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Freeze drying process of kiwi slices with various thicknesses and investigation drying characteristic of process

Farklı kalınlıklara sahip kivi dilimlerinin dondurulması ve kurutma işlemi özelliklerinin incelenmesi

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Freeze Drying Process of Kiwi Slices with Various Thicknesses and Investigation Drying Characteristic of Process

Highlights

- *Investigation of Freeze-Drying characteristic of kiwi slices with various thicknesses.*
- *The proper kinetic drying model was specified by using MATLAB software.*
- *The effective diffusivity (D_{eff}) values were computed by drawing drying value.*

Graphical Abstract

The effective diffusivity (D_{eff}) values were computed by drawing experimental drying data in terms of ln (MR) was plotted versus time. The effective diffusivity coefficient must be ranged from 10^{-12} to 10^{-8} m^2/s for food products in literature and it is determined that the calculated effective diffusivity coefficients for kiwi products have good agreement with the literature.

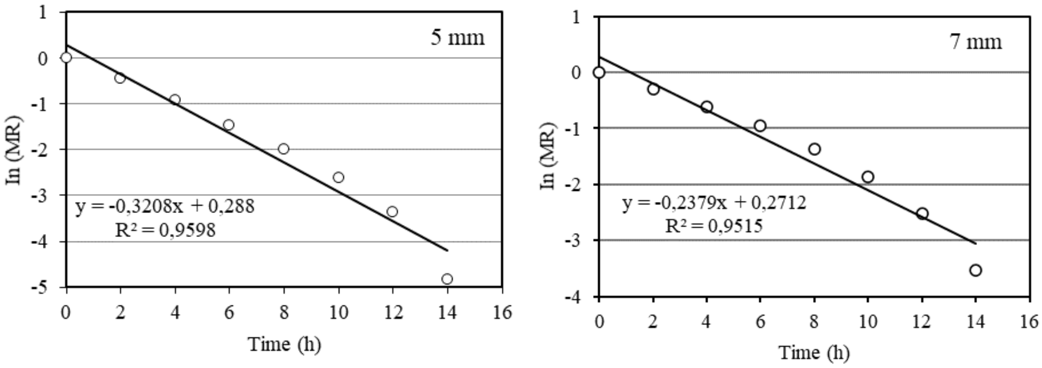

Figure. Plot of In (MR) versus freeze-drying time for kiwi samples

Aim

Aim of the present work was to identify the proper kinetic drying model by calculating MR and DR values for 8 different drying model with measuring mass losses in every two hours.

Design & Methodology

The kiwi fruit was sliced into various thicknesses as 5 mm and 7 mm, and those sliced specimens were put in the freeze-drying device. Considering the experimental results, 8 different kinetic drying models were performed using MATLAB software.

Originality

Freeze-drying process of kiwi slices with various thicknesses and investigation drying characteristic of process.

Findings

Results have shown that the effective diffusivity coefficients were within the limits that were presented in the literature as 10^{-12} – 10^{-8} m^2/s for food products. Among the 8 different kinetic drying models, the Logarithmic model was chosen as a proper kinetic drying model for kiwi products.

Conclusion

The proper kinetic drying model was specified by calculating MR and DR values for 8 different drying model with measuring mass losses in every two hours. The proper kinetic drying model was the Logarithmic model because the R^2 value was about 0.9999, X^2 values for 5mm and 7mm thicknesses were about $8.261x10^{-6}$ and $1.705x10^{-5}$, RMSE values for 5 mm and 7 mm were about 0.002865 and 0.004146 respectively.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission

Freeze Drying Process of Kiwi Slices with Various Thicknesses and Investigation Drying Characteristic of Process

Araştırma Makalesi / Research Article

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ABSTRACT

In the study, the kiwi fruit was sliced into various thicknesses as 5 mm and 7 mm, and those sliced specimens were put in the freeze-drying device. the mass losses of the specimens were measured and saved during the drying process and kinetic drying models were performed using those measurements. The mass losses of each kiwi slices in 100 g mass were measured every two hours in the experiment lasting 14 hours in total and moisture ratios (MR) were calculated as well. Considering the experimental results, 8 different kinetics drying models were performed using MATLAB software. As a result, the lowest reduced chi-square (X^2) values for 5 mm and 7 mm thicknesses were calculated about $8.261x10^{-6}$ and $1.705x10^{-5}$ respectively, the root means square error values (RMSE) were about 0.002865 and 0.004146, respectively. Also, the coefficient of determination (R^2) for both thicknesses was calculated as 0.9999 which was the highest result closest to 1. Among the 8 different kinetic drying models, the Logarithmic model was chosen as a proper kinetic drying model for kiwi products. When the moisture contents and drying rates were considered it was seen that the drying rate of kiwi slices with 7 mm thickness exhibited slow behavior because of the higher moisture content. Besides, it was determined that the effective diffusivity coefficients for specimens with 5 mm and 7 mm thickness were calculated as 2.25×10^{-10} m^2/s and 3.28×10^{-10} m^2/s respectively.

