

## Drying behavior and quality assessment of nectarine slices dried by different drying methods

Farklı kurutma yöntemleriyle kurutulan nektarin dilimlerinin kuruma davranışı ve kalite değerlendirmesi

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ARTICLE INFO	ABSTRACT
<p><b>Article history:</b> Received / Geliş: 08.05.2025 Accepted / Kabul: 20.06.2025</p> <p><b>Keywords:</b> Nectarine Drying Color Energy</p> <p><b>Anahtar Kelimeler:</b> Nektarin Kurutma Renk Enerji</p> <p>✉Corresponding author/Sorumlu yazar: Ahmet POLAT ahmetpolat@uludag.edu.tr</p> <p>Makale Uluslararası Creative Commons Attribution-Non Commercial 4.0 Lisansı kapsamında yayınlanmaktadır. Bu, orijinal makaleye uygun şekilde atıf yapılması şartıyla, eserin herhangi bir ortam veya formatta kopyalanmasını ve dağıtılmasını sağlar. Ancak, eserler ticari amaçlar için kullanılamaz. © Copyright 2022 by Mustafa Kemal University. Available on-line at <a href="https://dergipark.org.tr/tr/pub/mkutbd">https://dergipark.org.tr/tr/pub/mkutbd</a></p> <p>This work is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.</p>  	<p><b>ABSTRACT</b></p> <p>In this study, nectarines were dried using four methods: microwave, hot air, microwave-hot air combination, and freeze drying. The effects of these methods were evaluated based on drying time, moisture diffusion, modeling, color, rehydration, energy use, and surface temperature. Two different microwave power values (200 and 300 W) and a single temperature value (50 °C) were used for product drying. The relation of the length of drying time of nectarine samples according to the methods was found as Freeze-dry&gt;hot air&gt;microwave&gt;microwave-hot air. While the lowest effective moisture diffusion coefficient was obtained in freeze dry method, the highest effective moisture diffusion coefficient was found in 300 W-50 °C application. Midilli et al. model could be chosen to represent the thin-layer drying of nectarine slices for all cases. The greatest total color change (<math>\Delta E</math>) was observed in samples dried at 300 W-50 °C, whereas the minimal color change was recorded in the freeze-dried samples. Both rehydration capacity values (<math>3.152\pm 0.053</math>) and energy consumption (<math>4.152\pm 0.215</math>) values of freeze dried samples were found to be higher than the other methods. The highest product surface temperatures were found in products dried by microwave method. The study indicates that microwave-hot air drying offers shorter drying time with acceptable quality, while freeze drying, though less energy-efficient, provides superior quality.</p> <p><b>ÖZET</b></p> <p>Bu çalışmada, nektarinler dört yöntem kullanılarak kurutulmuştur: mikrodalga, sıcak hava, mikrodalga-sıcak hava kombinasyonu ve dondurarak kurutma. Bu yöntemlerin etkileri kurutma süresi, nem difüzyonu, modelleme, renk, rehidrasyon, enerji kullanımı ve yüzey sıcaklığı temelinde değerlendirilmiştir. Ürün kurutması için iki farklı mikrodalga güç değeri (200 ve 300 W) ve tek bir sıcaklık değeri (50 °C) kullanılmıştır. Nektarin örneklerinin kuruma sürelerinin yöntemlere göre ilişkisi Dondurarak-kurutma&gt;sıcak hava&gt;mikrodalga&gt;mikrodalga-sıcak hava şeklinde bulunmuştur. En düşük etkin difüzyon katsayısı dondurarak kurutma yönteminde elde edilirken, en yüksek etkin difüzyon katsayısı 300W-50 °C uygulamasında bulunmuştur. Midilli ve ark. modeli tüm durumlar için nektarin dilimlerinin ince tabaka kurutmasını temsil etmek üzere seçilebilir. En büyük toplam renk değişimi (<math>\Delta E</math>) 300 W-50 °C'de kurutulan örneklerde gözlenirken, en az renk değişimi dondurarak kurutulan örneklerde kaydedilmiştir. Dondurularak kurutulmuş numunelerin hem rehidrasyon kapasitesi değerleri (<math>3,152\pm 0,053</math>) hem de enerji tüketimi (<math>4.152\pm 0.215</math>) değerleri diğer yöntemlere göre daha yüksek bulunmuştur. En yüksek ürün yüzey sıcaklıkları mikrodalga yöntemiyle kurutulan ürünlerde bulunmuştur. Çalışma, mikrodalga-sıcak hava ile kurutmanın daha kısa sürede kabul edilebilir kalite sağladığını, dondurarak kurutmanın ise daha düşük enerji verimliliğine rağmen üstün kalite sunduğunu göstermektedir.</p>
<p><b>Cite/Atıf</b></p>	<p>Polat, A. (2025). Drying behavior and quality assessment of nectarine slices dried by different drying methods. <i>Mustafa Kemal Üniversitesi Tarım Bilimleri Dergisi</i>, 30 (2), 611-628. <a href="https://doi.org/10.37908/mkutbd.1695251">https://doi.org/10.37908/mkutbd.1695251</a></p>

