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RESEARCH ARTICLE

Experimental and mathematical modeling analysis of freeze-drying kinetics for ginger slices with different thickness

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Abstract

In this study, the freeze-drying (FD) behavior of ginger (Zingiber officinale) at thicknesses of 5 and 7 mm was analyzed experimentally and statistically. The drying process was evaluated using ten empirical models to decide which was most proper for predicting weight reduction. Among the evaluated models, the Logarithmic Model was the most correct in describing the drying kinetics for both sample thicknesses, showing the lowest error rates of 8.39% for 5 mm samples and 8.42% for 7 mm samples. The 5 mm samples had statistical parameters of correlation coefficient (R^2) = 0.9902, chi-square (X^2) = 1.402×10^{-3} and root mean square error (RMSE) = 0.03211. The 7 mm samples had R^2 = 0.9986, X^2 = 1.153×10^{-3}, and RMSE = 0.03411. Additionally, the calculated effective moisture diffusion coefficient (D_{eff}) values for 5 mm and 7 mm were 2.075×10^{-7} m^2/s and 4.079×10^{-10} m^2/s, respectively, which are in line with the values reported for different food items.

Keywords: Freeze drying technology, ginger (zingiber officinale), kinetics of drying, logarithmic model

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Highlights

- The freeze-drying behavior of ginger samples of different thicknesses (5 and 7 mm) was analyzed using mathematical models supported by experimental results.
- Among ten empirical models in the literature for predicting drying kinetics, the Logarithmic Model was the most successful for both thicknesses, showing the lowest error rates and the highest goodness-of-fit coefficients.
- It can consistently and accurately predict drying kinetics, as shown by the high correlation coefficients (R^2), low chi-square (X^2), and RMSE values found between experimental findings and mathematical models.
- The consistency of the calculated effective moisture diffusion coefficients across different sample thicknesses with values reported in the literature supports the validity and innovative aspects of the study, both experimentally and theoretically.

1. Introduction

Extending the shelf life of fruits and vegetables is an important issue in the contemporary food industry. The purpose of drying processes is to extend the shelf life of products by preventing spoilage agents such as oxidation and microbiology [1]. In addition, drying processes significantly reduce product preservation and packaging costs, logistics transfer weight, and cold storage times. The reduction of these parameters and costs enables the products to be widely used globally and the process to be managed efficiently [2]. Drying products using a proper

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method affects their spoilage, shelf life, and durability. Which drying process to use will depend on the properties of the specific product or its processing requirements [3–5]. The possibility of applying freeze-drying (FD) technology to sludge treatment, as an alternative to traditional thermal drying methods, is conceptually attractive. Nevertheless, one of the main limitations of that technique is the long drying period. The advantages of freezing and drying are accentuated to produce a dry, biologically active, stable product that is easily decomposable [6]. Consequently, the FD method is designed to preserve heat-sensitive materials, including foodstuffs (fruits, vegetables, seafood) and pharmaceutical microbial cultures.

Studies on FD are available in literature. For example, two research groups conducted a study on FD processes applied to kiwifruit and evaluated their efficiency based on performance index scores, processing time, and energy consumption. The best was found based on these parameters [7,8]. One study investigated the FD of mango slices. Emphasis was placed on drying time, moisture content, rehydration ratio, color, and phenol. In drying studies, the effects of factors such as freezing rate, vacuum pressure, and vacuum temperature were investigated to decide the most suitable drying parameters. The results suggest that the best values for achieving commercially desired quality characteristics are a vacuum pressure in the range of 500–650 mTorr, a temperature between 0–2°C, and a freezing rate of approximately 0.4°C/min [9]. Using freeze-drying technology, Shishehgarha et al. [10] examined the drying process of strawberry slices and assessed important factors such drying rate, color change, and volume loss. The study also examined the effects of drying temperature and slice thickness on these parameters. The results showed that an increase in temperature did not lead to significant changes in color or volume. However, increasing the temperature parameter above 50°C led to a marked increase in the rate of structural degradation. In the study conducted by Taskın [11], the freeze-drying of banana product was examined in terms of moisture content, vitamin C content and sensory properties. The effects of parameters such as freezing and drying temperatures, slice thickness, and vacuum pressure on product quality were analyzed. The study results show that the drying at 45°C and a vacuum pressure of 20–30 Pa produced the best appearance and taste characteristics in banana slices 5–7 mm thick. Topical drug delivery is one of the most successful therapeutic approaches for local treatment. Ginger (Zingiber officinale) is a popular spice as well as a traditional medicine, which is used for treating various diseases, and has been in use since antiquity [12]. Ginger is widely used in food due to its rich phytochemicals and high antioxidant content [13]. The edible part of the plant, the rhizome, is commonly called ginger or ginger root. This rhizome structure can vary in color from red to various shades of yellow across species. The outer surface may be thin or thick and is covered by a brownish shell. The rhizome inside this outer shell is used as a spice for medicinal purposes, or as a flavoring agent [14]. Ginger has 40-70% starch, 1.5-3% essential oil, 6-20% protein, and 9-12% moisture [15–17]. FD is a drying method in which products are first frozen and then the ambient pressure is reduced, allowing the ice they have to sublimate directly into the vapor phase [18]. This drying method is particularly important for the high-quality drying of heat-sensitive products such as fresh ginger, which has bioactive components that begin to deteriorate at high temperatures [19].