Keywords: Drying kinetics, drying of kiwi, kinetic drying model, logarithmic model.

Farklı Kalınlıklara Sahip Kivi Dilimlerinin Dondurulması ve Kurutma İşlemi Özelliklerinin İncelenmesi

ÖZ

Bu çalışmada kivi meyvesi 5 mm ve 7 mm kalınlıklarında dilimlenmiş ve dilimlenen numuneler dondurularak kurutma cihazına konulmuştur. Kurutma işlemi sırasında numunelerin ağırlık kayıpları ölçülerek kaydedildi ve bu ölçümler kullanılarak kinetik kurutma modelleri gerçekleştirildi. Toplam 14 saat süren deneyde 100 gr ağırlıktaki her bir kivi diliminin ağırlık kayıpları iki saatte bir ölçülerek nem oranları (MR) da hesaplanmıştır. Deneysel sonuçlar ışığında MATLAB yazılımı kullanılarak 8 farklı kinetik kurutma modeli gerçekleştirilmiştir. Sonuç olarak, 5 mm ve 7 mm kalınlıklar için en düşük indirgenmiş ki-kare (X^2) değerleri sırasıyla yaklaşık $8.261x10^{-6}$ ve $1.705x10^{-5}$ olarak hesaplandı, kök ortalama kare hata değerleri (RMSE) ise 0.002865 ve 0.004146 hesaplanmıştır. Ayrıca, her iki kalınlık için belirleme katsayısı (R^2) 1'e en yakın en yüksek sonuç olan 0.9999 olarak hesaplanmıştır. 8 farklı kinetik kurutma modeli arasından kivi ürünlerinin her iki kalınlıkları içinde uygun olan kinetik kurutma modelinin Logaritmik kurutma modeli olduğu gözlemlenmiştir. Nem içerikleri ve kuruma oranları göz önüne alındığında 7 mm kalınlığındaki kivi dilimlerinin kuruma hızının, daha yüksek nem içeriği nedeniyle yavaş davranış sergilediği görülmüştür. Ayrıca 5 mm ve 7 mm kalınlığındaki numuneler için efektif difüzivite katsayılarının sırasıyla $2,25 \times 10^{-10}$ m^2/s ve $3,28 \times 10^{-10}$ m^2/s olarak hesaplanmıştır.

Anahtar Kelimeler: Kurutma kinetiği, kivinin kurutulması, kinetik kurutma modeli, logaritmik model.

1. INTRODUCTION

The kiwi is an indigenous fruit to northern central China according to the literature and the Actinidia plant has 60 different types of species. The commercialization of these fruits has been started at the beginning of the 20th century and "Hayward" farming is the well-known and commercialized method for kiwi fruit [1]. It has rich content in terms of nutrition content such as having dietary fiber, bioactive compounds as vitamins (C, E, and A vitamins, etc.) phenolic compounds and minarels.

Kiwi fruit contains about 1 kilogram of vitamin C in citrus. In addition to the antioxidant property of the kiwi fruit, the essential factor is to strengthen the immune system is containing a high amount of C vitamin in it [2]. Besides, it helps the softening of the skin and prevents the skin against wrinkles. Moreover, it provides the production and proliferation of the blood cells. It helps the digestive system because of containing a high amount

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of fiber and strengthens it as well. It protects the whole structure of human to the various diseases by strengthening the immune system if it especially is eaten in the winter period. Contributing to the slimming by cleaning the intestine by eliminating flatworms and free radicals from the body and activating functionless and/or slow operating intestine can be considered other benefits of the kiwi fruit [3,4].