## INTRODUCTION

Nectarines (*Prunus persica* L. Batsch), members of the *Prunus* genus within the *Rosaceae* family, are notable for their high content of vitamins, phenolic compounds, flavonoids, and anthocyanins. As a climacteric fruit, nectarines exhibit increased ethylene production and heightened cellular respiration during ripening, leading to alterations in biochemical constituents and consequently limiting postharvest shelf life (Yancló et al., 2022). To mitigate postharvest losses, various preservation technologies have been developed. Among these, drying stands out as one of the most widely adopted methods globally for agricultural commodities.

Dehydration not only extends the shelf life of fruits and vegetables by significantly lowering water activity but also stabilizes products in a safe form for long-term storage. Furthermore, drying contributes to reducing the overall weight and volume of produce, thereby decreasing packaging and transportation costs, while simultaneously enhancing the value of agricultural products through processing (Dev et al., 2011). Many traditional thermal and non-thermal methods, including airflow drying, vacuum drying, ultrasound, electrohydrodynamics, freeze drying, microwave, and combinations thereof, are used depending on the purposes mentioned above. Among various dehydration techniques, freeze-drying is recognized for its ability to produce high-quality products by maintaining the structural integrity, morphology, and bioactive constituents of biological materials, largely due to the low temperatures involved in the process. Nevertheless, compared to conventional drying methods, freeze-drying is characterized by substantially higher energy demands and production costs, compounded by prolonged processing durations. To address these limitations, recent studies have concentrated on enhancing process efficiency through improvements in heat transfer mechanisms and minimizing vacuum requirements to achieve reduced drying times and operational expenses (Bhatta et al., 2020). Microwave drying offers rapid processing, high energy efficiency, and minimal environmental impact; however, its application is limited by high operational costs and the risk of localized overheating or burning of the product. In contrast, hot air drying is widely utilized due to its low energy requirements and operational simplicity, yet it often results in lower product quality and reduced drying efficiency. The integration of microwave and hot air drying methods has been proposed as a promising strategy to enhance drying rates and product quality while simultaneously reducing energy consumption and mitigating the individual limitations of each technique (Md Salim et al., 2017; Li et al., 2021). In the literature, nectarine products have been dried by solar, hot air, microwave, hybrid hot air-microwave, infrared, hybrid infrared, and microwave methods with different dryer designs. In these studies, the effects of drying methods on drying and physicochemical characteristics, energy consumption and color of nectarine were investigated, and modeling of drying kinetics, effective moisture diffusivity and composition of volatile compounds were also carried out (Sunthonvit et al., 2007; İsmail et al., 2016; İsmail et al., 2017; Miraei Ashtiani et al., 2018). However, there is no publication in the literature comparing microwave, microwave-hot air, hot air and freeze drying methods used in this study for nectarine drying. In this study, unlike other studies, the effects of freeze drying, which promises the best final product, and microwave, hot air, microwave-hot air methods on nectarine drying were investigated. The effects of different methods on drying time, diffusion coefficient, color, rehydration, energy values, surface temperature were examined and drying kinetics of nectarine were determined by modeling ten different thin layers.

