GIDA
THE JOURNAL OF FOOD
E-ISSN 1309-6273, ISSN 1300-3070

Research / Araştırma
GIDA (2020) 45(6) 1201-1214
doi: 10.15237/gida.GD20107

DRYING KINETICS OF REDUCED FAT WHITE CHEESE DRIED BY DIFFERENT METHODS

Özgün Köprüalan[1], Feyza Elmas[2], Anıl Bodruk[1], Şeyma Arıkaya[1], Mehmet Koç[2], Nurcan Koca[1], Figen Kaymak-Ertekin[1*]
[1]Department of Food Engineering, Ege University, İzmir, Turkey
[2]Department of Food Engineering, Adnan Menderes University, Aydın, Turkey

Received / Geliş: 14.09.2020; *Accepted* / Kabul: 04.11.2020; *Published online* / Online baskı: 21.11.2020

Köprüalan, Ö., Elmas, F., Bodruk, A., Arıkaya, Ş., Koç, M., Koca, N., Kaymak-Ertekin, F. (2020). Drying kinetics of reduced fat white cheese dried by different methods. GIDA (2020) 45(6) 1201-1214 doi: 10.15237/gida.GD20107.

Köprüalan, Ö., Elmas, F., Bodruk, A., Arıkaya, Ş., Koç, M., Koca, N., Kaymak-Ertekin, F. (2020). Farklı yöntemler ile kurutulmuş yağı azaltılmış beyaz peynirin kuruma kinetiği. GIDA (2020) 45(6) 1201-1214 doi: 10.15237/gida.GD20107.

ABSTRACT
In the current study, three different drying methods, including hot air drying (50, 60, 70 °C and 1.8 m/s), microwave drying (180, 360, 540 W) and freeze-drying (0.2, 0.15, 0.1 mbar) were experimentally studied and the drying kinetics of reduced-fat white cheese (RFWC) were determined. Microwave drying process time was significantly shorter than hot air drying and freeze-drying for RFWC. Semi-empirical models were applied to determine the most appropriate drying model targeting the highest R^2 and the lowest RMSE and χ^2 values representing the drying kinetics of RFWC. The effective diffusion coefficient values for different drying methods varied from 1.521 x 10^{-9} to 4.432 x 10^{-8} m^2/s. Through increasing the temperature, microwave power, and vacuum pressure, effective diffusion coefficient values increased. The activation energy values were determined as 12.421 kJ/mol for hot air drying and 5.599 W/g for microwave drying.
Keywords: Microwave drying, freeze-drying, reduced-fat white cheese, effective diffusion coefficient, drying behavior

FARKLI YÖNTEMLER İLE KURUTULMUŞ YAĞI AZALTILMIŞ BEYAZ PEYNİRİN KURUTMA KİNETİĞİ

ÖZ
Bu çalışmada, sıcak hava ile kurutma (50, 60, 70 °C ve 1.8 m/s), mikrodalga kurutma (180, 360, 540 W) ve dondurarak kurutma (0.2, 0.15, 0.1 mbar) olmak üzere üç farklı kuruma yöntemi deneysel olarak incelenmiş ve yağı azaltılmış beyaz peynirin (RFWC) kurutma kinetiği belirlenmiştir. Mikrodalga kurutma yönteminde işlem süresi, RFWC için sıcak havayla kurutma ve dondurarak kurutma yöntemlerinden önemli ölçüde daha kısadır. RFWC'nin kuruma kinetiğini temsil eden en

* *Corresponding author* / Yazışmalardan sorumlu yazar
✉: figen.ertekin@ege.edu.tr, ✆:(+90) 232 311 3006 🖷:(+90) 232 342 7592

Özgün Köprüalan; ORCID no: 0000-0001-8800-7714
Feyza Elmas; ORCID no: 0000-0003-1847-5541
Anıl Bodruk; ORCID no: 0000-0002-2663-5800
Şeyma Arıkaya; ORCID no: : 0000-0001-9277-940X
Mehmet Koç; ORCID no: 0000-0002-7295-7640
Nurcan Koca; ORCID no: 0000-0002-0733-4500
Figen Kaymak-Ertekin; ORCID no: 0000-0001-5042-3659

yüksek R^2 ve en düşük RMSE ve χ^2 değerlerini hedefleyen en uygun kurutma modelini belirlemek için yarı deneysel modeller uygulanmıştır. Farklı kurutma yöntemleri için efektif difüzyon katsayısı değerleri 1.521 x 10^{-9} ile 4.432 x 10^{-8} m^2/s arasında değişmiştir. Sıcaklık, mikrodalga gücü ve vakum basıncının artırılmasıyla efektif difüzyon katsayısı değerleri artmıştır. Aktivasyon enerjisi değerleri sıcak havayla kurutma için 12.421 kJ/mol ve mikrodalga kurutma için 5.599 W/ g olarak belirlenmiştir.
Aahtar kelimeler: Mikrodalga kurutma, dondurarak kurutma, yağı azaltılmış beyaz peynir, efektif difüzyon katsayısı, kuruma davranışı

INTRODUCTION

Cheese is known as the most privileged product of the dairy industry in terms of both the indisputable importance of nutrients in human nutrition and its economic yield (Gobbetti et al., 2018). Since cheese contains high-quality protein, calcium, phosphorus, zinc, and vitamins (B12, riboflavin, and A) and essential nutrients for the human body, its inclusion in the diet may assist to minimize the risk of osteoporosis (Miller et al., 2006). Cheese, one of the most consumed dairy products in the world, is available in the market as fresh or ripened. Although more than 1000 cheese varieties exist around the world among them, white cheese is the most consumed cheese variety in Turkey (Hayaloğlu et al., 2002). White cheese is a semi-soft cheese, salted in brine, and graded as fresh or ripened (TGK, 2015).

Drying is one of the most widely used methods to minimize the biochemical reactions that occur during storage by reducing the water activity of the food (İlter et al., 2018). However, the chemical, textural, and physical properties of food also alter the end of the drying process due to simultaneous mass and heat transfer (Koç et al., 2008). Cheese can be subjected to drying because of decreasing the moisture content, increasing shelf life, providing ease of transportation, and developing a product instead of cheese to use in other foods as a component. Dried cheese provides ease of use in the industry, especially for products such as chips, pasta, instant soup, pizza, salad dressing, biscuits, and cakes (Kaya, 2004).