The kiwi production in Turkey was started in 1994. Over the past years, Turkey has been among the top ten countries in the kiwi production. An average of 40 thousand tons of kiwi is produced annually in 21 provinces throughout the country. Yalova is in the first place of kiwi production in Turkey. Ordu and Rize are also among the top three with product volumes varying over the years [5]. In recent years, kiwi production in the Black Sea Region has significantly increased [6]. On the other hand, kiwi fruit has less shelf life because the structure of it decays rapidly within time. The drying process has become a proper food protection method to store foods and increase the shelf life of food products. Many fruits need to be protected in several ways to extend their shelf lives [7]. Over the years, the drying processes have attracted the attention of the people because of increasing customers' resistance against the protecting food products using chemicals and the rising popularity of the high quality dried food products that have good rehydration properties [8]. From technological development, the rehydration process is the last step of industrial food processing and it determines the quality of the final product gradually. The common drying method in the food industry has been the hot air-drying duration. But there is a disadvantage of the hot air-drying duration. According to the studies, when fresh food products exposed to high drying temperatures for a lengthy time in the hot air-drying duration, the Physico-chemical properties of the fresh product changed dramatically [9,10]. It can be considered that the most properties of the kiwi product, especially the amount of the C vitamin level, can be affected by drying conditions [11,12]. For this purpose, many studies in national and international literature have been performed on the drying process of the kiwi fruit. Orikasa et al. [13] examined the drying properties of kiwi slices with 10 mm thickness and changes of L-ascorbic acid by the hot air-drying process using four different temperature levels ranged from 40 °C to 70 °C. In the experiments, they observed the intercourse among the drying rate and the hardening of the kiwi surface. They performed the exponential model for the first drying period and diffusion equations for the second drying period as well using experimental results. Changes of empirical moisture content for both models were accepted. The diffusion coefficients were determined as 3.79×10^{-12} m^2/s and 7.53×10^{-12} m^2/s. They used an Arrhenius type equation to correlate the diffusion coefficient of the kiwi fruit with temperature and examined actuation energy for the hot air-drying process of kiwi fruit. Besides, they predicted that the drying ratio of kiwi fruit can increase by preventing the hardening of the sample surface. They performed a first-order ratio equation to changes in decomposition of L-ascorbic acid content during the drying process to investigate nutrition changes of the kiwi fruit throughout the hot air-drying process. Thus, they determined that the activation energy was about 38.6 kj/mol for decomposition during the hot air-drying process of kiwi. Femenia et al. [14] have revealed the effects of air-drying temperature on the cell wall compounds of three-set fresh kiwi fruit that were in various ripening period. They observed that modifications that are effected on the Physico-chemical properties of polysaccharides in cell wall depended significantly on not only used air drying temperatures (range from 30 °C to 90 °C) but also the first step of the ripening period of processed kiwi fruit. Thus, when the fresh fruits compared with dehydrated and underripe kiwi fruits, it was determined that they exhibited much better protection of general cell wall compounds and ripe kiwi fruits were more sensitive to the cell wall distortion and temperature as well. Besides, the heating showed significant changes in the methyl-esterification (DME) grade of pectins. In general, it was estimated that the increment of DME caused the rising of the ripening level of the processed specimens and higher resistance exhibition against the distortion by the heating process. As a result, they showed both the importance of the ripening period for determining the final quality of the cell wall and considering the properties of dietary fiber (DF) obtained from processed kiwi specimens. Özdemir et al. [5] based on the kiwi drying process using heat recovery infrared drying system under various drying temperatures with 0.5 m/s constant airspeed. Besides, they investigated the energy consumption of the system and the drying kinetic of the product by performing artificial neural networks (ANN). They showed that energy efficiency ranged from 2.85% to 32.17%. They performed the ANN model to compute the energy consumption of the system and estimate the moisture ratio of the kiwi product. They calculated that the root means square error (RMSE), the coefficient of specification (R^2), that is absolute percentage error (MAPE) were 0.99, 0.001, and 0,34 respectively. Besides, they obtained that estimated results had good agreement with the experimental results. Zhou et al. [15] considered on the drying duration of kiwi fruits using the combined radio frequency-vacuum and hot air system. They researched the impact of the drying system on the drying homogenous, energy efficiency, and product quality as well. Two drying methods as a single specimen drying process and various combinations drying process were performed in a combined drying system to enhance energy efficiency and product quality and decrease the drying time. In the experiments, the kiwi slices with 6 mm thickness were dried with a three-layered drying process. Based on the previous studies, the electrode gap and vacuum were chosen as 95 mm and 20.1 kPa respectively for RFVK applications. As a result, it was seen that the total drying times were about 480 minutes for the RFVK method, 600 minutes for RFVK + SHK method, 900 minutes for the SHK method. Herein, it was determined that the shortest drying time was reached using the RFVK method. Besides, it was shown that the SHK method took almost twice the drying time and RFVK+SHK method higher than the RFVK method of about 20%. However, irregular drying models were observed in both RFVK and SHK methods. On the other hand, the RFVK + SHK method exhibited more homogenous moisture distribution both in fruit slices and between each other. Simal et al. [16] reported to the usability of three different mathematical models to investigate the drying kinetic of kiwi fruit. They investigated the drying characteristic of kiwi fruit in terms of average moisture content between 30 °C -90 °C temperature range using hot air within 4.65-0.15 kg water/kg dry matter range. It was seen that drying kinetic exhibited only a downward rate period. Besides, it was determined that the drying time of specimens decreased through hot air and this phenomenon affected the drying curves. They presented that the Page model supply the proper simulation results for kiwi drying curves. On the other hand, the Exponential model gave unsatisfying results lower than expected. Also, it was pointed out that the only diffusion model had sufficient simulation in defining step of the model parameters under the different temperatures and specimen geometry conditions. Maskan [18] experimentally examined on the drying properties of the kiwi slices with 5 mm thickness using hot air, microwave and combined hot air-microwave ways. In present study, drying ratios of drying regimes, shrinkage, and rehydration capacities were compared individually. It was sighted that drying with micro-wave energy or warm air-drying process combined with micro-wave caused the increasing the drying ratios and decreasing the drying time significantly. In addition, it was determined that the micro-wave drying process led to more shrinkage levels of the kiwi fruit than the hot air-drying process. It was presented that during the combined hot air-microwave method, the shrinkage level was lower than other drying processes. As a result, it was pointed out that dried kiwi slices using the micro-wave drying process had lower rehydration capacity and a rapid water absorption ratio when compared with other drying processes. Variyenli [19] designed and produced plane surface and incarcerating surface with absorber-plated drying ovens and compared performances of those as experimentally. In the experiments, kiwi slices with 4 mm and 6 mm thicknesses in 100 g mass were dried. The experiments were performed using different airspeeds As a result of experiments, it was determined that while the average temperature in the drying chamber was about 41.6 °C for plane surface drying oven, it was about 44.1 °C for incarcerating surface drying oven. At the end of experiments, it was concluded that the incarcerating surface drying oven performed the drying process in less than 30 minutes on average when compared with the plane surface drying oven. Kaya et. al. [20] was also investigated drying process of the kiwi fruits. They examined the effects of various drying conditions on the drying rate of kiwi fruits in terms of airspeed, temperature, and relative humidity. They performed numerical external flow and temperature simulation using CFD software. They outline the local distribution of surface convection heat transfer coefficients and mass transfer coefficient, by similarity approach between thermal and concentration boundary layers for fruits. Besides, time-dependent temperature and moisture distributions for different conditions could be obtained by advanced code that was developed for investigating heat and mass transfer properties in fruits. They compared the calculated results with experimental results, and it was emphasized that the calculated results had good agreement with the experimental results.