## MATERIALS and METHODS

### *Sample preparation*

Nectarine samples (var. nucipersica) used in the study were obtained from a local market. Ripe, microbial and mechanically undamaged nectarine samples were cleaned with tap water to remove foreign materials. Water on the product surface was removed by drying with absorbent paper. The products were vacuum-sealed to preserve their quality and stored at  $4\pm 1$  °C until drying. The initial moisture content of the product was found to be 6.28 (g

water g dry matter<sup>-1</sup>) on a dry basis (d.b.) after drying randomly selected samples in an oven (Electromag, Turkey) at 70 °C for 24 hours (AOAC, 1980). Prior to drying, the nectarine samples taken from the cooler were kept at room temperature. After the products were peeled, they were cut into 4 mm thickness and placed on a glass plate and prepared for drying. Nectarine samples with a mass of 80 ± 0.01 g were used in all drying experiments.

### Dehydration procedure

A specially designed microwave-hot air oven (Figure 1) and a laboratory type lyophilizator (Alpha 1-2 LD Plus) were used for drying. Four different methods (microwave, hot air, microwave-hot air combination and freeze drying) were used for drying. Two different power levels (200 and 300 W) were used for microwave and one temperature value (50 °C) was used for hot air. Using the determined values, the products were dried at 200 W, 300 W, 200W-50 °C, 300W-50 °C, 50 °C, and freeze-drying (52 Pa, -50 °C). The drying processes were continued until the final weight of the nectarine products was 0.1 (g water g dry matter<sup>-1</sup>) on a dry basis (Tepe & Kadakal, 2022). The weight losses of the products were measured every 3 minutes for microwave and microwave-hot air methods and every 30 minutes for freeze-dry and hot air methods using a digital balance (Shimadzu, Japan) with a precision of 0.01 g.

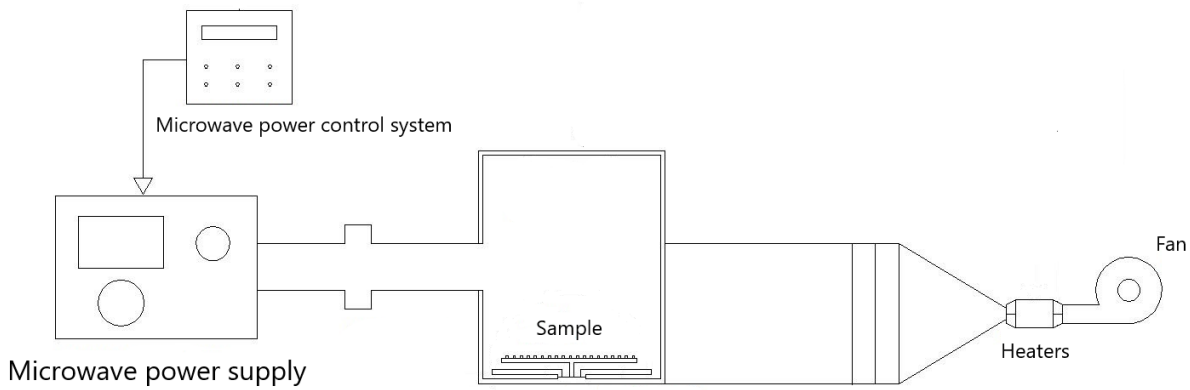


Figure 1. Specially designed microwave-hot air oven  
Şekil 1. Özel olarak tasarlanmış mikrodalga-sıcak hava fırını

### Mathematical modeling

A wide range of mathematical models has been introduced in the literature to simulate the drying kinetics of food materials. In the present study, ten widely accepted semi-theoretical and empirical thin-layer drying models, detailed in Table 1, were employed to describe the experimental drying behavior. In these formulations, 't' denotes the drying time, while 'k,' 'k<sub>0</sub>,' and 'k<sub>1</sub>' are designated as drying rate constants with units of min<sup>-1</sup>. Furthermore, coefficients such as 'a,' 'b,' 'c,' 'g,' and 'n' were identified as model-specific fitting parameters. The moisture ratio (MR) necessary for the modeling process was derived using the expression given in Eq. (1).