Although the hot air drying method is frequently used for drying food in the literature (İlter et al., 2018), long drying time, significant color changes, reduction in nutritional value, and case hardening problems have pushed the researchers into the search for new drying techniques. Microwave drying, a relatively new and innovative method, has various benefits compared to hot air drying, including higher drying rate and minimum heating of locations with less water (Chandrasekaran et al., 2013). The heating effect in food materials is a consequence of dipolar rotation and ionic conduction. Water, which is the main component of most food material, is caused to the generation of frictional heat with vibrational and rotational energies. The heat generated in the food material causes the pressure gradient and allowing moisture to be removed from the food quickly. This allows the microwave drying method to be a very fast dehydration method (Vallejo-Castillo et al., 2020).

The faster drying improves the quality of the food and provides a higher output. Freeze drying, one of the most advanced drying methods, supplies a product with a porous structure, superordinate taste and aroma, and better rehydration properties (Krokida et al., 1998).

In the literature, there are some studies focused on drying of cheese with various drying methods. Izmir Tulum, a kind of Turkish cheese was dried in a tray dryer at different drying conditions (Kizilalp et al., 2018). The researchers found that the sample with the highest sensory acceptance was dried at 55°C. In another study, cheese was dried with hot air (43 and 52 ℃, 1.2 m/s air velocity), microwave (350, 500, 650, 750 and 850 W) and freeze-drying (6, 12 and 24 hours) methods and microwave drying were found to be the most effective method considering the drying rate of water from the cheese (Pinho et al., 2017). Chudy et al. (2019) also used hot air and microwave vacuum drying methods as a combination to dry Harzer cheese. The dried cheese with a porous structure was obtained using pre-drying of the cheese in the tray drier at 44°C till a dry matter content of 72 %, then, using microwave vacuum drying at 1000 W microwave power, 30 kPa pressure, and 80 °C. Rakcejeva et al. (2009) studied microwave vacuum drying process, which was performed at 38 °C, 56-70 mm Hg pressure range and maximum 798 kJ/kg microwave power, to produce dried Cheddar cheese and reported that the moisture content of cheese decreased from 50 % to 14.37 % in 23 minutes.

Drying kinetics of foods is a complex circumstance that requires simplification for estimating results and optimization of the parameters (Karathanos and Belessiotis, 1999). Especially for microwave and freeze-drying, the information on moisture diffusion models that could define the processes exactly is more useful at the industrial level. There are limited studies in the literature about the modeling of cheese drying. Castell-Palou and Simal (2011) investigated the drying kinetics of pressed cheese with a heat pumpfresh drying at four different temperatures and a diffusion model was proposed. Also, Ermolaev (2019) developed a model considering the drying temperature, residual pressure, and the area of the dried cheese to calculate the duration of the vacuum drying process of cheese. However, no information has been reported on the drying behavior of reduced-fat cheese with these methods.

The objective of this study was to examine the drying kinetics of RFWC as a function of drying methods (hot air, microwave, freeze-drying) and process parameters (different temperatures, powers, and vacuum pressures). The kinetic parameters were determined for each drying method data using different semi-empirical models besides the 2nd Fick diffusion model.

MATHEMATICAL MODELING

In order to model the drying data, the driving force for the moisture movement during drying is assumed as a liquid concentration gradient. Since the heat transfer proceeds too quickly during drying, the heat transfer effect is neglected. Moreover, the moisture diffusion coefficient is assumed as the same in all directions (isotropic material) and the sample shrinkage is negligible. In the falling drying rate period, moisture transfer from the solid sample can be characterized by unsteady-state Fick's law of diffusion equation with these conditions (Kaymak-Ertekin, 2002; Eren et al., 2008; Tlatelpa-Becerro et al., 2020).

$$\frac{\partial C}{\partial t} = D_{eff}\ \frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C: Moisture content (kg water/kg dry matter), D_{eff}: Effective diffusion coefficient (m^2/s), x: Thickness of sample (m), t: Time (s).

To solve Eq. 1, moisture in the sample is assumed to be uniformly distributed and mass transfer resistance in the gas phase is negligible. Therefore, moisture transfer is controlled by internal resistance and the surface concentration of the sample does not vary with time. Analytical solutions of Eq. 1 for an infinite slab geometry are given in Eq. 2 Crank (1979), considering these assumptions, which help to determine initial and boundary conditions.

$$\psi = \frac{(\overline{C_t} - C_e)}{(C_0 - C_e)} = \frac{8}{\pi^2}\sum_{i=1}^{\infty} \frac{1}{(2i-1)^2} \exp\left(-\frac{(2i-1)^2.\pi^2.D_{eff}.t}{4.L^2}\right) \tag{2}$$

where C_t: Moisture content (kg water/kg dry matter) at time t, C_o: Initial moisture content (kg water/kg dry matter), C_e: Equilibrium moisture content (kg water/kg dry matter), L: The half-thickness of the sample (m), ψ: dimensionless moisture ratio, which was calculated from experimental drying curves of cheese samples.

Using the first term (n = 1) of Eq. 2 is sufficient for long drying times as;

$$\psi = \frac{(\overline{C_t} - C_e)}{(C_0 - C_e)} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2.D_{eff}.t}{4.L^2}\right) \tag{3}$$

After the Eq. 3 is linearized, the change of ln (ψ) relative to time is plotted and Deff is calculated using the slope of the obtained curve with Eq. 4

$$D_{eff} = \frac{\text{Slope}\cdot 4\cdot L^2}{\pi^2} \tag{4}$$

The mathematical model explained above was developed by Crank assuming constant diffusion coefficient to determine D_{eff} based on the unsteady state Fick's law of diffusion.

In addition to the theoretical Fick diffusion model, many semi-empirical models are commonly used in the modeling of food drying to simulate the drying curves. Although the empirical models represent the experimental data for a good fit, the model parameters are physically insufficient. These simple models show a direct relationship between the moisture content of the food and the drying time (Simal et al., 2005; Eren et al., 2008; İlter et al., 2018). Among these, seven semi-empirical drying models were used to describe the drying kinetics of reduced-fat white cheese in this study and are given in Table 1.

Table 1. Semi-empirical models for drying of reduced- fat white cheese

Model No	Model name	Model	References	Equation Number
1	Newton	$MR = \exp(-k.t)$	Mujumdar (1995)	(5)
2	Page	$MR = \exp(-k.t^n)$	Diamante and Munro (1993)	(6)
3	Henderson and Pabis	$MR = \mathrm{a}.\exp(-k.t)$	Henderson and Pabis (1961)	(7)
4	Modified Page Model	$MR = \exp(-k.t)^{\,n}$	White et al. (1980)	(8)
5	Wang and Singh	$MR = 1 + a.t + b.t^2$	Wang and Singh (1978)	(9)
6	Two Terms	$MR = \mathrm{a}.\exp(-k_0.t) + \mathrm{b}.\exp(-k_1.t)$	Henderson (1974)	(10)
7	Logarithmic	$MR = \mathrm{a}.\exp(-k.t) + c$	Yağcıoğlu et al. (1999)	(11)

where, a, k, b, n, k_0, k_1, c are constants in models and t is time.