Considering the above findings, it is seen that several studies were performed on the drying processes. In this study, sliced kiwi fruit with various thicknesses dried by freeze-drying process and the proper kinetic drying model was determined by calculating mass losses along the drying duration and the drying characteristics were examined.

2. MATERIAL AND METHOD

In the study, the kiwi was sliced into 5 mm and 7 mm thicknesses with 100 g mass of each of them as seen in Figure 1 and placed into the plastic containers. 7 slices were prepared for each thickness and those slices were put into the deep freezer for a day and the experiments were performed after this process.

Figure 1. The kiwi specimens with 5 mm and 7 mm thickness

In the experiments, the Labogene brand Scanvac Coolsafe model freeze-drying device was used. In this device, the drying process could be achieved efficiently by means of decreasing the evaporator temperature to -55 °C. The freeze-drying device works with the vacuum pump equipment with 4×10^{-4} mbar power and the vacuum pressure were decreased to 0.01 kPa pressure in the experiments as well. Figure 2 shows the schematic view of the freeze-drying device used for the experiments. The fundamental principle of the freeze-drying machine is showed in Figure 2, depends on the performing of the sublimation process by increasing the temperature of the frozen product under lower pressure. Here, the vacuum pump helps the decreasing of the pressure in the drying cell and the compressor balanced the inner temperature of the freezing chamber as well. In the freeze-drying process, the product was put into the drying chamber at the beginning of the process and then the temperature and the pressure values were set on the control panel.

