | a | k | | c | R² | MSD | RD |
| Logarithmic | 55 | 0.972474 | 0.003617 | | 0.031033 | 0.9946 | 0.0194 | B |
| | 65 | 0.985251 | 0.005532 | | 0.013277 | 0.9992 | 0.0094 | B |
| | 75 | 0.942884 | 0.006881 | | 0.024794 | 0.9949 | 0.0123 | B |
| | T (°C) | a | k | | b | R² | MSD | RD |
| Diffusion Approximation | 55 | 0.79986 | 0.00452 | | 0.184653 | 0.9980 | 0.0158 | R |
| | 65 | 0.928354 | 0.006003 | | 0.164746 | 0.9998 | 0.0042 | R |
| | 75 | 0.742509 | 0.010209 | | 0.198593 | 0.9998 | 0.0043 | R |
| | T (°C) | a | $k_0$ | b | $k_1$ | R² | MSD | RD |
| Two-Terms | 55 | 0.2294 | 0.0009 | 0.79658 | 0.00495 | 0.9986 | 0.0133 | R |
| | 65 | 0.0816 | 0.0011 | 0.9259 | 0.0062 | 0.9998 | 0.0036 | R |
| | 75 | 0.73624 | 0.01045 | 0.26847 | 0.00209 | 0.9998 | 0.0042 | R |
| | T (°C) | a | k | n | b | R² | MSD | RD |
| Midilli | 55 | 1.051215 | 0.009550 | 0.821550 | 0.000005 | 0.9948 | 0.0256 | R |
| | 65 | 1.01643 | 0.00782 | 0.993010 | 0.000003 | 0.9990 | 0.0103 | R |
| | 75 | 1.046459 | 0.021723 | 0.773528 | 0.000003 | 0.9980 | 0.0140 | B |

R: Random Distribution; B: Biased distribution

**Table 3 -** Obtained parameters, coefficients of determination ($R^2$), mean squared deviations (MSD) and residual distribution (RD) of the mathematic models adjusted to the drying curves of the germinated jackfruit seeds at three temperatures and air velocity of 1.3 m $s^{-1}$