The FD process generally involves three steps. First, the product is frozen; then the moisture molecules that have turned into ice are sublimated; and finally, bound water is removed during the desorption phase. To complete the drying process effectively, it is crucial to accurately analyze drying kinetics, decide the best drying time, and regularly check moisture loss data. Mathematical models derived from parameters such as effective diffusion coefficient (Deff), moisture ratio (MR), and drying ratio (DR) are considered important criterion in evaluating the performance of FD process. In addition, kinetic models are mathematical relationships used to analyze chemical transformations and drying rates. These empirical models contribute to studying the dynamics of the drying process and improving process conditions [20].

In this study, statistical and mathematical predictive techniques were used to examine the freeze-drying kinetics of fresh ginger slices of varying thickness. Throughout the drying process, the products' MR and DR values were checked, and agreement between model predictions and experimental data was assessed. The best model enables analysis of ginger drying under various conditions and optimization of freeze-drying process parameters, such as temperature and time. According to a review of drying studies in the literature, there is a dearth of research examining the drying behavior of fresh ginger slices of varying thicknesses and deciding the best kinetic models. Drying kinetic models were solved using MATLAB, and the most proper kinetic model was decided based on statistical parameters such as correlation coefficient (R^2), chi-square (X^2), and root mean square error (RMSE). In this study, a suitable kinetic drying model was found for ginger slices using the FD process. Samples of 100g of ginger slices, 5 and 7 mm thick, were placed in the drying device and were removed every two hours over a 14-hour drying period to obtain weight-loss data. Ten drying-kinetic models were fitted to the data using MATLAB.

2. Material and method

2.1. Drying equipments

Fresh ginger samples were obtained from a local farm. After purchase, these samples were precisely sliced to thicknesses of 5 mm and 7 mm. Following slicing, the samples were weighed using a 300-g-capacity scale with a precision of 0.001 g. Fourteen samples were prepared, seven for each thickness, ensuring a constant mass of 100 g per sample. After these procedures, 14 samples were numbered and frozen. Once completely frozen, they were placed in a deep freezer set to -30°C and left there for one day. After freezing, the samples were placed in the FD. The subject device offers several configuration options to tailor the FD process to specific experimental needs. For a long working life, the condenser of the device is coated with Teflon, a material that is easy to clean and provides corrosion protection, particularly when dealing with aggressive acidic chemicals [21,22]. The FD device was designed to dry samples that require evaporator temperatures as low as -55°C. During the experiment, the pressure within the closed volume of the drying device was reduced to a critical value of 0.01 kPa. To achieve this critical value, a vacuum pump with a vacuum power of 1×10^{-4} mbar was connected to the device. To create the necessary drying conditions, the vacuum pump was run using the device's vacuum capacity until the pressure dropped from a first pressure of 4×10^{-4} mbar to a target pressure of 0.01 kPa. The FD device used in the tests is shown in Figure 1.

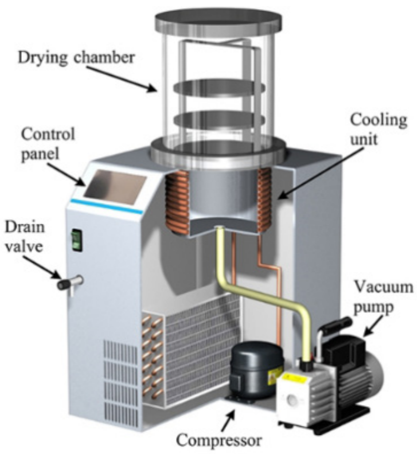


Figure 1. FD device and components

Seven ginger samples, each of the same weight and cut to different thicknesses, were prepared. These samples were frozen and placed in an FD set according to a pre-programmed protocol. After drying was complete, the products were removed from the FD device and placed in an oven to cut residual moisture. In this process, the samples were kept at 105°C for 45 minutes. The final weights of the samples after moisture loss were measured and recorded.