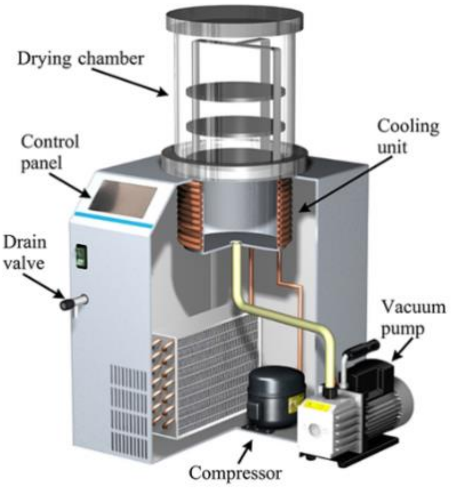

Figure 2. The schematic view of the freeze-drying device

The proper pressure, temperature, and time values were set on the control panel of the freeze-drying machine before the beginning of the process. The duration of the process took about 14 hours for each specimen. Time and temperature values were arranged as seen in Figure 3. The specimens were taken from the deep freezer at -15 °C and placed into the freeze-drying machine. The process was performed at -40 °C temperature under 0.01 kPa pressure for the first 60 minutes. After the first hour, the pressure was kept as constant and the temperature values were set as -30 °C for 180 minutes, -20 °C for 180 minutes, -10 ° for 120 minutes, 0 °C for 120 minutes, 5 °C for 120 minutes, and 10 °C for 60 minutes respectively.

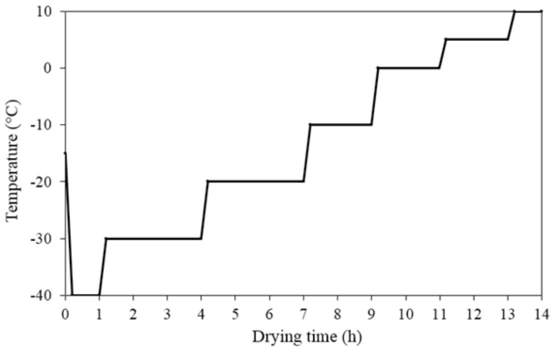

Figure 3. The temperature values as a function of drying time

The reason for preparing 7 dissimilar kiwi specimens is to measure mass losses in every two hours. For this, the first specimen was placed into the machine and the drying process was triggered. After the 120 minutes, the first specimen was taken out from the machine and the mass loss was measured using a precision scale with 0.001 g resolution. After the first specimen drying process, the second specimen was put into the machine and the drying process was performed during 4 hours using the same drying parameters. The previous mass loss calculating method was applied for the second specimen.

This sequacious drying process was applied for the rest of the kiwi specimens and the specimens were taken out from the machine at the end of 6th, 8th, 10th, 12th, and 14th hours. After this process, the specimens left into the drying oven for 60 minutes. When the specimen took out from the drying oven, it put into the desiccator for 15 minutes which has made from curved glass and contain plenty of silica gel in it. Afterward, the dried specimen took out from desiccator and the mass was measured using a precious scale. This process aims to remove moisture content from the product even if the freeze-drying process was completed. In this way, the accurate and precious calculation of the moisture ration in the product can be achieved. Empirical models can be applied to many materials and conditions. However, the usage of those models is decreased because the equations for solution contain several parameters and complex structures. On the other hand, although semiempirical models are fewer complex structures, the usage of these models is limited since the parameters in equations only related to the relevant product. The complex equations are not needed to determine the drying rate based on the values obtained by experimental methods. But the built equations only valid for the experimental specimens and experiment conditions as well. It is known that the logarithmic drying equation is the proper and commonly used equation in semiempirical models [21].

The moisture ratio (MR) is a non-dimensional term and it shows the changes of the kiwi as a function of time can be computed by equation (1). From this point, the drying rate (DR) can be calculated using equation (2) as well

$$MR = \frac{M_\mathrm{t} - M_\mathrm{d}}{M_0 - M_\mathrm{d}} \qquad (1)$$

$$DR = \frac{M_{\mathrm{t+dt}} - M_\mathrm{t}}{dt} \qquad (2)$$

In Equation 1, M_0, M_t, and M_d define the initial moisture, the moisture content at t moment, and balanced moisture respectively. The left section of Equation 1 gives the Moisture Ratio (*MR*) values of the drying process at various t moments. In Equation 2, *DR*, M_t, and M_{t+dt} indicate the drying rate, the moisture content at t moment, and the moisture content at t+dt moment respectively [22].

3. RESULT AND DISCUSSION

The experimental moisture ratio curve for kiwi slices with 5 mm and 7 mm thicknesses as a result of the freeze-drying process after 14 hours is shown in Figure 5.