MATERIAL AND METHODS

Materials

Turkish fresh reduced-fat white cheese (RFWC) was used as raw material provided by Sütaş Dairy Company (Bursa, Turkey). The same batch of cheese was used in all drying trials and stored at +4 °C until the experiments. The average initial moisture content of RFWC was 72.45±0.21 % on a wet basis. The chemical composition of white cheese samples was determined as 63.69±0.77 % protein, 26.32±0.18 % fat, 7.18±0.22 % salt on a dry basis. Samples of fresh RFWC were analyzed for moisture by the gravimetric method (TS, 2006), fat content according to the Gerber method (TS, 1990), and the salt content according to the Mohr method (IDF, 1988), protein content using the Kjeldahl method (AOAC, 2005).

Drying Procedures

Hot Air Drying

The hot air drying process was carried out with a tray drier (Eksis Makine, Isparta, Turkey) after the samples were cut into the appropriate size (1x1x2 cm). Then, the samples were spread on the tray and dried at 50, 60, and 70 °C under airflow of 1.8 m/s.

Microwave Drying

The microwave drying process was performed using a microwave oven (Arçelik MD 595) with the power of 180, 360 and 540 W for RFWC samples cut into dimensions of 1x1x2 cm.

Freeze Drying

RFWC samples cut into 1x1x2 cm size were frozen -18 °C for 24 hours before the freeze-drying. The freeze-drying process was performed using a freeze dryer (Telstar Lyoquest -55 Plus Eco) under 0.2, 0.15, and 0.1 mbar vacuum pressures.

Water loss analyses

Water loss during drying was measured by weighing the product using an electronic balance

(Shimadzu BL620S, Tokyo, Japan) with an accuracy of ± 0.01 g at regular intervals (per minute or seconds or hour). The drying process with different methods was continued until a 1 % difference in weight between the last two measurements was obtained. In order to determine the weight loss in especially freeze drying, the samples were taken out at definite time (15 min) by stopping the system, the weight measurement was taken and the new fresh sample was fed again into the dryer and this sample was dried until the time reached to 30 min. This measurement process was repeated until the end of drying.

Data Analysis

Experimental data analysis and statistical modeling were carried out by linear and nonlinear regression analysis (SPSS, IBM SPSS Statistic Base 22.0). Among the different semi-empirical models that used in this study, the best-fitted model for the drying behavior of RFWC was evaluated by considering the coefficient of determination (R^2), root means square error (RMSE) and reduced chi-square (χ^2) values as criteria. The best model defining the drying behavior was selected as the model with the highest R^2 and the least *RMSE* and χ^2 value. The *RMSE* and χ^2 values can be calculated using the following equations (Eq. 12 and Eq.13).

$$RMSE = \sqrt{\frac{\sum_i^N (\psi Predicted_i - \psi Actual_i)^2}{N}} \qquad (12)$$

$$\chi^2 = \frac{\sum_i^N (\psi Predicted_i - \psi Actual_i)^2}{N-Z} \qquad (13)$$

where ψ_{actual} is the experimental dimensionless moisture value, $\psi_{predicted}$ is the predicted dimensionless moisture value from the model N is the number of observations and Z is the number of constant.

Uncertainty Analysis

Uncertainty analysis is used to detect the inaccuracy of experiments used in modeling and designing experiments (Koç et al., 2008; İlter et al., 2018). Uncertainties in the drying trials usually arise from the selection and calibration of measuring devices, environmental conditions, personal observation, and reading. The hot air temperature, microwave power, vacuum pressure, change of weight of the sample dried, the thickness of samples, drying time were independent parameters measured in the drying experiments. The uncertainties of the measured parameters, the total uncertainties of calculated moisture contents, effective diffusion coefficient, and activation energy values are given in Table 2. The uncertainty values obtained for RFWC drying were about the limit of 5%.

RESULTS AND DISCUSSION

The drying curves of RFWC sticks for hot air, microwave, and freeze-drying are shown in Figures 1, 2, and 3, respectively. The results showed that the overall drying process took place during the falling rate period for all drying methods. A constant drying rate period in these experimental conditions employed was not observed. This is due to the fact that the main mechanism of mass transfer is through diffusion.

The drying of RFWC with hot air drying method caused case hardening on the surface of the cheese. The case hardening prevented the water from removing and caused samples having high moisture content at the end of the drying process. Especially, case hardening increased by increasing temperature in the hot air drying process. The case hardening causes the formation of a thin and extremely dry layer outside of the food, which has different transport and mechanical properties than the core. It has been reported that case hardening increases especially when the food material is exposed to high drying temperatures, high air velocities, and low air relative humidity (Gulati and Datta, 2015).

Table 2. Uncertainties of the experimental measurements and total uncertainties for the predicted values

Parameters	Unit	Results (Drying)		
		Hot air	Microwave	Freeze
Experimental measurements				
Temperature	°C	±2.00	-	-
Power	W	-	±0.1	-
Pressure	mbar	-	-	±0.01
Weight	g	±0.01	-	-
Time	s	±0.033	±0.033	±0.033
Thickness	cm	±0.0001	±0.0001	±0.0001
Estimated values				
Moisture ratio (MR)	dimensionless	±1.01[a]	±0.39[d]	±1.46[g]
Effective diffusion coefficient	m^2/s	±0.60[b]	±1.32[e]	±1.63[h]
Activation energy	kJ/mol* and W/g**	±0.77[c]	±4.32[f]	-

* activation energy unit for hot air drying
** activation energy unit for microwave drying
a Nominal value was taken as 0.0006
b Nominal value was taken as $1.77*10^{-12}$ m^2/s
c Nominal value was taken as 12.42 kJ/mol
d Nominal value was taken as 0.0009
e Nominal value was taken as $1.57*10^{-10}$ m^2/s
f Nominal value was taken as 5.599 W/g
g Nominal value was taken as 0.001
h Nominal value was taken $4.57*10^{-12}$