2.2. Drying behavior

During the drying process, the experimental MR and DR value of the ginger samples were calculated using Equations (1) and (2), respectively. To reveal the drying behavior of the samples and to decide the most suitable mathematical model, a comprehensive analysis was conducted using ten different drying models presented in Table 1. These kinetic models were chosen because they are consistent with earlier drying studies and are suitable for the current experimental conditions. A detailed statistical evaluation was performed to decide the model with the highest prediction accuracy. In this context, the performance of each model was compared considering statistical criteria such as the chi-square (X^2) expressed by Eq. (3) and the root mean square error (RMSE) given by Eq. (4). The goal was to minimize the values of these parameters to improve model accuracy [23]. In addition, R^2 was employed as one of the significant performance indicators, whereby higher values of R^2 indicate improved association between model-predicted values and experimental data [24]. Based on these assessment measures, the most relevant mathematical models describing the drying characteristics of freeze-dried Ginger slices were decided, providing a good platform to explain the kinetics of moisture desorption under the experimental conditions [1].

$$MR = \frac{M_t - M_d}{M_0 - M_d} \quad (1)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

where M_t is the moisture content at time (g water/g dry matter), M_0 is the initial moisture content (g water/g dry matter), M_d is the final equilibrium moisture content (g water/g dry matter), Mt+dt is the moisture content at time t +dt (g water/g dry matter), and t is the drying time (min). The FD process, applied in each sample's dehydration, took a total duration of 14 hours. The specific temperature and time profile employed during the process is diagrammatically shown in Figure 2. All samples were initially subjected to a controlled freezing regime that decreased to -15°C [25]. Because it enables moisture molecules within the substances to change into ice crystals and proliferate, the first freezing step is essential. This procedure helps to keep the integrity of the sample while minimizing the possibility of structural damage during later drying steps. The drying process starts at -40°C and 0.01 kPa pressure for an hour after this first freezing. Under these conditions, the first drying step enables the direct conversion of ice crystals into the vapor phase, hence cutting moisture and easing sublimation, the essential mechanism of the FD process. In contrast to earlier studies, the temperature and pressure are gradually raised in a regulated manner while keeping the pressure constant in the later step. First, samples are stored for three hours at -30°C. The same procedure is then used for two hours at each of the following temperatures: -20°C, -10°C, 0°C, and 5°C. For the last hour, the drying process is finished at 10°C. This temperature increase during the second drying stage removes any remaining bound moisture, thereby increasing the efficiency of the process. It is also used to further reduce the final moisture content of freeze-dried samples.

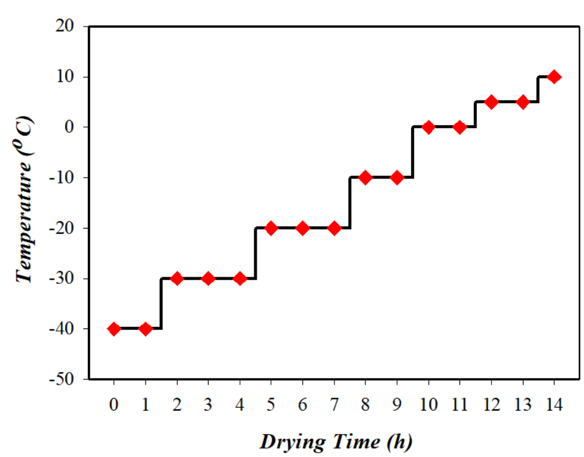


Figure 2. Temperature change of product during FD

During the 14-hour FD process, temperatures must be carefully controlled to minimize chemical changes in the ginger slices and to achieve the correct moisture content. This controlled process resulted in the complete freeze-drying of all products. After calculating the moisture content of the samples and recording weight losses over 14 hours, graphs were generated to decide the most suitable model among ten different models [26]. MATLAB was used to perform these analyses. Table 1 shows ten drying kinetic models, implemented in MATLAB, that predict MR.

Table 1. Drying kinetic models

Model No.	Model Name	References
1	Newton	[27]
2	Page	[28]
3	Two Term	[29]
4	Two-Term Exponential	[1]
5	Henderson and Pabis	[1]
6	Logarithmic	[27]
7	Wang and Singh	[29]
8	Diffusion Approach	[29]
9	Verma et al.	[27]
10	Midilli et al.	[30]

To statistically compare the relationship between the experimentally calculated MR values and the MR values predicted by the kinetic models, RMSE, X^2 values, and R^2 were calculated using the equations given in Equations (3), (4), and (5) respectively, for model validation [31].

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right]^{\frac{1}{2}} \quad (3)$$

$$X^2 = \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{N - z} \quad (4)$$

$$R^2 = \left[1 - \frac{\sum(MR_{pre,i} - MR_{exp,i})^2}{\sum MR_{exp}^2}\right] \quad (5)$$

where N is the number of observations performed, MR_{pre} is the estimated moisture content, and MR_{exp} is the experimentally calculated moisture content. D_{eff} is an important property affected by both the moisture content and temperature of the samples. As explained below, solving this equation provides a theoretical concept for studying drying kinetics [32,33]. Fick is known as the first scientist to use the solution of the diffusion equation for a flat shape in Eq. (6). Fick based his analyses on several fundamental assumptions [34].