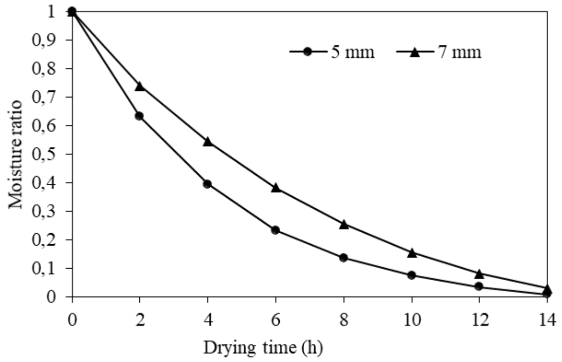

Figure 4. The moisture ratio curves of kiwi slices as a function of drying time

After determination, the moisture content of the product, and calculation of the time-dependent mass losses, the graphs dependent on the mathematical models were created and the most suitable and proper model of 8 different drying kinetic models was determined. In this step, MATLAB software was used for the determination kinetic drying model. Table 1 shows the 8 different kinetic drying models used in MATLAB to determine the estimated moisture ratio (MR) [23].

Table 1. Empirical and semiempirical equations for drying kinetics

Model no	Model name	Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page I	$MR = \exp[-(kt)^n]$
4	Henderson ve Pabis	$MR = a.\exp(-kt)$
5	Logarithmic	$MR = a.\exp(-kt) + c$
6	Two-term eksponential	$MR = aexp(-kt) + (1-a)\exp(-kat)$
7	Wang and Singh	$MR = 1 + at + bt^2$
8	Diffusion approach	MR = aexp(-kt)+(1-a)exp(-kbt)

Equation 3, Equation 4, and Equation 5 can be used to calculate root means square errors (RMSE) and reduced chi-square (X^2) of estimated values, and coefficient of decision (R^2) of kinetic models respectively to prove the agreement between moisture ratios obtained by experiments and estimated by kinetic models as a statistical approach [24,25].

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

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

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

In Equation 3, the root means square error (RMSE) indicates the deflection between the experimental value and the estimated kinetic model value. Besides, it is stated that the decreasing behavior of reduced chi-square (X^2) in Equation 4 shows the increment of the good agreement between experimental and kinetic model values. Besides, closing the coefficient of determination (R^2) in Equation 5 to 1 is an indicator that states the usability of the kinetic model. In the results of the statistical approach, the coefficients of the proper kinetic models are determined by multiple regression analysis.

In light of results obtained by experiment and kinetic drying models, 8 different kinetic drying models were applied, and the suitable and efficient drying model was determined. For this determination process, the criteria are dependent on the R^2, X^2, and RMSE values as well.

In Table 2, the calculated R^2, X^2, and RMSE results by 8 kinetic drying models are given. As seen in Table 2, when the R^2 and X^2 values are considered, the Logarithmic model is the proper kinetic drying model for both 5 mm and 7 mm thicknesses because the R^2 value of the Logarithmic model is 0.9999 as the closest value to 1 and the X^2 values for 5 mm and 7 mm thicknesses of the Logarithmic model are 8.261×10^{-6} and 1.705×10^{-5} respectively as closest values to 0. Moreover, the root means square error (RMSE) values for 5 mm and 7 mm thickness are 0.002865 and 0.004146 respectively as the closest values to 0 is another supporting factor that shows the suitability of Logarithmic model.

Table 2. The results calculated by 8 kinetic drying models

Model name	Specimen Thickness (mm)	Model parameters	R^2	X^2	RMSE
Newton	5	k: 0.2436	0.9979	2.528×10^{-4}	0.0159
	7	k: 0.1722	0.9882	1.380×10^{-3}	0.03717
Page	5	k: 0.2094 n: 1.092	0.9994	8.286×10^{-5}	0.009103
	7	k: 0.1159 n: 1.209	0.997	4.134×10^{-4}	0.02035
Modified Page I	5	k: 0.2348 n: 1.108	0.9992	1.093×10^{-4}	0.02035
	7	k: 0.1669 n: 1.221	0.9969	4.224×10^{-4}	0.02059
Henderson and Papis	5	a: 1.010 k: 0.2458	0.9981	2.75×10^{-4}	0.01657
	7	a: 1.028 k: 0.1769	0.9894	1.44×10^{-3}	0.03797
Logarithmic	**5**	**a: 1.042** **c: -0.04043** **k: 0.221**	**0.9999**	$\mathbf{8.261\times10^{-6}}$	**0.002865**
	7	**a: 1.189** **c: -0.1888** **k: 0.1228**	**0.9999**	$\mathbf{1.705\times10^{-5}}$	**0.004146**
Two-term eksponential	5	a: 1.549 k: 0.2955	0.9995	7.442×10^{-5}	0.008627
	7	a: 1.729 k: 0.2326	0.9969	4.448×10^{-4}	0.02111
Wang ve Sing	5	a: -0.1699 b: 0.007291	0.9995	1.747×10^{-3}	0.0418
	7	a: -0.1285 b: 0.004282	0.9969	1.570×10^{-4}	0.01254
Diffusion Approach	5	a: -12.98 b: 0.9693 k: 0.3585	0.9974	8.007×10^{-5}	0.008947
	7	a: -11.49 b: 0.951 k: 0.2939	0.9972	4.619×10^{-4}	0.02151