| Model | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Lewis | T (°C) | | k | | | $R^2$ | MSD | RD |
| | 55 | | 0.003630 | | | 0.9988 | 0.0122 | R |
| | 65 | | 0.006972 | | | 0.9909 | 0.0302 | B |
| | 75 | | 0.005829 | | | 0.9817 | 0.0425 | B |
| Thompson | T (°C) | a | | b | | $R^2$ | MSD | RD |
| | 55 | 0.000012 | | 0.000234 | | 0.9203 | 0.1016 | B |
| | 65 | 0.000083 | | 0.000220 | | 0.9422 | 0.0762 | B |
| | 75 | 0.000078 | | 0.000200 | | 0.9601 | 0.0628 | B |
| Modified Page | T (°C) | k | | n | | $R^2$ | MSD | RD |
| | 55 | 0.003655 | | 1.004011 | | 0.9988 | 0.0121 | R |
| | 65 | 0.006657 | | 0.972068 | | 0.9916 | 0.0289 | B |
| | 75 | 0.005052 | | 0.922726 | | 0.9884 | 0.0338 | B |
| Page | T (°C) | k | | n | | $R^2$ | MSD | RD |
| | 55 | 0.003617 | | 1.000677 | | 0.9994 | 0.0123 | R |
| | 65 | 0.013978 | | 0.853965 | | 0.9950 | 0.0222 | B |
| | 75 | 0.019857 | | 0.751819 | | 0.9978 | 0.0146 | B |
| Henderson and Pabis | T (°C) | a | | k | | $R^2$ | MSD | RD |
| | 55 | 1.004011 | | 0.003655 | | 0.9988 | 0.0120 | R |
| | 65 | 0.972068 | | 0.006657 | | 0.9916 | 0.0289 | B |
| | 75 | 0.922726 | | 0.005052 | | 0.9884 | 0.0338 | B |
| Two-Terms Exponential | T (°C) | a | | k | | $R^2$ | MSD | RD |
| | 55 | 0.000091 | | 39.76808 | | 0.9988 | 0.0122 | R |
| | 65 | 0.323032 | | 0.015163 | | 0.9962 | 0.0194 | B |
| | 75 | 0.221152 | | 0.019450 | | 0.9947 | 0.0227 | B |
| Logarithmic | T (°C) | a | k | | c | $R^2$ | MSD | RD |
| | 55 | 0.994829 | 0.003766 | | 0.012315 | 0.9993 | 0.0091 | R |
| | 65 | 0.957172 | 0.007194 | | 0.025922 | 0.9945 | 0.0233 | B |
| | 75 | 0.904970 | 0.005567 | | 0.030309 | 0.9919 | 0.0283 | B |
| Diffusion Approximation | T (°C) | a | k | | b | $R^2$ | MSD | RD |
| | 55 | 0.325109 | 0.0139678 | | 0.236983 | 0.9988 | 0.0113 | R |
| | 65 | 0.811590 | 0.0095751 | | 0.162533 | 0.9992 | 0.0089 | R |
| | 75 | 0.564223 | 0.0121581 | | 0.187125 | 0.9998 | 0.0045 | R |
| Two-Terms | T (°C) | a | $k_0$ | b | $k_1$ | $R^2$ | MSD | RD |
| | 55 | 0.962423 | 0.003979 | 0.048766 | 0.000589 | 0.9997 | 0.0074 | R |
| | 65 | 0.794167 | 0.010202 | 0.222412 | 0.001793 | 0.9996 | 0.0079 | R |
| | 75 | 0.416007 | 0.002200 | 0.574965 | 0.011482 | 0.9998 | 0.0039 | R |
| Midilli | T (°C) | a | k | n | b | $R^2$ | MSD | RD |
| | 55 | 1.007901 | 0.003948 | 0.988848 | 0.000003 | 0.9995 | 0.0108 | B |
| | 65 | 1.051312 | 0.020112 | 0.793229 | 0.000004 | 0.9963 | 0.0191 | B |
| | 75 | 1.039791 | 0.025584 | 0.712585 | 0.000003 | 0.9986 | 0.0109 | B |

R: Random Distribution; B: Biased Distribution

**Figure 1** - Drying rates of germinated jackfruit seeds at temperatures of 55, 65 and 75 °C at the air velocities of (a) 1.0 m s$^{-1}$ and (b) 1.3 m s$^{-1}$

