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Thin-layer drying characteristics of Easter lily (*Liliumlongiflorum*Thunb.) scales and mathematical modeling

Cuntang WANG[1*], Yueyi LU[1], Xuanzhe AN[1], Shengxin TIAN[1]

Abstract

This study investigated the effects of temperature on the drying behavior and kinetic features of lily scales. A series of experiments were carried out at 65, 75, and 85 °C to dry the scales in a laboratory air-ventilated oven dryer. Drying temperature was found to significantly affect drying times and drying rates. The rate curves suggested that the drying process of lily scales occurred entirely within the descending rate period. During the simulation of drying kinetics, Page and Logarithmic models were proven highly accurate by evaluating the efficacy of seven different thin layer models. Based on Fick's second law, the effective moisture diffusivity was determined as 4.12×10^{-9}, 7.71×10^{-9}, and 9.49×10^{-9} m^2/s for temperatures of 65, 75, and 85 °C, respectively. The calculated figure of activation energy was 42.42 kJ/mol.

Keywords: lily scales; hot-air drying; mathematical modeling; Arrhenius relationship.

Practical Application: Hot-air drying mathematical model of Lily scales can be used as a guideline toward optimal design of drying methods and conditions. Drying-kinetics models are essential for equipment design, process optimization and product quality improvement.

1 Introduction

The bulbs of the Easter lily (*Liliumlongiflorum* Thunb. family Liliaceae), an important cash crop, are commonly used in many Asian countries (particularly China) both nutritionally and medicinally. In China, lily bulbs are often included in stir-fries, soups, and stew-like dishes as well as traditional medicinal treatments for sedative, anti-inflammatory, and antitussive applications (Munafo & Gianfagna, 2015). The beautiful white flowers and delicate aroma of the plant are appreciated worldwide as attractive ornamental elements, as well. The lily bulb contains an array of useful constituents including dietary fibers, starch, protein, microelements, and bioactive phytochemicals such as phenolics, alkaloids, flavonoids, carotenoids, sterols, steroidal saponins, and steroidal glycoalkaloids (Luo et al., 2012).

Lily bulbs are easily degraded due to their abundant nutrient and water contents, so they are often preserved by drying. Fresh lily bulbs are consumed in small quantities and larger amounts can be used also for food and as medicine after drying. Sun drying, the oldest traditional method of drying lily bulb scales, yields a product with ideal color, taste, and texture, but is highly time-consuming and exposes the bulbs to contaminants such as dust and insects (Osman et al., 2015). Hot-air drying technology is an attractive alternative because it is far quicker and provides uniform, high-quality products (Jha & Sit, 2020).

The drying kinetics of food is a complex system. As a necessary element, simple representations are required to predict drying characteristics and optimize drying parameters. Previous studies have evaluated the precise characteristics and established mathematical models describing drying behavior of various vegetables [e.g., garlic (Demiray & Tulek, 2014), carrot (Doymaz, 2017), araticum epicarp (Ataides et al., 2022), banana (Silva et al., 2022), red ginseng (Ning et al., 2021)]. There is limited empirical information on these aspects of hot-air dried lily scales, however.

The present study shows the calculation of effective moisture diffusivity and activation energy of the lily scale drying process and examines the drying behavior of lily scales while comparing the accuracy of various mathematical models in representing the drying process.

2 Materials and methods

2.1 Raw materials

Lily bulbs for use in this study were purchased directly from local farm in YuZhong, Lanzhou, China. The bulbs were stored in a refrigerator at 4 ± 1 °C until use (at most one week). The bulbs were manually separated into scales by applying mild pressure. Any injured, damaged, or tainted scales were discarded and the remaining were blanched for 3 min at 80 °C followed by immediate cooling in room-temperature tap water for 3 min. Excess water on the sample surface was removed with tissue paper. The initial moisture content of samples was determined to be 1.43 ± 0.06 g water/g dry matter after holding in an oven (Type-101-3, Shanghai Ruda Experimental Apparatus Co., Ltd., China) at 105 °C for 6 h.