The moisture content curve of the kiwi is given in Figure 6. The moisture content indicates the ratio of water content in product to dry matter. In the beginning, the moisture content exhibited rapid decline behavior through the first 2 hours. After the next period, the decreasing behavior became slowed down.

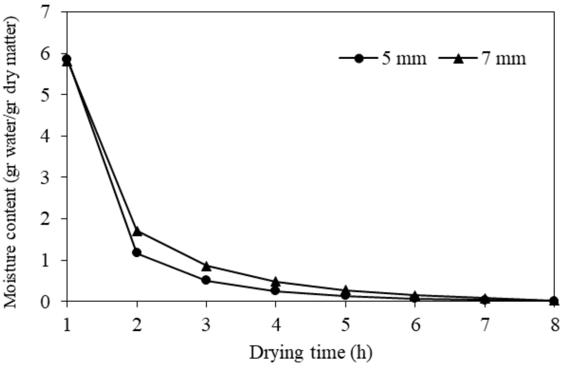

Figure 5. The moisture content curves of kiwi slices as a function of drying time

The drying rate of the freeze-dried kiwi slices is shown in Figure 7. At the early on the freeze-drying duration, the drying ratio exhibits incline behavior because of the high concentration of the moisture at the face of the product. Afterward, the drying rate showed the rapid decline behavior within the initial 2 hours period because the temperature of the plate in the freeze-drying device was about -30 °C. The moisture content (MC) at the superficies of the product dried significantly. To the end of the first 2 hours drying period, the drying rate decreased leisurely up to the end of the drying duration because of the increasing temperature of the plate in the freeze-drying device According to Figure 5, it is seen that the drying rate diminished in parallel with decreasing of the moisture content. When the various thickness compared with each other, it is shown that the drying of the specimen with 7 mm thickness presented slow drying behavior during the drying process due to containing a high amount of moisture content in it. On the other hand, the drying of the specimen with 5 mm thickness shows rapid drying behavior because the moisture content in the product was less than 7 mm thickness. Water vapor on the surface because of sublimation occurs utilizing transferring dried region of the freeze-dried specimen by the capillaries. Water vapor reached the surface of the specimen removed by the condenser of the freeze-drying device.