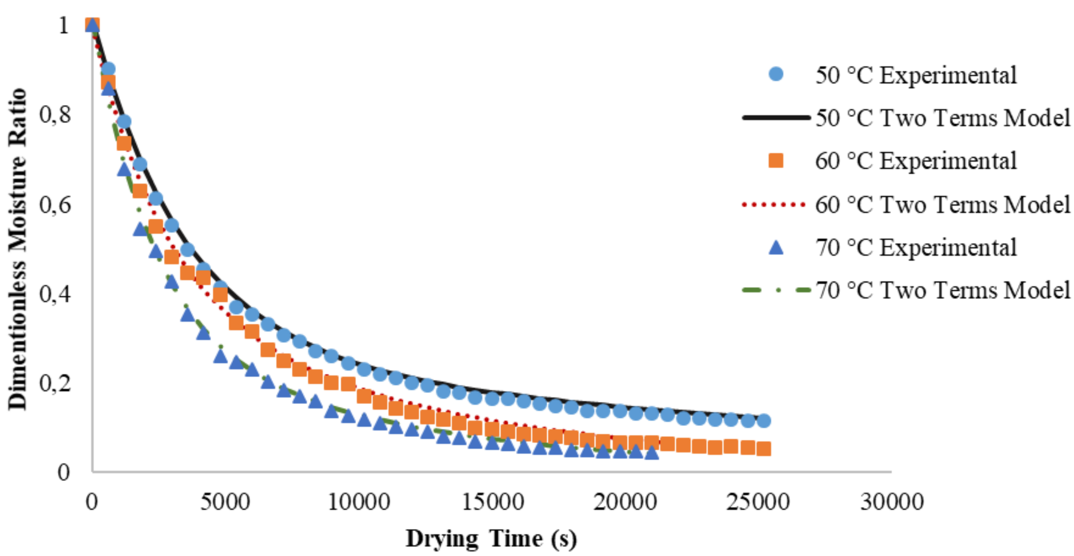

Figure 1. Experimental and predicted drying curves of reduced-fat white cheese for hot air drying at 50, 60 and 70 °C.

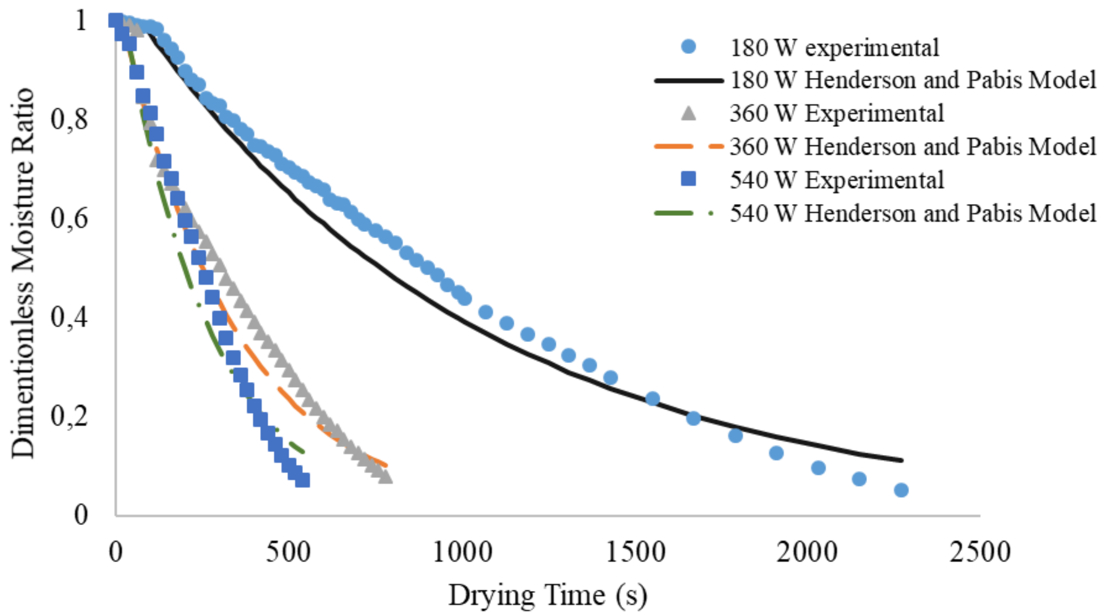

Figure 2. Experimental and predicted drying curves of reduced-fat white cheese for microwave drying at 180, 360 and 540 W.

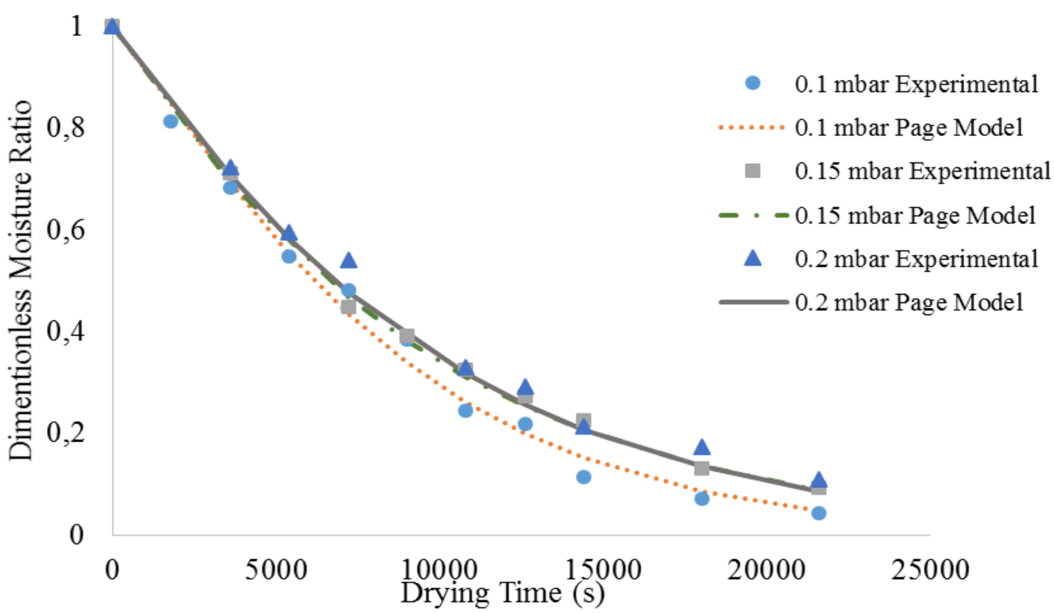

Figure 3. Experimental and predicted drying curves of reduced-fat white cheese for freeze drying at 0.20, 0.15 and 0.10 mbar.