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[1] *College of Food and Biological Engineering, Qiqihar University, Qiqihar, Heilongjiang, China*
*Corresponding author: wangcuntang1980@163.com

2.2 Drying procedure

Drying experiments were performed in a heating air blast drying cabinet (DHG-9053A, Shanghai Jinghong Experimental Facilities Corporation Ltd, Shanghai, China) installed in the College of Food and Biological Engineering of Qiqihar University, China. The constant temperature blast drying cabinet is mainly composed of a motor equipped with centrifugal impeller, an electric heater, a reasonable air duct structure and a temperature controller. The dryer is able to accurately maintain desired drying temperatures ranging from 35 to 300 °C.

The dryer was adjusted to the desired temperature for approximately 60 min before the experiment to ensure a steady working condition. The temperature of the air was set at 65 °C, 75 °C, 85 °C, respectively in a heating air blast drying cabinet, and employed for the dehydration of the lily scales. A steady flow of air was maintained at a velocity of 1.0 m/s. Then, about 100 g of the scale samples were uniformly distributed on a single-sided square basket. The drying procedure utilized a scale to measure the weight of the samples at 10 min intervals (CP423S, Sartorius AG, Gottingen, Germany, 0.01 g accuracy). The weighing process lasted less than 20 s. Dehydration continued until the moisture loss was at an insignificant level, at which point the moisture content was considered to be in equilibrium. All experiments were repeated three times at the respective temperatures, and the average measurements are contained within this study.

2.3 Mathematical modeling of drying curves

The drying kinetics of the lily scales were determined by evaluating eight commonly selected empirical thin layer models (Table 1). In these models, MR denotes the moisture ratio (Aydar, 2021) (Equation 1):

$$MR = (M - M_e) / (M_0 - M_e) \tag{1}$$

Where MR represents the dimensionless moisture content ratio; M_0 is moisture content at initial stage; M_t is the moisture content at any given time, and M_e is the equilibrium moisture content. The M_e values are much smaller than M_t and M_0, and are negligible during the simplification of the equation, resulting in MR = M/M_0 as the simple form of Equation 1. Equation 2 was used to calculate the drying rate (DR) as follows (Nadi & Tzempelikos, 2018):

$$DR = M_{t+\Delta t} - M_t / \Delta t \tag{2}$$

Where $M_{t+\Delta t}$ represents moisture content at the time of t + Δt (g water/g dry matter). The drying time was recorded in minutes.

2.4 Statistical analysis

Statistical software OriginPro8.5 was employed to perform non-linear regression analysis. The fitting quality of the data was evaluated according to the determination coefficient (R^2), reduced chi-square (χ^2), and root mean square error (RMSE). Lower χ^2 and RMSE values along with higher R^2 values are evidence of better fit in the model. χ^2 and RMSE were calculated as follows (Engin, 2020) (Equations 3-4):

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{\text{pre},i} \right)^2}{N - z} \tag{3}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pre,i} \right)^2} \tag{4}$$

Where $MR_{exp,I}$ denotes the experimental moisture ratio while $MR_{pre,i}$ represents the estimated moisture ratio. N represents observations number; z is the number of drying constants.

2.5 Effective moisture diffusivity coefficient

The effective moisture diffusion coefficient parameter is essential for simulating the moisture migration mechanism of a food drying process (Février et al., 2017). For most foodstuffs, the drying process takes place in the descending rate period, during which internal diffusion of water dominates moisture transfer. Equation 5 is the second diffusion of Fick, which is often used to define the falling rate period of agricultural materials during drying (Crank, 1975):

$$\frac{\partial M}{\partial t} = \nabla \left[D_{eff} (\nabla M) \right] \tag{5}$$

Crank originally developed the solution to this equation (Crank, 1975). With assumption of even moisture distribution at initial stage, negligible shrinkages well as constant diffusivity, Equation 6 is advisable for slab geometry:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2} \right) \tag{6}$$

Table 1. Thin-layer drying models used for mathematical of drying of lily scales.

No.	Model name	Model	References
1	Lewis	MR = exp(-kt)	Engin (2020)
2	Page	MR = exp(-kt^n)	Osman et al. (2015)
3	Henderson and Pabis	MR = aexp(-kt)	Doymaz (2007)
4	Logarithmic	MR = aexp(-kt)+c	Demiray & Tulek (2014).
5	Two-term	MR = aexp(-kt)+bexp(-k_0t)	Doymaz (2007)
6	Two-term exponential	MR = aexp(-kt)+(1-a)exp(-kat)	Nadi & Tzempelikos (2018)
7	Approximation of diffusion	MR = aexp(-kt)+(1-a)exp(-kbt)	Jha & Sit (2020)

Where a, b, c, k and k_0 are characteristic constants of different models; and t is drying time (min).