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \quad (6)$$

Fick's second law of diffusion, or the mass-diffusion equation, considers the temporal and spatial variation in concentration of the diffusing entity. In this context, diffusion is proposed to be one of the most critical transport properties, depending on both the moisture level and temperature of the samples. Fick's second law solution, which generally takes various forms depending on the boundary conditions and system geometry, forms the basis for analyzing effective diffusion behavior in drying processes [35]. From such a solution, one can quantify moisture movement in the material as a function of space and time and ultimately predicting drying rate and final MC [36]. Dimensionless quantity of diffusing water in terms of first uniformity of moisture, uniform diffusivity, inert shrinkage, and negligible external resistance can be expressed as;

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

In Eq. (7), diffusivity is now D_{eff} (m^2s^{-1}), half-thickness of the samples is L(m), drying time is t(s), and m is a positive integer. The plotting of ln (MR) against drying time from experimental process data allows calculation of D_{eff} values. The slope of the straight line of the plot is denoted by K and can be calculated as [27].

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (8)$$

3. Results and discussion

Weight loss was decided by monitoring mass loss of the samples over time on a high-precision balance of high precision during which FD. All the samples had a first weight of 100g. There was, however, some residual moisture content in the samples following freeze-drying. That is, samples of 5mm thickness weighed 5.938g of product remaining, while those of 7mm weighed 7.485g.

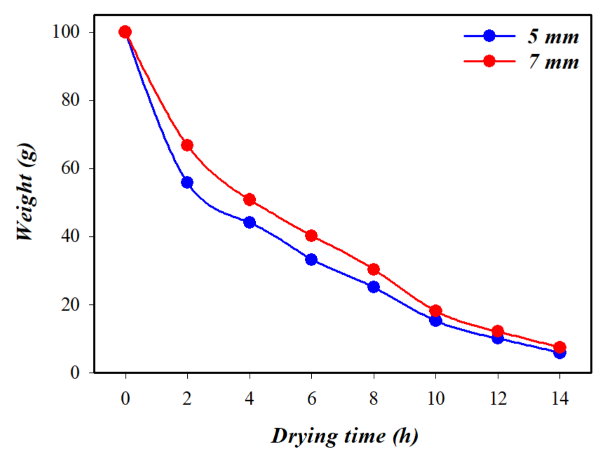


Figure 3. Weight loss of ginger slices over time

The temporal variation of mass loss during the FD process of ginger samples is shown in Figure 3, in which the measurements were made at two-hour intervals. Figure 4 illustrates variations in moisture amount (MA) of the ginger slices under FD conditions. The outcome showed that 14 hours were needed for the drying process to achieve the final MA. It can be said for thin layers of ginger slices that the FD caused slow moisture content reduction as expected. Freeze-drying kinetics of several fruits have been investigated in various studies.

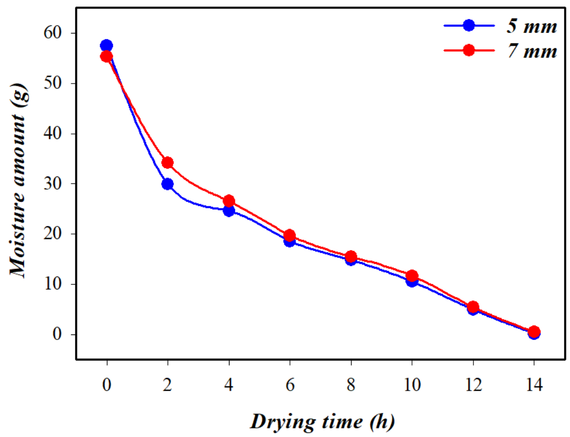


Figure 4. The moisture number of ginger slices over time

The drying rates of ginger samples during the 14-hour FD process are presented in Figure 5. As can be seen from Figure 5, the drying rate was significantly higher during the first two hours, particularly due to the high moisture content on the sample's upper surface. After the first two hours, the drying rate decreased rapidly. This observation is thought to be due to the low shelf temperature of the device. After this time, the drying rate decreased by 2-3%. However, with increasing shelf temperature, the drying rate gradually decreased until the 12th hour. After this time, the drying rate remained almost constant.

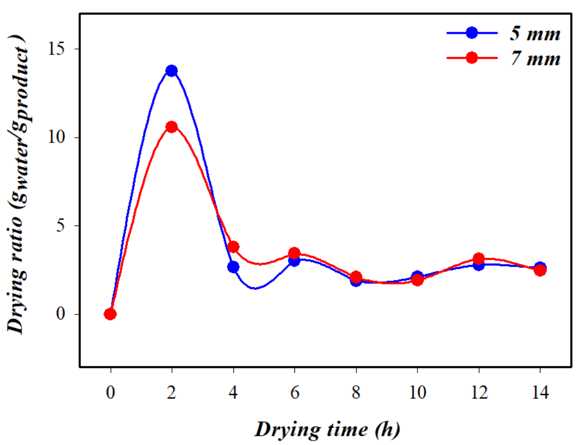


Figure 5. Drying ratio of ginger slices over time

As seen from Figure 6, the moisture ratio showed a steady decline from 1 to 0.7 during the first two hours, and the declined trend extended to the 14th hour of drying. Because Figures 5 and 6 are explained based on a mass transfer mechanism perspective, it can be noted that the moisture content decreased rapidly during the first two hours. This is because of the large transfer of moisture from the outside surface of the specimen to the surrounding environment. Thus, an extraordinary reduction in the absolute moisture content and the moisture ratio of the specimen was seen. This phenomenon highlights the contribution of surface moisture evaporation in the first drying phase, which leads to added moisture loss as drying progresses.