As seen in Figures 1, 2, and 3, for each drying method, moisture content was continuously decreased by increasing drying time. As the temperature, microwave power, and vacuum pressure increased in the drying process, the diffusion rate of water in the samples increased in the falling drying period. The cause of this that as the drying temperature increases, the humidity pressure in the sample considerably increases (Khamjae and Rojanakorn, 2016). Similarly, an increase in microwave power and vacuum pressure increases the water diffusion rate by increasing the energy transferred to the product and provides a high water removal rate. For hot air drying, an increase in the temperature decreased the drying time, but this was more clearly observed for microwave power. The increase in microwave power has been effective in reducing drying time. This can be explained as the volumetric heat generation in the moist sample owing to the energy transmitted directly and absorbed by the water molecules leads to higher internal temperatures. Therefore, the water achieves the boiling point faster (Baysal et al., 2003). Pinho et al., (2017), investigated hot air, microwave, and freeze-drying process to reduce the cheese water content. The researchers found that drying time decreased with the increase in temperature and microwave power. They also suggested that microwave drying is the quickest and most effective drying process for sliced cheese. However, the time required for freeze-drying was a little shorter than hot air drying (Fig. 3). The chamber pressure has a combined effect for controlling the sublimation temperature and changing parameters affecting the drying kinetics. At constant temperature, the drop in the chamber pressure causes decreasing the vapor pressure on the product surface. Thus, the driving force required for the drying process increases, and the total drying time is shortened (Arsem and Ma, 1990; Lombrana, 1997). Drying times for 0.2 and 0.15 mbar vacuum pressures were not notable different while it decreased at 0.1 mbar vacuum pressure.

Evaluation of Semi-Empirical Models

Experimental results of dimensionless moisture content with drying time were fitted to the proposed semi-empirical models, Eqs. 5-11, in Table 1 to mathematically clarify the effect of drying conditions on the drying properties of RFWC. The constants of the semi-empirical models were calculated by nonlinear regression analysis. Table 3 shows the parameters of the models and the criteria (R^2, χ^2, RMSE) for the models for different air temperatures, microwave powers, and vacuum pressures.

Table 3. Non-linear regression analysis results of semi-empirical models during drying of reduced- fat white cheese using different drying methods

Hot Air Drying											
Model Name	Temperature (°C)	a	b	c	k	k_0	k_1	n	χ^2	RMSE	R^2
Newton	50				0.009				1.09×10^{-4}	0.0267	0.912
	60				0.011				1.33×10^{-4}	0.0417	0.968
	70				0.015				2.24×10^{-5}	0.0414	0.969
Page	50				0.042			0.678	2.76×10^{-6}	0.0550	0.985
	60				0.035			0.762	2.48×10^{-6}	0.0153	0.996
	70				0.043			0.762	4.14×10^{-4}	0.0192	0.993
Henderson and Pabis	50	0.865			0.007			1.000	1.26×10^{-5}	0.1106	0.939
	60	0.905			0.010			1.000	6.21×10^{-5}	0.0340	0.978
	70	0.923			0.014			1.000	6.93×10^{-3}	0.0373	0.974
Modified Page	50				0.009			0.678	3.23×10^{-4}	0.0607	0.985
	60				0.012			0.762	6.91×10^{-4}	0.0626	0.996
	70				0.016			0.762	6.76×10^{-3}	0.0373	0.993
Wangh and Singh	50	-0.006	1.10×10^{-5}						1.10×10^{-3}	0.0110	0.849
	60	-0.007	1.20×10^{-5}						3.68×10^{-3}	0.0950	0.833
	70	-0.009	1.80×10^{-5}						6.57×10^{-7}	0.1360	0.791
Two Terms	50	0.730	0.278			0.017	0.002		2.90×10^{-7}	0.0120	1.000
	60	0.397	0.597			0.005	0.022		2.48×10^{-6}	0.0151	0.997
	70	0.33	0.682			0.006	0.027		9.96×10^{-7}	0.0107	0.998
Logarithmic	50	1.000		-0.120	0.380				1.66×10^{-1}	0.0120	0.997
	60	1.000		-0.122	0.377				3.51×10^{-6}	0.0166	0.995
	70	0.919		0.590	0.018				9.71×10^{-7}	0.5010	0.994

Microwave Drying											
Model Name	Power (W)	a	b	c	k	k_0	k_1	n	χ^2	RMSE	R^2
Newton	180				0.001				2.76×10^{-3}	0.0817	0.971
	360				0.002				1.54×10^{-3}	0.0783	0.981
	540				0.003				7.84×10^{-4}	0.0721	0.946
Page	180				0.022			1.293	$1.16\times10^{+1}$	0.6544	0.996
	360				0.109			1.165	$2.62\times10^{+0}$	0.4993	0.996
	540				0.084			1.517	$2.53\times10^{+0}$	0.5382	0.997
Henderson and Pabis	180	1.076			0.001			1.000	3.16×10^{-4}	0.0471	0.986
	360	1.061			0.003			1.000	2.55×10^{-4}	0.0493	0.987
	540	1.113			0.004			1.000	5.51×10^{-4}	0.0648	0.966
Modified Page	180				0.001			1.293	3.36×10^{-2}	0.1519	0.996
	360				0.002			1.165	1.42×10^{-4}	0.0428	0.996
	540				0.003			1.517	8.92×10^{-3}	0.1312	0.997
Wangh and Singh	180	-0.001	9.33×10^{-8}						7.95×10^{-1}	0.3351	0.996
	360	-0.002	1.02×10^{-6}						5.45×10^{-5}	0.0337	0.991
	540	-0.002	7.75×10^{-7}						5.78×10^{-4}	0.0662	0.996
Two Terms	180	0.49	0.586			0.001	0.001		3.21×10^{-4}	0.0471	0.986
	360	0.539	0.522			0.003	0.003		2.62×10^{-4}	0.0493	0.987
	540	0.555	0.557			0.004	0.004		5.81×10^{-4}	0.0649	0.966
Logarithmic	180	1.431		-0.393	0.001				2.37×10^{-1}	0.2466	0.998
	360	1.209		-0.184	0.002				3.11×10^{-5}	0.0291	0.993
	540	2.075		-1.038	0.001				2.06×10^{-3}	0.0901	0.998
Freeze Drying											
Model Name	Vacuum Pressure (mbar)	a	b	c	k	k_0	k_1	n	χ^2	RMSE	R^2
Newton	0.20				0.006				2.44×10^{-6}	0.0221	0.994
	0.15				0.006				2.13×10^{-6}	0.0214	0.997
	0.10				0.007				2.33×10^{-5}	0.0372	0.985
Page	0.20				0.004			1.090	8.42×10^{-6}	0.0292	0.997
	0.15				0.005			1.050	4.53×10^{-7}	0.0141	0.998
	0.10				0.003			1.175	6.97×10^{-6}	0.0268	0.992
Henderson and Pabis	0.20	1.016			0.006			1.000	2.12×10^{-6}	0.0199	0.995
	0.15	1.009			0.006			1.000	4.06×10^{-6}	0.0234	0.998
	0.10	1.026			0.007			1.000	3.16×10^{-5}	0.0380	0.986
Modified Page	0.20				0.006			1.090	2.87×10^{-5}	0.0397	0.997
	0.15				0.006			1.050	4.49×10^{-7}	0.0140	0.998
	0.10				0.007			1.175	1.34×10^{-4}	0.0562	0.992
Wangh and Singh	0.20	-0.005	6.66×10^{-6}						2.38×10^{-5}	0.0379	0.996
	0.15	-0.005	7.29×10^{-6}						8.13×10^{-6}	0.0289	0.994
	0.10	-0.005	7.86×10^{-6}						1.07×10^{-3}	0.0944	0.995
Two Terms	0.20	-0.188	1.187			0.017	0.007		3.97×10^{-6}	0.0222	0.997
	0.15	0.073	0.936			0.006	0.006		4.87×10^{-6}	0.0234	0.998
	0.10	0.435	0.591			0.007	0.007		3.61×10^{-5}	0.0380	0.986
Logarithmic	0.20	1.062		-0.060	0.005				6.47×10^{-6}	0.0263	0.996
	0.15	1.033		-0.280	0.006				5.41×10^{-2}	0.2516	0.998
	0.10	1.141		-0.140	0.006				2.42×10^{-5}	0.0356	0.994