Where is a positive integer; D_{eff} represents the effective diffusivity with a unit of m^2/s; L_0 represents 1/2 of slab thickness (m). In practice, over a lengthy drying duration, Equation 6 can be further simplified to Equation 7 by leaving only the first term of the series (Doymaz, 2017):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L_0^2}\right) \tag{7}$$

The experimental drying data were plotted to obtain a straight line. The X-axis is drying time and the Y-axis is ln (MR). The effective moisture diffusivity was calculated from the slope of the line. Equation 8 is the logarithmic form after transformation (Demiray & Tulek, 2014).

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \tag{8}$$

The slope of the straight line is defined as follows (Engin, 2020) (Equation 9):

$$Slope = \frac{\pi^2 D_{eff}}{4L_0^2} \tag{9}$$

2.6 Activation energy

In this study, Arrhenius-type relationship is utilized to describe relationship between temperature and the effective moisture diffusivity, as shown in Equation 10 (Demiray & Tulek, 2014):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{10}$$

Where D_0 represents the pre-exponential factor of the Arrhenius equation (m^2/s); E_a represents the activation energy in kJ/mol units; R represents the universal gas constant, which equals to 8.314 kJ/mol K, and T is the absolute temperature (K). Activation energy can be calculated by plotting the natural logarithm of D_{eff} versus the reciprocal of the absolute temperature. Equation 9 can be rearranged into the following form (Omolola et al., 2019) (Equation 11):

$$lnD_{eff} = lnD_0 - \frac{E_a}{R} \cdot \frac{1}{T} \tag{11}$$

E_a can be calculated from the slope of the straight line of ln D_{eff} versus 1/Tas-described in the Arrhenius equation (Omolola et al., 2019) (Equation 12).

$$Slope = \frac{E_a}{R^2} \tag{12}$$

3 Results and discussion

3.1 Effect of drying air temperature on moisture ratio

We used a convective hot-air dryer to dry lily scale samples at 65, 75, and 85 °C. The moisture content initially was about 1.45 ± 0.06 g water/g dry matter and the equilibrium moisture content was 0.001 g water/g dry matter. The typical drying curves are shown in Figure 1, where moisture ratio decreases constantly over the prolonged drying span. The times needed to achieve the equilibrium moisture content were 510, 310, and 260 min at 65, 75, and 85 °C, respectively. As expected, within any given temperature range, increasing the drying temperature accelerated the drying process and truncated the drying time. These results are consistent with previous investigations on the drying of vegetables [i.e., garlic slices (Demiray & Tulek, 2014), pumpkin slices (Doymaz, 2007) and sweet potato slices (Doymaz, 2011a)], and fruits [pear slices (Doymaz & Ismail, 2012) and apple slices (Menges & Ertekin, 2006)].

3.2 Effect of drying air temperature on drying rate

The drying rates of the thin-layer lily scale samples were calculated using Equation 2. Figure 2 shows the impact of drying air temperatures on drying rate, where the drying rate decreases constantly as moisture content decreases. The rate of moisture removal was faster at the initial stage than that at the later stage of the experiment. As expected, hot-air temperature had a tremendous impact on drying rate. Interestingly, two distinct falling rate periods were observed. At moisture content greater than 0.0088 g water/g dry matter, the temperature increase brought about an increase in drying rate. When moisture contents were below 0.0088, the temperature increase led to a reduction in drying rate. This is mainly because the rates of moisture migration from the interior to exterior part decreased at the final stage, resulting in a reduced rate (Rajkumar et al., 2007). This result is consistent with results from apple pomace (Wang et al., 2007), for carrot pomace (Kumar et al., 2012), and leek slices (Doymaz, 2008).