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

In the present study,  $M_t$ ,  $M_0$ , and  $M_e$  represent the moisture contents at a given time  $t$ , at the initial state ( $t = 0$ ), and at equilibrium, respectively. Given that  $M_e$  is typically negligible when compared to  $M_t$  and  $M_0$ , Eq. (1) can often be simplified, resulting in the reduced form presented as Eq. (2) (Shi et al., 2013).

$$MR = \frac{M_t}{M_0} \quad (2)$$

Table 1. Thin layer mathematical modeling equations to be used for the comparison of the moisture ratio values.

Çizelge 1. Nem oranı değerlerinin karşılaştırılması için kullanılacak ince tabaka matematiksel modelleme denklemleri

No	Model name	Model	References
1	Henderson and Pabis	$MR = a \exp(-kt)$	Caliskan and Dirim (2017)
2	Newton	$MR = \exp(-kt)$	Pirnazari et al. (2016)
3	Page	$MR = \exp(-kt^n)$	Sacilik and Unal (2017)
4	Logarithmic	$MR = a \exp(-kt) + c$	Amiri Chayjan and Shadidi(2014)
5	Two term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Bhattacharya et al. (2015)
6	Two term exponential	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Ergün et al. (2016)
7	Wang and Singh	$MR = 1 + at + bt^2$	Belghith et al. (2016)
8	Diffusion Approach	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$	Perea-Flores et al. (2012)
9	Verma et al	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	Taşkın et al. (2018)
10	Midilli et al.	$MR = a \exp(-kt^n) + bt$	Midilli et al. (2002)

#### Determination of effective moisture diffusivity

Eq. (3), derived as one of the simplified forms of Fick's second law of moisture diffusion for slab geometry, as presented by Crank (1979), was employed to determine the effective moisture diffusion coefficient during the drying process, assuming uniform initial moisture distribution, constant diffusivity, negligible external resistance, and negligible shrinkage.

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp \left[ -(2n+1)^2 \frac{\pi^2 D_{eff} t_i}{L^2} \right] \quad (3)$$

Here,  $D_{eff}$  represents the effective diffusion coefficient of moisture diffusivity ( $m^2 s^{-1}$ ), while  $L$  denotes the half-thickness of the nectarine slices. Eq. (3) can be further simplified into a one-term exponential model, enabling the determination of the effective diffusion coefficient for drying food samples in logarithmic form, as expressed in Eq. (4) (Zhu & Shen, 2014).

$$\ln(MR) = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t_i}{L^2} \quad (4)$$

The effective diffusion coefficient was determined by plotting  $\ln(MR)$  against the drying time ( $t_i$ ). The slope of this plot is represented in Eq. (5).

$$Slope = \frac{\pi^2 D_{eff}}{L^2} \quad (5)$$

### **Determination of color parameters**

Color analyses of fresh and different drying methods were carried out using a calorimetry device (Hunter Lab). Color readings were taken from 5 different points on the product surface. The color values of fresh products were expressed as  $L_0^*$ ,  $a_0^*$ , and  $b_0^*$  and the color values of dried products were expressed as  $L^*$ ,  $a^*$ , and  $b^*$ . In addition, Chroma ( $C$ ), hue angle ( $h^\circ$ ) and total color change ( $\Delta E$ ) were calculated using  $L^*$ ,  $a^*$ , and  $b^*$  values to determine the color change during the drying process (Eqs. 6, 7, and 8). Chroma (saturation index) is a parameter indicating the saturation of color and is directly related to color intensity. Hue angle is a widely used criterion for the characterization of color in food products. 0 or  $2\pi$  radian angles represent red hue, while  $\pi/2$ ,  $\pi$  and  $3\pi/2$  radian angles represent yellow, green, and blue hues, respectively (Guiné & Barroca, 2012).