All models were at a compliance level to explain the drying behavior of RFWC with hot air drying. However, the Two Terms model gave the most appropriate model for all temperatures having the highest R^2 and the lowest RMSE and χ^2 values. The Two Terms model contains constants a, b, k_0, and k_1. The constant "a" decreased with an increase in air temperature whereas the values of "b" and "k_1" increased (Table 3). Mohapatra and Rao (2005) stated that the "Two Terms model" offered the highest R^2 and the lowest RMSE value in the drying of boiled wheat with hot air drying as a thin layer. In the microwave drying, the most suitable model was found to be the "Henderson and Pabis" model at all microwave powers. It was observed that an increase in k value with an increase in microwave power. Duan et al. (2005) concluded that Henderson and Pabis's models also gave the best fit in the microwave oven drying of Bighead carp. In the freeze-drying of RFWC, the Page model gave the highest R^2, lowest RMSE, and χ^2 values for all vacuum pressures. Page model constants, k, and n values were ranged between 0.003 to 0.005 1/s and 1.050 to 1.175, respectively (Table 3).

Experimental and predicted moisture ratio data determined using the best-fitted empirical models for hot air drying, microwave drying, and freeze-drying were compared, also shown in Figures 1, 2, and 3, respectively. There was a strong fitting between the values of experimental and predicted moisture ratio for hot air drying and freeze-drying whereas weaker agreement was found for microwave drying.

Determination of Effective Moisture Diffusivity

For each sample, with a change in time, non-dimensional moisture ratio values were obtained. The effective diffusion coefficients were determined from the slopes of the logarithmic curves for each experimental condition neglecting the shrinkage effects and are given in Table 4 together with the R^2 values at different temperatures, microwave powers, and vacuum pressures.

Table 4. The effective diffusivity values for different air temperatures, microwave powers and vacuum pressure

Drying Methods	Temperature (°C)/ Power (W)/ Vacuum Pressure (mbar)	D_{eff} x 10^9 (m²/s)	R^2
Hot Air Drying	50 °C	2.150	0.956
	60 °C	2.384	0.986
	70 °C	2.799	0.970
Microwave Drying	180 W	13.185	0.978
	360 W	37.020	0.978
	540 W	44.322	0.954
Freeze Drying	0.20 mbar	1.521	0.980
	0.15 mbar	1.633	0.945
	0.10 mbar	1.897	0.959

As expected, the D_{eff} values of white cheese samples increased by increasing drying temperature, microwave power, and vacuum pressure. The effective diffusion coefficient values for microwave drying were higher than those for freeze-drying and hot air drying (Table 4). The effective diffusivity values for hot air drying, microwave drying, and freeze-drying were found in the range of 2.150 x 10^{-9}-2.799 x10^{-9} m²/s, 1.319 x10^{-8}-4.432 x 10^{-8} m²/s and 1.521x10^{-9}-1.897 x10^{-9} m²/s, respectively. In drying processes carried out with hot air and freeze-drying methods, the drying of cheese samples start from the surface and move towards the interior. Besides, along with the drying time, the moisture content of the sample decreases, and the solid content increases. As a result, the mobility of the water in the sample decreases, and the transfer of water becomes difficult. The increased resistance to moisture transfer and the drop in the mobility of the water caused a low effective diffusion coefficient in hot air and freeze-drying processes. However, since the heat transfer takes place directly into the sample in the microwave drying process, the resistance to moisture transfer is lower and the mobility of the water is higher. As a result, a higher effective diffusion coefficient was achieved in a microwave dried cheese sample. Therefore, the microwave drying process offers a great advantage in terms of effective diffusion coefficients in white cheese samples. Our results are similar to the effective diffusivity values proposed by different authors for different food products. In the drying of fresh pressed cheese with a heat pump, the effective diffusion coefficient increased by increasing drying temperature (Castell-Palou and Simal, 2011). In a study conducted with apple pulp, effective diffusion coefficients for different microwave powers (between 150-600 W) were reported to vary in the range of 1.0465×10^{-8} - 3.6854×10^{-8} m^2/s. In addition, an effective diffusion coefficient increased with increasing microwave power (Wang et al., 2007). A similar increase was also reported during the drying of potato slices in a microwave belt dryer running between 1500 and 2100 W microwave power (Çelen et al., 2015).

The temperature and microwave power dependence of D_{eff} were described by the Arrhenius type relation (Eqs 14 and 15).

$$D_{eff} = D_0 exp\left(-\frac{E_a}{R\,T_a}\right) \tag{14}$$

$$D_{eff} = D_0 exp\left(-\frac{m\,E_a}{P}\right) \tag{15}$$

where D_0: Exponential coefficient of Eq. 14 and 15, Ea: Activation energy for moisture diffusion (kJ/mol) or (W/g), R: Universal gas constant (8.314×10^{-3} kJ/mol.K), T_a: Absolute temperature (K), P: Microwave power (W), m: Mass of the sample (g).

The activation energy values were found to be 12.421 kJ/mol for hot air drying and 5.599 W/g for microwave drying (Table 5). The higher effective diffusion coefficient resulted in lower activation energy required to remove water from the product in microwave drying. Similarly, Dadalı et al. (2007) determined the activation energy as 5.54 W/g in the microwave drying of okra.

Table 5. Arrhenius parameters for the hot air drying and microwave drying of reduced-fat white cheese

Drying methods	$D_0\times 10^8$ (m^2/s)	E_a	R^2
Hot air drying	21.48	12.421 (kJ/mol)	0.985
Microwave drying	7.68	5.599 (W/g)	0.990

In order to evaluate the accuracy of the proposed theoretical model using the 2nd Fick diffusion equation, the experimental versus predicted dimensionless moisture ratio values for hot air, microwave, and freeze-drying at different conditions are plotted in Figure 4. As can be observed, the good agreement was obtained when the model was solved by the Fickian diffusion for hot air drying and freeze-drying, but the Fickian diffusion model was not able to predict accurately the experimental moisture ratio for microwave drying.