No drying period with a constant rate was observed for lily scales under any of the experimental conditions we employed. All the drying occurred in the descending rate period, during which the predominant variations in drying rate took place, indicating that diffusion is the dominant factor controlling

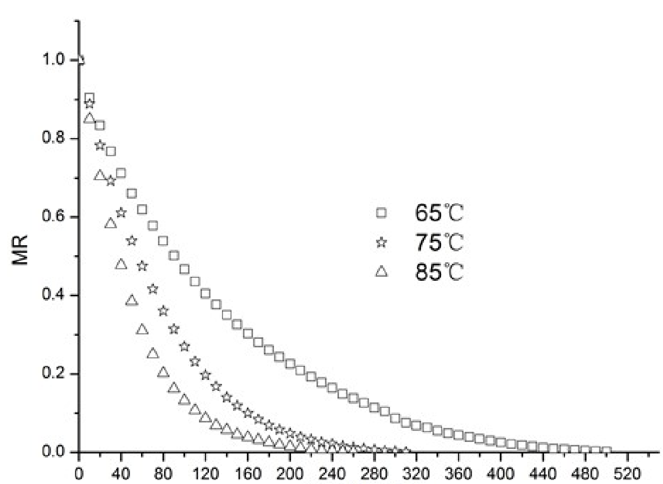

Figure 1. Thin-layer drying curves of lily scales at different temperatures.

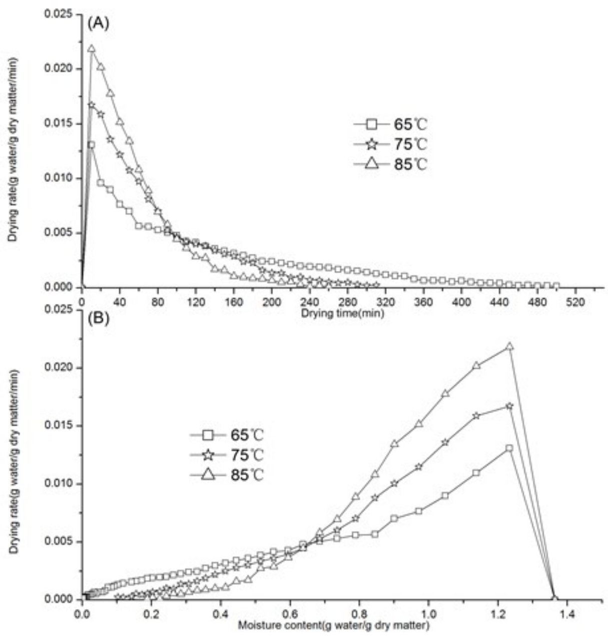

Figure 2. Drying rate versus drying time (A) and moisture content (B) of lily scales at different temperatures.

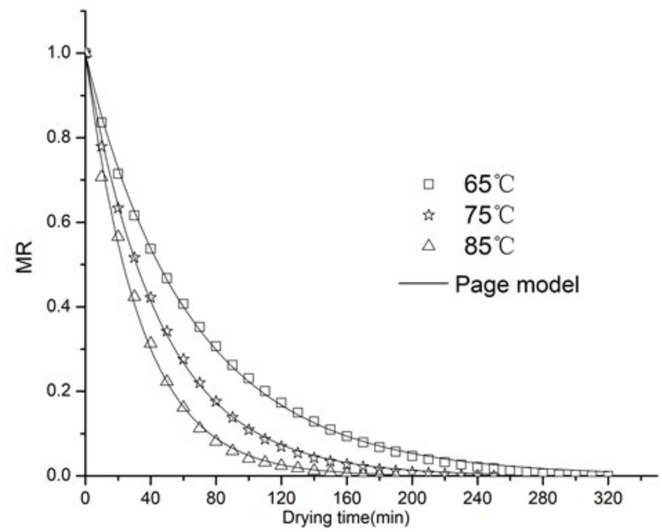

Figure 3. Comparison between the experimental moisture ratios of shredded lily and those predicted by Page model.

moisture removal. Similar results have been reported in pear slices (Doymaz & Ismail, 2012), Asian white radish slices (Lee & Kim, 2009) and tomato slices (Sadin et al., 2014).

3.3 Fitting mathematical models to drying curves

The moisture ratios obtained under different drying temperatures were plugged into seven thin-layer drying models (Table 1) for fitting. Table 2 lists the statistical regression of all models, including R^2, χ^2, and RSME values. All the R^2 values in these cases were higher than 0.99 suggesting a good fit of the models. χ^2 and RSME were lower than$3.29 \times 10^{-6}$and 1.82×10^{-4}, respectively.