$$C = \sqrt{a^{*2} + b^{*2}} \quad (6)$$

$$h = \tan^{-1} \left( \frac{b^*}{a^*} \right) \quad (7)$$

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (8)$$

### **Rehydration capacity measurement**

The rehydration procedure for dried nectarine slices was conducted by immersing the samples in glass beakers filled with distilled water at an ambient temperature of 20 °C for a duration of 14 hours, following the method outlined by Vásquez-Parra et al. (2013). Each drying treatment was tested in triplicate to ensure data reliability. Upon completion of the rehydration period, the samples were gently retrieved from the beakers and carefully blotted with filter paper to eliminate surface moisture. Subsequently, the sample weights were recorded using an analytical precision balance. The rehydration capacity was determined according to the Eq. (9), where  $W_1$  denotes the initial weight of the dried sample and  $W_2$  represents the weight after rehydration.

$$\text{Rehydration Capacity (\%)} = \frac{W_2 - W_1}{W_1} \times 100 \quad (9)$$

### **Indicators of drying systems energy efficiency**

The energy consumption values ( $E_c$ ) of the drying systems used in the experiments were determined in kilowatt-hours (kWh) with a power meter (EU TS-836A; Floureon, China). In order to evaluate the performance of the drying system, parameters such as specific energy consumption (SEC), moisture extraction rate (MER), and specific moisture extraction rate (SMER) were calculated using the Eqs. (10-12).

In this context:

SEC is defined as the total amount of energy consumed to remove one kilogram of water.

SMER is the amount of moisture removed per kilowatt-hour consumed.

MER indicates the amount of moisture removed in a given time period, especially on an hourly basis, and also helps to determine the capacity or efficiency rate of the drying device (Altay et al., 2019).

$$SEC = \frac{\text{Total energy supplied in drying process (kWh)}}{\text{Amount of water removed during drying (kg)}} \quad (10)$$

$$SMER = \frac{\text{Amount of water removed during drying (kg)}}{\text{Total energy supplied in drying process (kWh)}} \quad (11)$$

$$MER = \frac{\text{Amount of water removed during drying (kg)}}{\text{Drying time (h)}} \quad (12)$$

### Determination of surface temperature

Since temperature is the primary factor affecting the quality of food products during drying, and excessive heat can lead to undesirable changes in color, aroma, texture, and nutritional content, monitoring the product's surface temperature is essential to prevent thermal damage and preserve overall quality (Vega et al., 2016). The surface temperature of nectarine slices dried by different methods was determined using an infrared thermometer (62 Max+, Fluke), as described by Ahamed et al. (2023). For each sample, temperature readings were collected from four distinct points within the same area, and the mean value of these measurements was calculated to represent the surface temperature.

### Statistical assessment

MS-Excel software was used to enter the data obtained as a result of drying processes. Statistical analyses were performed using JMP (Version 7, USA) package programme with analysis of variance and comparison tests. The data were evaluated at 5% significance level. Modelling studies were carried out using MATLAB (MathWorks Inc., Natick, MA) software package. The following statistical parameters were used to determine the suitability of the experimental data for thin layer drying models: Coefficient of determination ( $R^2$ ), chi-square ( $\chi^2$ , Eq. 13), and root mean square error (RMSE, Eq. 14).

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N-z} \quad (13)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (14)$$

Where  $MR_{exp}$  is the experimental humidity;  $MR_{pre}$  is the predicted humidity;  $i$  is the experimental data points;  $N$  is the number of observed experimental data;  $z$  is the number of independent variables in the model.