CONCLUSION

The drying behavior of RFWC was examined with different drying methods and conditions (hot air drying, microwave drying, and freeze-drying). It was determined that the drying rate increased as the drying temperature, microwave power, and vacuum pressure increased and consequently the drying time decreased. For the hot air drying, the Two Terms model showed a better fit for all temperatures and Henderson and Pabis's model was found to be a most suitable model for all microwave powers of microwave drying. In the freeze-drying method, the Page model gave the best fit for all vacuum pressures. The moisture diffusion coefficients were calculated to be in the range of 1.521×10^{-9} to 4.432×10^{-8} m^2/s and the highest effective diffusivities were determined for the microwave drying. The activation energy values were obtained to be 12.421 kJ/mol and

5.599 W/g for hot air drying and microwave drying, respectively. The microwave drying method was more effective than hot air and freeze-drying of white cheese samples and resulted in saving to the extent of drying time. In addition, due to the formation of case hardening on the cheese surface in the hot air drying method, the moisture content could not be reduced to the desired value. This study made it possible to evaluate the drying characteristics of RFWC in different drying methods.

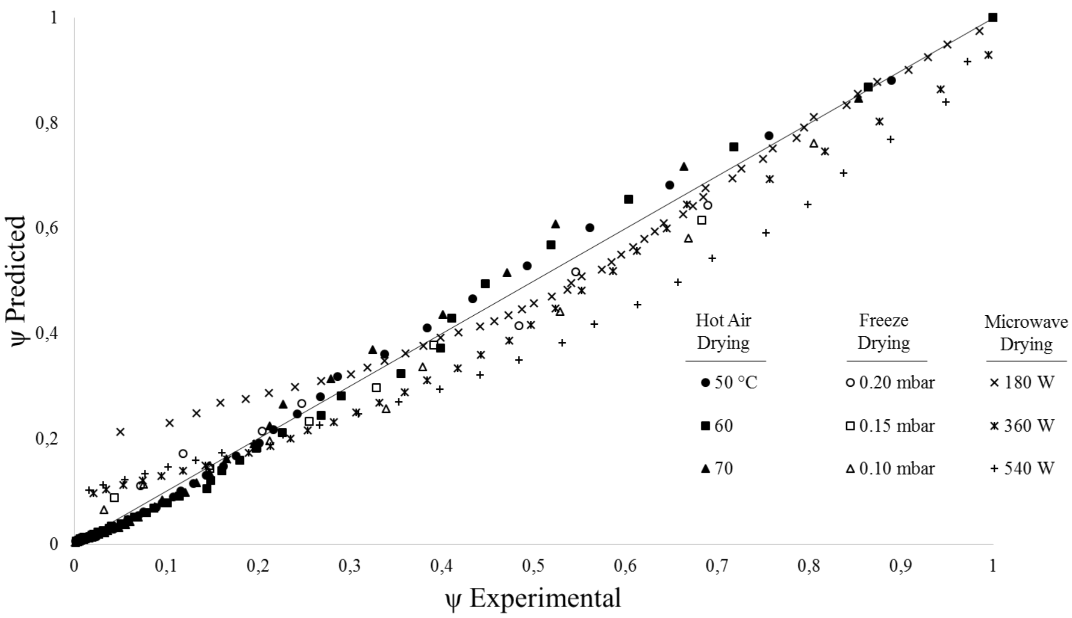

Figure 4. Comparison of the experimental and predicted values using Fickian diffusion model for hot air, microwave and freeze drying.

ACKNOWLEDGMENTS
The authors are thankful for the financial support provided by the Scientific and Technological Research Council of Turkey (TUBITAK 117 O 954). The authors are also grateful to Sütas Dairy Company for providing of white cheese.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTION
Anıl Bodruk and Feyza Elmas were responsible for drying of reduced fat white cheese samples. Şeyma Arıkaya performed the analyses and Özgün Köprüalan calculated the kinetic parameters and wrote the article. Mehmet Koç, Nurcan Koca and Figen Kaymak-Ertekin were responsible for experimental design, interpretation and discussion of the results.

REFERENCES
AOAC (2005). Official methods of analysis of the AOAC International. 18th edition, Gaithersburg, MD.

Arsem, H. B., Ma, Y. H. (1990). Simulation of a combined microwave and radiant freeze dryer. *Dry Techol,* 8: 993–1016, doi: 10.1080/07373939008959932.

Baysal, T., Icier, F., Ersus, S., Yildiz, H. (2003). Effects of microwave and infrared drying on the quality of carrot and garlic. *Eur Food Res Technol,* 218: 68–73.

Castell-Palou, Á., Simal, S. (2011). Heat pump drying kinetics of a pressed type cheese. *LWT-Food Sci Technol,* 44(2): 489-494, doi: 10.1016/j.lwt.2010.09.007.

Çelen, I. H., Çelen, S., Moralar, A., Buluş, H. N., Önler, E. (2015). Mikrodalga bantlı kurutucuda patatesin kurutulabilirliğinin deneysel olarak incelenmesi. *EJOVOC Electron J Vocat Coll,* 5: 242-287.

Chandrasekaran, S., Ramanathan, S., Basak, T. (2013). Microwave food processing-A review. *Food Res Int,* 52: 243–261, doi: 10.1016/j.foodres.2013.02.033.

Chudy, S., Makowska, A., Piątek, M., Krzywdzińska-Bartkowiak, M. (2019). Application of microwave vacuum drying for snack production: Characteristics of pure cheese puffs. *Int J Dairy Technol,* 72: 82–88, doi: 10.1111/1471-0307.12562.

Crank, J. (1979). *The Mathematics of Diffusion. London*, Oxford University Press.

Dadalı, G., Apar, D. K., Özbek, B. (2007). Microwave drying kinetics of okra. *Dry Techol,* 25: 917–924, doi: 10.1080/07373930701536767.

Diamante, L. M., Munro, P. A. (1993). Mathematical modeling of the thin layer solar drying of sweet potato slices. *Solar Energy,* 51: 271-276, doi: 10.1016/0038-092X(93)90122-5.

Duan, Z., Zhang, M., Hu, Q., Sun, J. (2005). Characteristics of microwave drying of bighead carp. *Dry Techol,* 23: 637–643, doi: 10.1081/DRT-200054156.