The most accurate model representing the thin-layer drying features of lily scales was selected according to R^2, RMSE, and χ^2 values, as described above. The R^2, χ^2 and RMSE values of the Page model varied between 0.9992-0.9999, $0.62\text{-}6.36 \times 10^{-6}$, and $2.49\text{-}7.97 \times 10^{-4}$, respectively (Table 2). This model has also been recommended previously to describe the hot-air drying of garlic slices (Demiray & Tulek, 2014), carrots (Doymaz, 2017), raw mango slices (Goyal et al., 2006), and litchi (Janjai et al., 2011).

In order to validate the suitability of the Page model, we compared the experimental and predicted moisture ratio values (Figure 3). Results indicated that there was a good conformity between experimental and predicted moisture ratios at three different temperatures, which demonstrated this model had a good suitability in describing the drying behavior of lily scales in drying process.

Table 2. Statistical results obtained from various thin-layer drying models.

Model	Temperature (°C)	R^2	χ^2 ($\times 10^{-5}$)	RSME ($\times 10^{-3}$)
Lewis	65	0.9987	8.94	9.45
	75	0.9994	4.45	6.67
	85	0.9991	7.54	8.68
Page	65	0.9991	6.78	8.23
	75	0.9994	4.31	6.56
	85	0.9991	6.36	7.97
Henderson and Pabis	65	0.9991	6.73	2.03
	75	0.9994	4.30	6.55
	85	0.9990	6.23	7.89
Logarithmic	65	0.9993	4.87	6.97
	75	0.9995	3.09	5.55
	85	0.9992	6.28	7.92
Two term	65	0.9990	6.86	8.28
	75	0.9994	4.23	6.50
	85	0.9988	9.81	9.90
Two term exponential	65	0.9987	9.06	9.51
	75	0.9993	4.64	6.81
	85	0.9993	5.52	7.42
Approximation of diffusion	65	0.9986	9.53	9.76
	75	0.9993	4.86	6.97
	85	0.9989	8.31	9.11

3.4 Determination of effective moisture diffusivity

As obtained via Equation 8, the effective moisture diffusivity (D_{eff}) were4.12×10^{-9}, 7.71×10^{-9}, and 9.49×10^{-9} m^2/s for 65, 75, and 85 °C, respectively. D_{eff} increased as the drying temperature increased (Figure 4) and drying at 85 °C yielded the highest D_{eff} by far. The D_{eff} generally ranges from10^{-8} to 10^{-12} m^2/s for biological samples (Silva et al., 2022; Aghbashlo et al., 2008). D_{eff} values for lily scales were similar to those of other vegetables and fruits predicted in other studies: $1.02\text{-}2.65 \times 10^{-9}$ m^2/s for drying tomato slices from 60-100 °C (Purkayastha et al., 2013), 2.74-4.64 × 10^{-9} m^2/s for drying carrot pomace from 60-75 °C (Kumar et al., 2012), and 1.09-5.99 × 10^{-9} m^2/s for drying thyme from 40-60 °C (Doymaz, 2011b).

3.5 Determination of activation energy

The bonding potential of moisture mainly determines drying behaviors of moist materials. Activation energy is the starting energy required to remove 1 mol of moisture during the drying process. It reflects the ability of the moisture bonding potential in the material and the degree of difficulty in evaporating water from it. This index is determined by the moisture content and composition of the material itself. The greater the activation energy, the harder it is to remove the moisture. The natural logarithm of D_{eff}, as plotted in Figure 5, demonstrated an Arrhenius-type linear relationship. The activation energy was obtained from the slope. We calculated activation energy to be 42.42 kJ/mol by applying Equation 11 to the line slope (Figure 5).The *Ea* of lily scales appears to be close to that of pear slices (44.78 kJ/mol) (Doymaz & Ismail, 2012) and aonla shreds (43.98 kJ/mol)

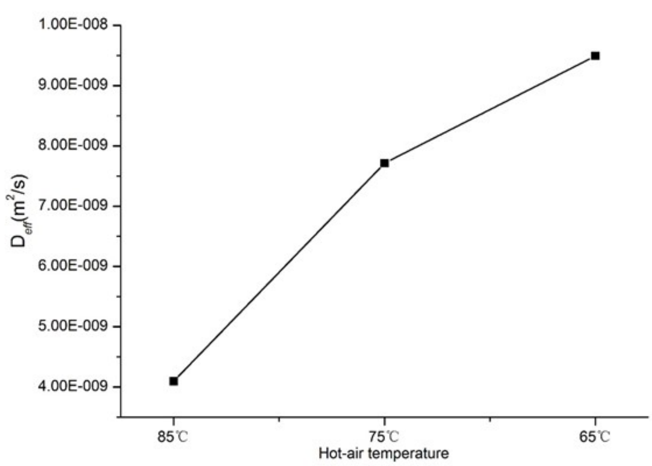

Figure 4. Variation of effective moisture diffusivity with drying air temperature.