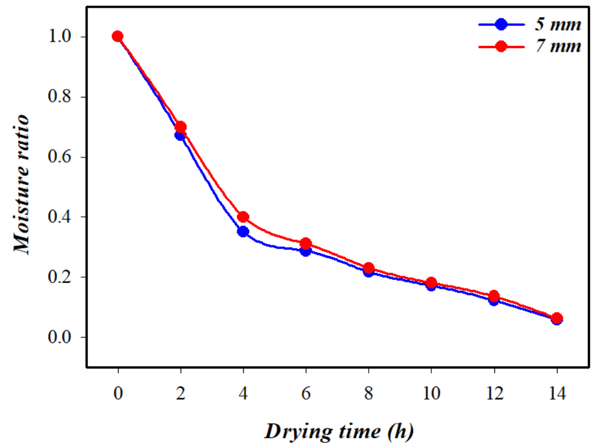


Figure 6. Moisture ratio of ginger slices over time

The experimental data obtained from the FD process of ginger slices were analyzed using ten empirical models, as shown in Table 1, where the semi-empirical kinetic drying models are presented. The parameters of the models were determined to be the drying behavior, while Table 2 presents the statistical evaluation of the models based on R^2, X^2, and RMSE. According to the literature, kinetic drying models with the highest R^2 value and lowest X^2 and RMSE values are the best in being the drying process [39]. R^2 values for the drying models used in this study range from 0.9170 to 0.9986; the highest and lowest R^2 values were obtained when using the Logarithmic Model for 5mm and 7mm. In the logarithmic model, the X^2 values were calculated to be between 1.153×10^{-3} and 1.402×10^{-3}. Similarly, RMSE values vary between 0.03211 and 0.03411, as calculated by the Logarithmic Model. Figure 7 illustrates the comparison between experimental data and predictions of FD kinetic models for moisture ratio and drying time.

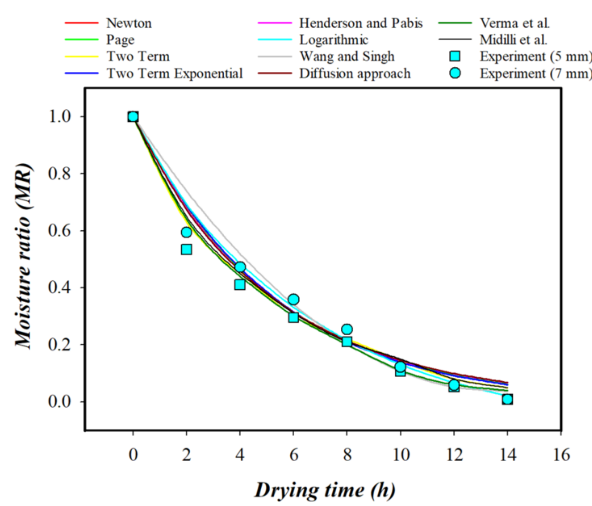


Figure 7. Comparison of moisture ratios of kinetic drying models and experimental results

Based on a general evaluation of the drying models, the logarithmic model was found to be the most suitable model for freezing ginger samples. Marques et al. [37] using the FD process, suggested drying times of 10 hours for crushed acerola fruit and 12 hours for sliced acerola fruit. In a separate study, Akar and Barutçu-Mazi [38] investigated the drying of kiwifruit samples using different methods and suggested a freeze-drying time of 1440 minutes to reach a moisture content of approximately 11% on a dry basis. The calculated drying rates showed a characteristic decreasing trend during the FD process. As can be understood from the slope of the curve, the drying rate is initially sharper, showing a faster moisture uptake.

Table 2. Statistical results obtained from the application of ginger slices to drying models