## RESULTS and DISCUSSIONS

### Drying times

Figure 2 illustrates the drying curves of nectarine samples subjected to various drying conditions. The duration required to achieve the final moisture content varied depending on the applied method, with freeze-drying exhibiting the longest drying time. While it took 450 minutes for the products to dry in the freeze drying method, this time was 390 minutes for the hot air method. The drying times of nectarine slices were recorded as 33, 30, 21, and 18 minutes under the drying conditions of 200 W, 200 W–50 °C, 300 W, and 300 W–50 °C, respectively. The results demonstrated that the application of the combined microwave–convective drying method at 200 W–50 °C and 300 W–50 °C led to reductions in drying time of 14.29% and 9.09%, respectively, when compared to microwave drying alone at 200 W and 300 W. Consequently, it was determined here that integrating microwave into the hot air method significantly reduced the drying time. The integration of microwave energy at different drying stages—initial, middle, or final—enhances internal heating, accelerates moisture migration, and facilitates the removal of bound water, thereby significantly reducing the overall drying time compared to conventional convective methods. This combined approach optimizes heat and mass transfer mechanisms, particularly by promoting internal vapor generation and maintaining higher drying rates throughout the process (Dehghannya et al., 2018). In addition, increasing the microwave power level decreased the drying time of the products. According to Yildiz and İzli (2019),

the application of the combined microwave–convective drying technique significantly shortened the drying time of pomelo compared to conventional methods. Zhao et al. (2023) determined that the total drying time required for freeze drying process was 24 hours, 835 minutes for hot air drying and drying time ranged between 430 minutes and 157 minutes for different microwave-hot air combination applications. The results of these studies were in line with the outputs obtained from our study.

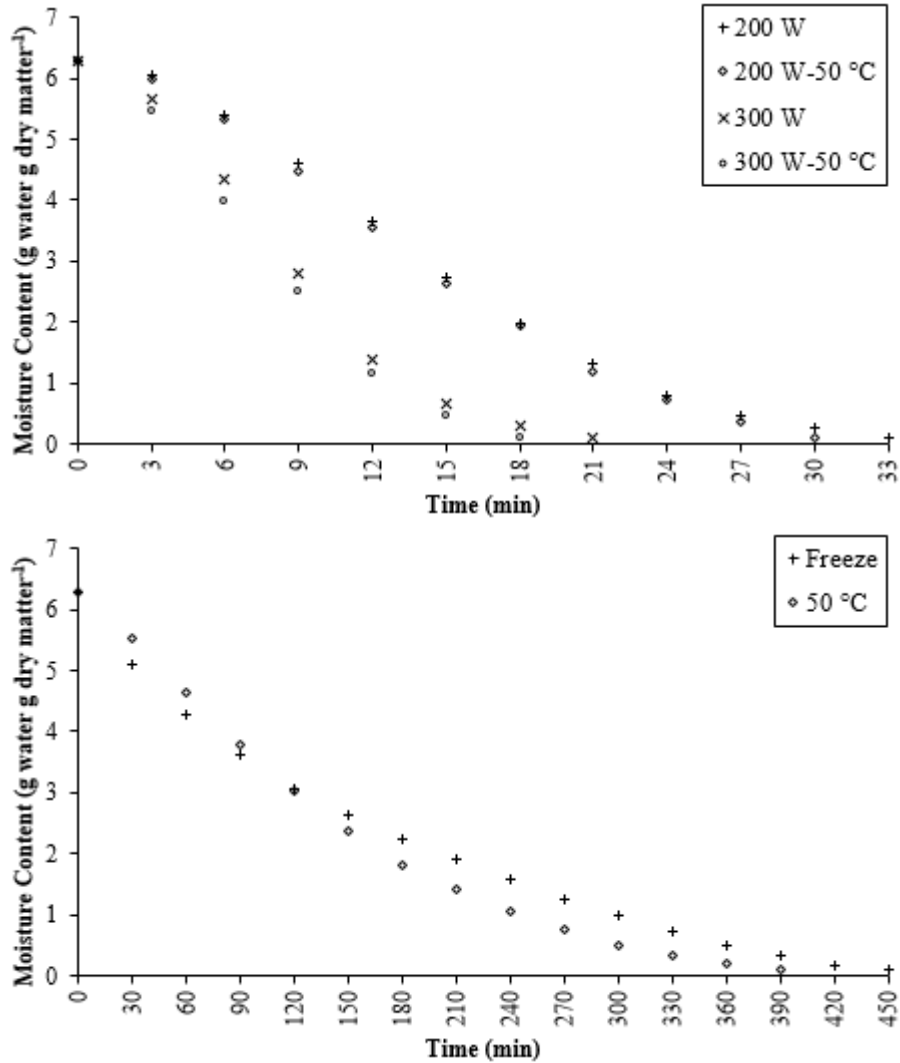


Figure 2. Variation of moisture content of nectarine samples dried by different drying methods with time