Eren, I., Yildiz-Turp, G., Kaymak-Ertekin, F., Serdaroĝlu, M. (2008). The effect of external mass transfer resistance during drying of fermented sausage. *Dry Techol,* 26: 1543–1551, doi: 10.1080/07373930802466724.

Ermolaev, V. A. (2019). Development of mathematical model for vacuum cheese drying. *Biointerface Res Appl,* 9: 3830-3833.

Gobbetti, M., Neviani, E., Fox, P., Varanini, G. M. (2018). *The cheeses of Italy: Science and technology.* Springer, 1–274, doi: 10.1007/978-3-319-89854-4.

Gulati, T., Datta A. K. (2015). Mechanistic understanding of case-hardening and texture development during drying of food materials. *J Food Eng,* 166: 119–138, doi: 10.1016/j.jfoodeng.2015.05.031.

Hayaloğlu, A. A., Guven, M., Fox, P. F. (2002). Microbiological, biochemical and technological properties of Turkish White cheese "Beyaz Peynir". *Int Dairy J,* 12: 635–648, doi: 10.1016/S0958-6946(02)00055-9.

Henderson, S. M. (1974). Progress in developing the thin layer drying equation. *Transactions of the ASAE,* 17: 1167-1168.

Henderson, S. M., Pabis, S. (1961). Grain drying theory (I) temperature effect on drying coefficient. *J Agric Eng Res,* 6: 169-174.

IDF, (1988). Détermination de l'indice d'insolubilité. Standard No. 129A.

İlter, I., Akyıl, S., Devseren, E., Okut, D., Koç, M., Ertekin, F. K. (2018). Microwave and hot air drying of garlic puree: drying kinetics and quality characteristics. *Heat Mass Transf,* 54: 2101–2112, doi: 10.1007/s00231-018-2294-6.

Karathanos, V. T., Belessiotis, V. G. (1999). Application of a thin-layer equation to drying data of fresh and semi-dried fruits. *J Agric Eng Res,* 74: 355–361, doi: 10.1006/jaer.1999.0473.

Kaya, S. (2004). Peynir kurutma üzerine bir araştırma. *Gıda,* 29: 89-93.

Kaymak-Ertekin, F. (2002). Drying and rehydrating kinetics of green and red peppers. *J Food Sci,* 67: 168–175, doi: 10.1111/j.1365-2621.2002.tb11378.x.

Khamjae, T., Rojanakorn,T. (2016). Foam-mat drying of passion fruit aril. *Int Food Res J* , 25: 204-212.

Kizilalp, G., Polat, I., Urgu, M., Koca, N. (2018). Evaluation of Izmir Tulum cheese pieces by drying with tray drier at different airflow rates and temperatures. IDS 2018, 21st International Drying Symposium Proceedings, 11–14 September, Valencia, Spain, 1676p.

Koç, B., Eren, I., Kaymak-Ertekin, F. (2008). Modeling bulk density, porosity and shrinkage of quince during drying: The effect of drying method. *J Food Eng,* 85: 340–349, doi: 10.1016/j.jfoodeng.2007.07.030.

Krokida, M. K., Karathanos, V. T., Maroulis, Z. B. (1998). Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products. *J Food Eng,* 35: 369–380, doi: 10.1016/S0260-8774(98)00031-4.

Lombrana, J. I. (1997). The influence of pressure and temperature on freeze-drying in an adsorbent medium and establishment of drying strategies. *Food Res Int,* 30: 213–222, doi: 10.1016/S0963-9969(97)00042-2.

Miller, G. D., Jarvis, J. K., McBean, L. D. (2006). *Handbook of dairy foods and nutrition.* CRC press.

Mohapatra, D., Rao, P. S. (2005). A thin layer drying model of parboiled wheat. *J Food Eng,* 66: 513–518, doi: 10.1016/j.jfoodeng.2004.04.023.

Mujumdar, A. S. (1995). *Handbook of Industrial Drying.* Florida, Boca Raton: CRC press.

Pinho, A. R. C., Assis, F. R., Peres, A. P., Pintado, M. E., Morais, A. M. (2017). Dehydration of cheese by hot air, microwave and freeze-drying. *Sci Study Res Chem Chem Eng Biotechnol Food Ind,* 18: 455–460.

Rakcejeva, T., Zagorska, J., Dukalska, L., Galoburda, R., Eglitis, E. (2009). Physical-chemical and sensory characteristics of Cheddar cheese snack produced in vacuum microwave dryer. *Chemine Technologija,* 3: 16–20.

Simal, S., Femenia, A., Garau, M. C., Rosselló, C. (2005). Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit. *J Food Eng,* 66: 323–328, doi: 10.1016/j.jfoodeng.2004.03.025.

TGK, (2015). Türk gıda kodeksi peynir tebliği, Tebliğ No: 2015/6. Resmi Gazete, 29261: TGK.

Tlatelpa-Becerro, A., Rico-Martínez, R., Urquiza-Beltrán, G., Calderón-Ramírez, M. (2020). Obtaining of crataegus mexicana leaflets using an indirect solar dryer. *Rev Mex Ing Química,* 19(2): 669-676, doi: 10.24275/rmiq/Alim896.

TS, (1990). Süt-yağ tayini-gerber metodu (Rutin Metot), No: 8189, Türk Standartları Enstitüsü, Ankara.

TS, (2006). Peynir ve İşlenmiş Peynir – Toplam kuru madde içeriği tayini (Referans yöntem), TS EN ISO 5534, Türk Standartları Enstitüsü, Ankara.

Vallejo-Castillo, V., Muñoz-Mera, J., Pérez-Bustos, M. F., Rodriguez-Stouvenel, A. (2020). recovery of antioxidants from papaya (Carica Papaya L.) peel and pulp by microwave-assisted extraction. *Rev Mex Ing Química,* 19(1): 85-99, doi: 10.24275/rmiq/Alim593.

Wang, G. Y., Singh, R. P. (1978). Single layer drying equation for rough rice. *Paper-American Society of Agricultural Engineers.*

Wang, Z., Sun, J., Chen, F., Liao, X., Hu, X. (2007). Mathematical modeling on thin layer microwave drying of apple pomace with and without hot air pre-drying. *J Food Eng,* 80: 536–544, doi: 10.1016/j.jfoodeng.2006.06.019.

White, G. M., Bridges, T. C., Loewer, O. J., Ross, I. J. (1980). Seed coat damage in thin-layer drying of soybeans. *Transactions of the ASAE,* 23: 0224–0227, doi: 10.13031/2013.34559.

Yağcıoğlu, A., Değirmencioğlu, A., Çağatay, F. (1999). Drying characteristics of laurel leaves under different drying conditions. 7th International Congress on Agricultural Mechanization and Energy, 565-569p.