Order	Model Name	Thickness (mm)	Parameters of Models	R2	X2 (10-3)	RMSE
1	Newton	5	k = 0.229	0.9793	2.195	0.04686
		7	k = 0.1937	0.9865	1.160	0.03886
2	Page	5	k = 0.3018, n = 1.8417	0.9860	1.734	0.04165
		7	k = 0.1829, n = 1.031	0.9868	1.732	0.04162
3	Two Term	5	a = 1.14, b = -0.137, k_0 = 0.00558	0.9852	1.610	0.04110
		7	a = 1.07, b = -0.121, k_0 = 0.00614	0.9757	1.410	0.05110
4	Two-Term Exponential	5	a = 0.1509, k = 1.304	0.9886	1.418	0.03753
		7	a = 1.421, k = 0.2201	0.9873	1.664	0.04079
5	Henderson and Pabis	5	a = 0.9653, k = 0.2211	0.9781	2.326	0.04822
		7	a = 0.9953, k = 0.1928	0.9866	1.757	0.04192
6	**Logarithmic**	**5**	**a = 0.969, c = -0.0058, k = 0.217**	**0.9902**	**1.402**	**0.03211**
		7	**a = 1.09, c = -0.1169, k = 0.148**	**0.9986**	**1.153**	**0.03411**
7	Wang and Singh	5	a = -0.1605, b = 0.00667	0.9335	2.719	0.08400
		7	a = -0.1407, b = 0.005137	0.9806	2.543	0.05044
8	Diffusion Approach	5	a = 0.1654, b = 0.04408, k = 4.35	0.9812	2.786	0.05278
		7	a = 0.0129, b = 0.05644, k = 3.39	0.9867	2.093	0.04575
9	Verma et al.	5	a=0.932, k = 0.0598, g = 0.572	0.9532	1.701	0.05541
		7	a=0.8812, k = 0.00224, g = 0.447	0.9684	1.886	0.04424
10	Midilli et al.	5	a=0.54, k = 0.41, n=1.10, b=0.017	0.9870	2.019	0.04669
		7	a=0.66, k = 0.52, n= 0.998, b=0.019	0.9170	2.971	0.04500

Note: Terms written in bold show the best results.

When deciding the most suitable drying model among these, the agreement between experimental and mathematical results is crucial. For this purpose, the logarithmic model has been suggested as the most suitable model for the FD process of ginger samples among kinetic models. While the models discussed can be applied to different materials under different parameters, they are not used due to the large number of variables needed for their complex structures and solubility. In contrast, semi-empirical models are described with simple mathematical expressions. Because the equation parameters are valid for specific samples, their applicability is limited. Drying rates can be decided not only by classical mathematical expressions but also by experimental methods. Furthermore, equations derived from experimental data are only applicable to the specific samples and conditions on which they are based. The logarithmic model, a semi-empirical model, is perhaps the most well-known and widely used. Table 3 illustrates the comparison of the experimental results with the percentage error of the kinetic drying models, while Figure 8 gives the comparison of the experimental moisture ratio against the Logarithmic Model over the duration of the drying process. Based on the mean percentage error of the kinetic drying models, the Logarithmic Model has a smaller mean error rate of 8.39%, 8.42% for 5mm and 7mm ginger compared to other models. Moreover, considering long-term drying, the Logarithmic Model follows a smaller mean percentage error of 13.82%, 13.73% for 5mm and 7mm ginger, than the other kinetic drying models at the 14th hour.

Table 3. Comparison of percentage errors between experimental and kinetic drying models

Drying Time (h)	Thickness (mm)	The Experiment	Newton Model	Page Model	Two Term Model	Two Term Exponential Model	Henderson & Pabis Model	Logarithmic Model	Wang & Singh Model	Diffusion Approach Model	Verma et al. Model	Midilli et al. Model
0	5	1	0.00%	0.00%	1.20%	2.40%	3.59%	**0.00%**	1.80%	1.50%	0.75%	1.35%
	7	1	0.00%	0.00%	0.16%	0.31%	0.47%	**0.00%**	0.24%	0.20%	0.10%	0.18%
2	5	0.534095	18.43%	8.27%	13.53%	13.72%	13.90%	**5.43%**	13.63%	13.58%	16.01%	14.40%
	7	0.643684	5.46%	6.46%	5.61%	5.25%	4.90%	**5.46%**	5.43%	5.52%	5.49%	5.48%
4	5	0.410599	2.55%	8.24%	4.60%	3.80%	3.00%	**2.55%**	4.20%	4.40%	3.48%	4.03%
	7	0.472941	2.57%	1.51%	2.27%	2.51%	2.75%	**2.57%**	2.39%	2.33%	2.45%	2.39%
6	5	0.295581	14.37%	15.58%	15.11%	15.25%	15.38%	**12.37%**	15.18%	15.15%	14.76%	15.03%
	7	0.358727	12.80%	14.44%	13.95%	14.28%	14.60%	**12.80%**	14.11%	14.03%	13.42%	13.85%
8	5	0.210677	24.01%	19.69%	23.89%	25.94%	27.98%	**8.01%**	24.92%	24.40%	24.21%	24.51%
	7	0.253751	16.32%	20.83%	18.79%	19.00%	19.21%	**8.32%**	18.89%	18.84%	17.58%	18.44%
10	5	0.106456	4.87%	13.40%	6.30%	3.47%	0.63%	**4.87%**	4.88%	5.59%	5.23%	5.24%
	7	0.122455	17.71%	12.69%	15.27%	15.34%	15.41%	**4.71%**	15.30%	15.28%	16.49%	15.69%
12	5	0.052659	21.64%	29.35%	24.51%	23.53%	22.54%	**11.64%**	24.02%	24.27%	22.95%	23.75%
	7	0.058468	17.34%	27.42%	28.46%	34.53%	40.61%	**11.34%**	31.49%	29.97%	23.66%	28.38%
14	5	0.008172	15.82%	26.80%	24.64%	27.97%	31.29%	**13.82%**	26.30%	25.47%	20.64%	24.14%
	7	0.008584	23.73%	26.18%	29.03%	33.10%	37.18%	**13.73%**	31.07%	30.05%	26.89%	29.33%
Average	5	-	14.53%	17.33%	16.26%	16.58%	16.90%	**8.39%**	16.42%	16.34%	15.43%	16.06%
	7	-	13.70%	15.65%	16.22%	17.76%	19.30%	**8.42%**	16.99%	16.60%	15.15%	16.25%