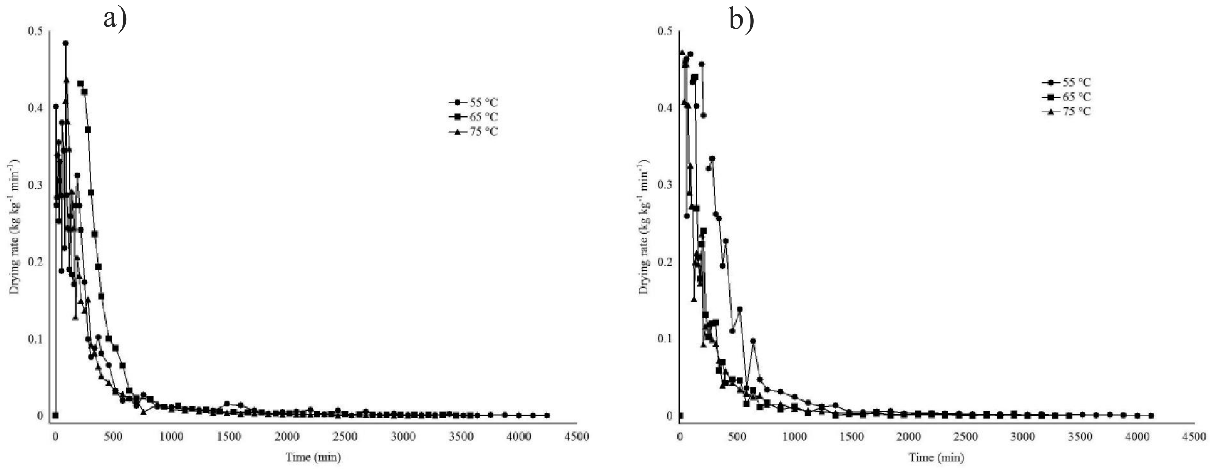



**Table 4** - Effective diffusivity ($D_{eff}$) and the coefficients of determination ($R^2$) obtained in drying germinated jackfruit seeds at temperatures of 55, 65 and 75 °C and air velocities of 1.0 and 1.3 m s$^{-1}$

| Temperature (°C) | Air velocity (m s$^{-1}$) | $D_{eff}$ (m$^2$ s$^{-1}$) | $R^2$ |
|---|---|---|---|
| 55 | 1.0 | 0.74 x 10$^{-7}$ | 0.9909 |
| | 1.3 | 0.82 x 10$^{-7}$ | 0.9876 |
| 65 | 1.0 | 1.24 x 10$^{-7}$ | 0.9894 |
| | 1.3 | 1.60 x 10$^{-7}$ | 0.9931 |
| 75 | 1.0 | 1.59 x 10$^{-7}$ | 0.9962 |
| | 1.3 | 1.84 x 10$^{-7}$ | 0.9984 |

It is verified that an increase in the diffusivity occurs with the increase in the temperature and the air drying speed, which represents the speed with which the water migrates from the interior to the material's surface, from where it is vaporized (MENEZES *et al*., 2013).

The dependence of the effective diffusivity on the drying air temperature was satisfactorily represented by the Arrhenius expression, according to Figure 2 (a and b), where, according to Melo *et al.* (2016), the lower the activation energy in the drying processes, the greater the moisture diffusivity in the product. It is observed that the ln $D_{eff}$ values as a function of the absolute temperature inverse (1/T) presented similar behavior for the temperatures of 55, 65 and 75 °C, in relation to the studied air drying velocities of 1.0 and 1.3 m s$^{-1}$.

Figure 3 (a and b) shows the drying kinetic curves of the germinated jackfruit seeds adjusted with the Two-Terms model for temperatures of 55, 65 and 75 °C and air velocities of 1.0 and 1.3 m s$^{-1}$, respectively. As already noted, the drying time decreases with increasing temperature and air velocity, and the moisture ratio decreases with the drying time. Similar behavior was observed in studies carried out by several researchers in drying agricultural products (GASPARIN; CHRIST; COELHO, 2017; SILVA *et al.*, 2016).

It can be seen that the dryings under all conditions are faster in the first 500 minutes; from that time the moisture loss decreases and the internal resistance of the moisture outlet of the seeds increases, and the moisture ratio consequently decreases more slowly.

**Figure 2 -** Arrhenius representation for the effective diffusivity of germinated jackfruit seeds at temperatures of 55, 65 and 75 °C and air velocities of (a) 1.0 m $s^{-1}$ and (b) 1.3 m $s^{-1}$