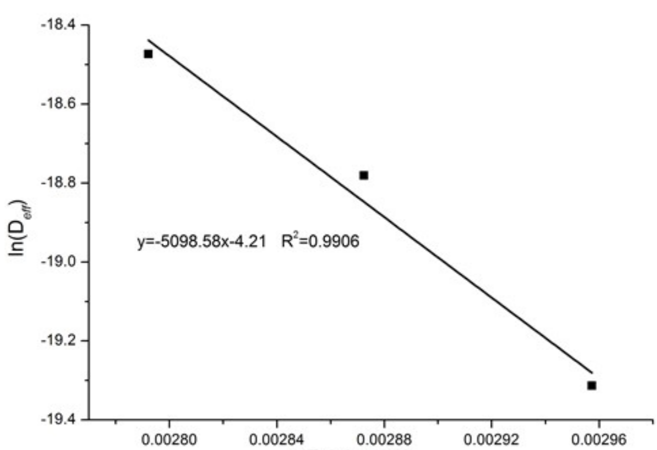

Figure 5. Arrhenius-type relationship between D_{eff} and drying air temperature.

(Gupta et al., 2014), lower than that of thyme (73.84 kJ/mol) (Doymaz, 2011b), pumpkin slices (78.93 kJ/mol) (Doymaz, 2007), and tomato slices (61.004 kJ/mol) (Purkayastha et al., 2013), and higher than that of apple slices (19.95-22.62 kJ/mol) (Kaya et al., 2007), sweet potato slabs(22.7-23.2 kJ/mol) (Doymaz, 2011a), radish slices (16.49-20.26 kJ/mol) (Lee & Kim, 2009), and garlic slices (30.58 kJ/mol) (Demiray & Tulek, 2014). Zogzas et al. (1996) reported energy activation values ranging from12.7 to 110 kJ/mol for a variety of foodstuffs. The energy activation value we obtained also falls in this range.

4 Conclusions

This study mainly investigated the impact of hot-air temperature on the drying behaviors of lily scales. The drying characteristics curves obtained under our experimental conditions only showed a descending rate drying duration without any constant drying rate period. Increase in hot-air temperature led to increased drying rate and decreased drying time. Among the eight thin-layer drying equations we studied, the Page model has the highest R^2 and lowest RMSE, and χ^2, which proves the best and accurate fit for determining the drying features of lily scales. Within the tested temperature range, the effective diffusivity increased from 4.12 to 9.49 × 10^{-9} m^2/s along the temperature gradient. The Arrhenius-type relation can be used to describe the temperature-dependent feature of effective diffusivity. The activation energy was determined to be 42.42 kJ/mol.

Abbreviations

D_0: Pre-exponential element in the Arrhenius equation (m^2/s). D_{eff}: Effective diffusivity (m^2/s). E*a*: Activation energy (kJ/mol). DW: Dry weight. DR: Drying rate. L_0: Half the thickness of the sample slice (m). M: Moisture content (g water/g dry matter). M_0: Initial moisture content (g water/g dry matter). M_e: Equilibrium moisture content (g water/g dry matter). MR: Moisture ratio. $MR_{exp,\ i}$: Respective actual measurements moisture content. $MR_{pre,\ i}$: Theoretically calculated moisture content. M_{t+dt}: (g water/g dry matter). M_t: (g water/g dry matter). N: Number of assessments. n: Positive integer. R^2: Correlation coefficient. RMSE: Root mean square error. R: Universal gas constant (8.314 kJ/mol K). T: Temperature (°C). T_{abs}: Absolute temperature (K). t: drying time (min). χ^2: Reduced chi-square. z: Number of drying constants.

Conflict of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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