Note: Terms written in bold show the best results.

The correlation between the MR values obtained from the predicted Logarithmic Model and the experimentally obtained MR values is presented in Figures 8 and 9 for 5 mm and 7 mm, respectively.

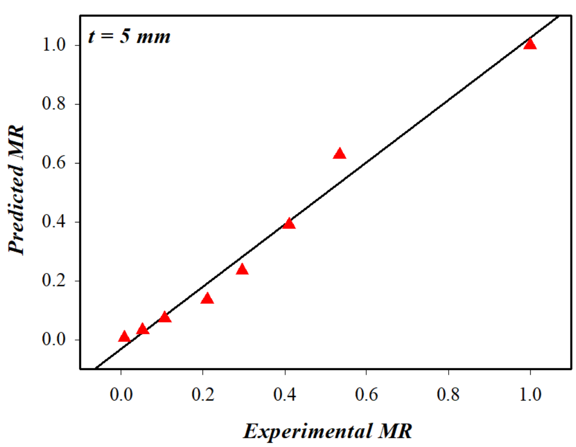


Figure 8. Comparison of the Logarithmic Model and experimental moisture ratio values for 5 mm sample

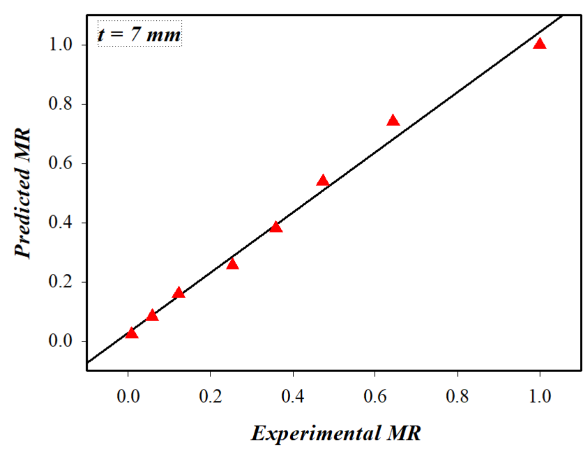
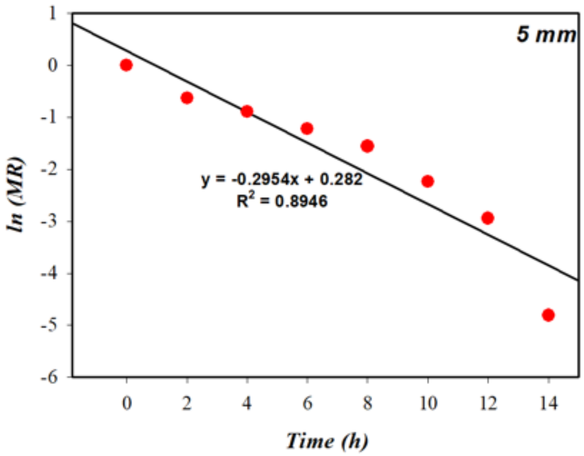
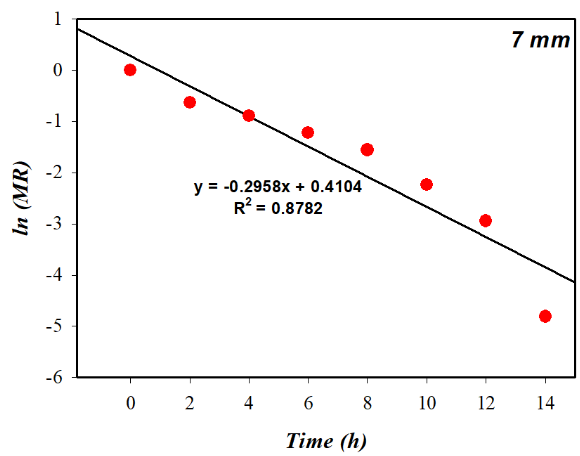


Figure 9. Comparison of the Logarithmic Model and experimental moisture ratio values for 7 mm sample

As can be seen from Figures 8 and 9, the data points are like the reference line, showing strong agreement between the Matlab-predicted and actual values. This agreement proves that the Logarithmic Model is a reliable approach for adequately being the drying characteristics of ginger samples. However, its applicability is limited because the inequality parameters are only valid for the same products [39].