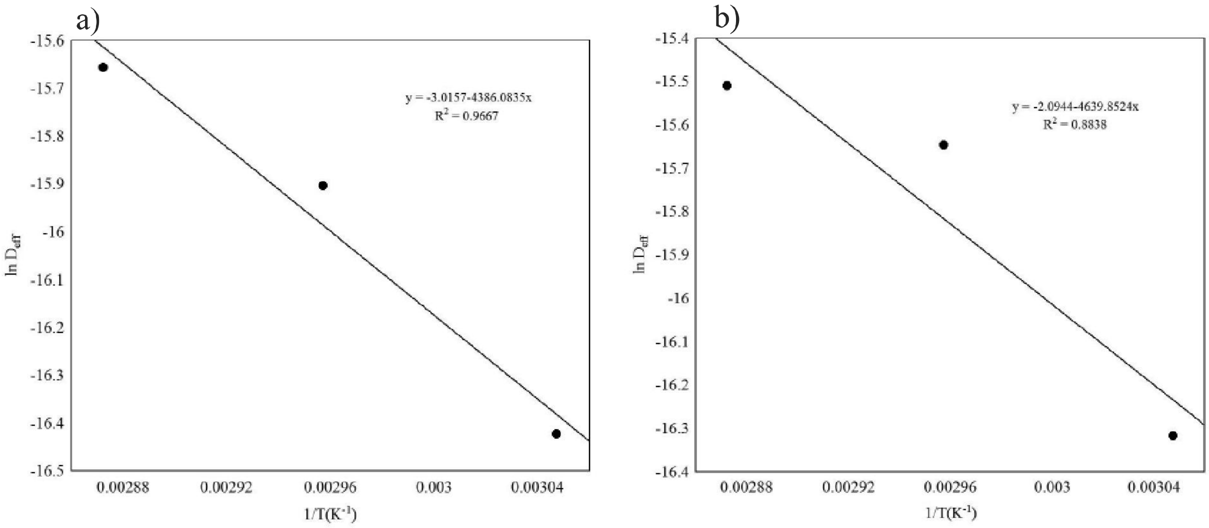
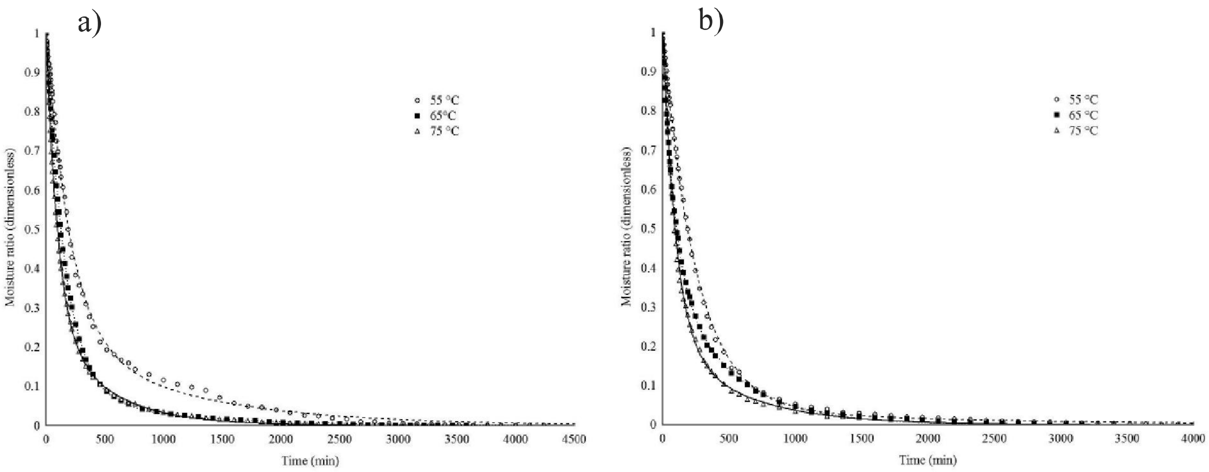



**Figure 3 -** Drying kinetics of germinated jackfruit seeds adjusted to the Two-Terms model, with drying air velocities of (a) 1.0 m $s^{-1}$ and (b) 1.3 m $s^{-1}$




## CONCLUSIONS

1. A higher moisture withdrawal rate of the product occurred with the increase in drying temperature and air velocities, proving the increase in the drying rate;
2. Among the tested mathematical models, the Two-Terms model best fit the experimental drying kinetics data of the germinated jackfruit seeds in all the evaluated conditions, presenting a larger $R^2$, smaller MSDs and random distribution of the residuals;
3. The germinated jackfruit seeds presented effective diffusivity in the order of $10^{-7}$ $m^2$ $s^{-1}$, increasing with increments in drying temperature and drying air velocity.

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