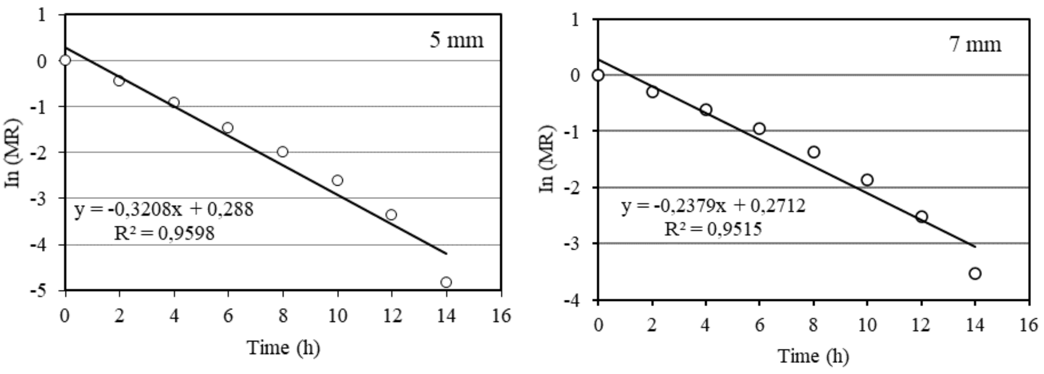

Figure 7. Plot of In (MR) versus freeze-drying time for kiwi samples

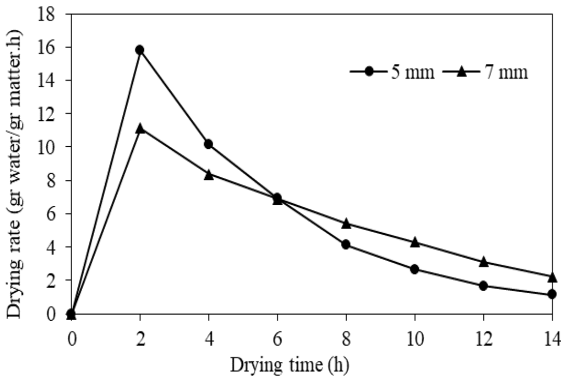

Figure 6. The drying rate curves of kiwi slices as afunction of drying time

The theoretical model of the thin film drying process of the diverse foods is determined with the solution of Fick's second law [22].

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

From Equation 6, Equation 7 can be computed by the keeping diffusion coefficient as constant for the cartesian coordinate system and simplifying using proper boundary conditions

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

In Equation 8, D_{eff} defines the effective diffusivity, t shows the drying time, L presents the half-thickness of samples, and n indicates a positive integer [22].

The effective diffusivity (D_{eff}) values were computed by drawing experimental drying value in terms of ln (MR) was plotted versus time (Figure 7).

According to Equation 7, a plot of ln (MR) versus drying time must give a straight line with a slope (K):

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

The effective diffusivity for the kiwi slices with 5 mm and 7 mm thicknesses can be calculated by Equation 8. It was calculated about 2.25×10^{-10} m^2/s for 5 mm thickness and 3.28×10^{-10} m^2/s for 7 mm thickness as well. The effective diffusivity coefficient must be ranged from 10^{-12} to 10^{-8} m^2/s for food products in literature and it is determined that the calculated effective diffusivity coefficients for kiwi products have good agreement with the literature [26].

4. CONCLUSION

In this study, the freeze-drying process was performed for sliced kiwi fruit with 5 mm and 7 mm thickness in an average 100 g mass. As you seen in Figure 7 was determined that sliced kiwi fruit with 5 mm and 7 mm thicknesses had 85.225 g water/g dry matter and 85.813 g water/g dry matter moisture contents respectively as a result of determination moisture content by stove and desiccator at the end of total 14 hours freeze-drying process. In addition to this, the proper kinetic drying model was specified by calculating MR and DR values for 8 different drying model with measuring mass losses in every two hours. The proper kinetic drying model was the Logarithmic model because the R^2 value was about 0.9999, X^2 values for 5mm and 7mm thicknesses were about 8.261×10^{-6} and 1.705×10^{-5}, RMSE values for 5 mm and 7 mm were about 0.002865 and 0.004146 respectively. Besides, when the moisture content and drying rate considered, it was shown that the drying rate of the kiwi slice with 7 mm thickness was slower because of the high amount of moisture content. Moreover, the drying rate of the kiwi slice with 5 mm thickness was higher due to the less moisture content in it. The effective diffusivity coefficients dependent on the moisture ratios were calculated as 2.25×10^{-10} m^2/s for the kiwi slice with 5 mm thickness and 3.28×10^{-10} m^2/s for the kiwi slice with 7 mm thickness. It was shown that the effective diffusivity coefficients were within the limits that were presented in the literature as $10^{-12} - 10^{-8}$ m^2/s for food products.

Nomenclature

a, b, c, n	The constants of the models
z	Number of parameters in the model
k, k_0, k_1	Drying rate constants (min^{-1})
t	Time (min)
M_0	The initial moisture content (g water/g dry matter)
M_t	The moisture content at a time t (g water/g dry matter)
M_d	The final equilibrium moisture content (g water/g dry matter)
MR	The moisture ratio (dimensionless)
N	Number of observations
MC	Moisture content (g water/g dry matter)
DR	Drying rate (g water/g dry matter)
D_{eff}	The effective diffusivity (m^{2}s^{-1})
L	Half-thickness of samples (m)
R^2	Coefficient of determination
χ^2	Reduced chi-square
RMSE	Root mean square error

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Bahadır ACAR: Conceptualization, Methodology, Validation, Data Curation, Writing, Supervision, Visualization.

Abdullah DAĞDEVİREN: Performed the experiments and analyse the results.

Mehmet ÖZKAYMAK: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration

Abdillahi Robleh GUİNALEH: Formal analysis, Writing-Original Draft

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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