(a)



(b)

Figure 10. Change of ln (MR) with time for the Ginger sample

From the average percentage error of the kinetic drying models, the Logarithmic Model has a lesser average error rate of 8.39%, 8.42% for 5 and 7 mm Ginger compared to the other models. Again, for long duration drying, the Logarithmic Model is better than the other kinetic drying models with an average percentage error of 13.82%, 13.73% for 5 and 7 mm Ginger at the 14th hour. FD kinetics reported for Ginger by Shishehgarha et al. [39]. Their observation also showed a first high drying rate that decreased progressively toward the end of the process. This phenomenon can be attributed to increasing resistance to heat and mass transfer presented by the dry layer formed as drying proceeds. This is also verified by Kırmacı et al. [40], who also saw a first higher drying rate with a continuous decline thereafter in the FD of Ginger. Figure 10 illustrates how the slope (K) is obtained from the plot of experimental data. Using Eq. (8) and the slope value calculated, the D_{eff} for 5 and 7mm thick Ginger slices was decided as 2.075×10^{-7} m^2s^{-1} and 4.079×10^{-10} m^2s^{-1}, respectively. This D_{eff} value determined is well within the range of 10^{-12} to 10^{-8} m^2s^{-1}, typically reported for drying of food materials of varying types. A thorough literature review revealed that research on the specific kinetic modeling of Ginger, variety-wise, was lacking [41]. Nobody had ever tried to measure the effective diffusivity or moisture content of Ginger in the FD process before. Therefore, this study reports novel data on these significant parameters. The D_{eff} value of Ginger calculated is in good agreement with the general D_{eff} range reported in the literature for other dried food products, which proves that the mass transport phenomena occurring during the FD of Ginger are consistent with basic principles of food drying.

4. Conclusion

FD is the most popular dehydration method for a great number of foodstuffs, including fruits, vegetables, spices, and even nonsensical food materials. In the present work, the FD phenomenon of ginger with two different thicknesses (5 and 7 mm) has been studied with both experimental and statistical methods. The results proved that the FD process can be used to dry ginger with high accuracy. To characterize the drying behavior, the MR was experimentally measured, and the obtained data were modeled with ten empirical drying models to decide the most proper one for simulating weight loss in FD. The kinetic models examined, the Logarithmic Model best described the drying characteristic of Ginger for both thicknesses of 5 and 7 mm for the entire FD process. The Logarithmic Model was determined to be the best to accurately describe the drying kinetics of the ginger for both 7 and 5 mm samples.

- For the 5mm samples, the model's statistical parameters showed high predictive power, with R^2, X^2, and RMSE values of 0.9902, 1.402×10^{-3}, and 0.03211, respectively. For samples with a thickness of 7 mm, the model's statistical metrics similarly proved strong predictive power, with R^2, X^2, and RMSE values of 0.9986, 1.153×10^{-3}, and 0.03411, respectively.
- The Logarithmic Model has the lowest error rate among the kinetic models analyzed, showing that it is a good fit for understanding the FD behavior of ginger.
- When comparing experimental results, the logarithmic model revealed an error rate of 8.39% for 5 mm samples and 8.42% for 7 mm samples. This illustrates how well the logarithmic model describes the drying behavior of ginger products of various thicknesses.
- D_{eff}, further, was determined to be 2.075×10^{-7} m^2s^{-1} for the 5mm and 4.079×10^{-10} m^2s^{-1} for the 7mm samples. These values are nicely related to Deff values reported for several food commodities, again endorsing the validity of the drying model in the simulation of the FD behavior of ginger at various thicknesses. The foregoing results illustrate the stability of the Logarithmic Model in predicting FD kinetics of ginger and providing meaningful information for perfecting FD conditions in related food products.

Nomenclature

a, b, c, n	Dimensionless constants
FD	Freeze-Drying
DR	Drying rate [g water/g dry matter]
M_d	The final equilibrium moisture content
M_t	The moisture content at a time t
N	Number of observations [-]
L	Half-thickness of samples [m]
MR_{pre}	Predicted moisture ratio [-]
MR	The moisture ratio [-]
R^2	Coefficient of determination
MC	Moisture content [g water/g dry matter]
D_{eff}	The effective diffusivity [m]
MR_{exp}	Experimental moisture ratio
M_0	The first moisture content
RMSE	Root means square error
X^2	Reduced chi-square
t	Time [min]
K	The determination of the slope

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Authors contribution

Dağdeviren: Conceptualization, Writing – review & editing, Writing – original draft, Data curation; Y. Daşdemirli: Project administration, Methodology; B. Acar: Software, Supervision, Writing – review & editing, Writing – original draft, Data curation; M. G. Mohammed: Formal analysis, Writing – review & editing, Writing – original draft, Visualization; Ö. İnanç: Data curation.

Declaration of interests

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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