Şekil 2. Farklı kurutma yöntemleri ile kurutulan nektarin örneklerinin nem içeriğinin zamanla değişimi

### Mathematical modeling of drying curves

The experimental data obtained for each experimental condition were fitted to ten different models listed in Table 1 and tested for  $\chi^2$  and  $RMSE$  values. The most appropriate model was determined as the model with the highest  $R^2$  value and the lowest  $\chi^2$  and  $RMSE$  values. The values obtained as a result of all statistical calculations are presented in Table 2. As a result of the analyses,  $R^2$  values ranged between 0.9063 and 0.9999,  $RMSE$  values between 0.0034 and 0.1319, and  $\chi^2$  values between  $0.2252 \times 10^{-4}$  and  $177.9509 \times 10^{-4}$ . Table 2 shows that the model proposed by Midilli et al. is the most appropriate choice to represent the thin layer drying process of nectarine slices. This model provided the highest  $R^2$  (0.9994-0.9999), the lowest  $RMSE$  (0.0034-0.0137) and the lowest  $\chi^2$  ( $0.2252 \times 10^{-4}$ - $1.3131 \times 10^{-4}$ ) values in all conditions. In Figure 3, the moisture contents predicted using the appropriate model are compared with the moisture contents observed in different drying techniques. These results

Table 2. Estimated values of coefficients and statistical analyses were obtained from various thin layer drying models for drying nectarine slices using different methods

Çizelge 2. Nektarin dilimlerinin farklı yöntemlerle kurutulması için çeşitli ince tabaka kurutma modellerinden tahmin edilen katsayı değerleri ve istatistiksel analizler

No	200 W				200 W-50 °C				50 °C			
	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )
1	a=1.146 k= 0.0701	0.9359	0.0981	96.5439	a=1.136 k=0.071	0.9324	0.0999	99.6191	a=1.069 k=0.0073	0.9856	0.0412	17.0635
2	k=0.0614	0.9094	0.1112	147.1876	k=0.0624	0.9069	0.1113	123.7653	k=0.0068	0.9796	0.0472	22.2210
3	k=0.0047 n=1.907	0.9998	0.0054	0.2575	k=0.0051 n=1.903	0.9992	0.0112	1.4238	k=0.0014 n=1.316	0.9994	0.0081	1.7112
4	a=1.965 k=0.0255 c=-0.8883	0.9833	0.0528	28.7985	a=2.615 k=0.018 c=-1.5523	0.9874	0.0457	20.2562	a=1.192 k=0.0052 c=-0.1586	0.9971	0.0193	3.7703
5	a=-0.351 k <sub>0</sub> =7.7598 b=1.351 k <sub>1</sub> =0.0823	0.9691	0.0761	57.1305	a=-44.821 k <sub>0</sub> =0.1494 b=-43.838 k <sub>1</sub> =0.1538	0.9920	0.0391	15.5765	a=1.168 k <sub>0</sub> =0.0079 b=-0.1683 k <sub>1</sub> =20.6948	0.9936	0.0300	9.1558
6	a=0.000102 k=600.8298	0.9093	0.1166	137.0345	a=2.193 k=0.1094	0.9882	0.0417	17.1959	a=0.000235 k=29.1032	0.9795	0.0491	24.1192
7	a=-0.0404 b=0.000265	0.9773	0.0584	35.2672	a=-0.0391 b=0.00015	0.9825	0.0508	25.2205	a=-0.0051 b=-0.0000066	0.9989	0.0115	2.7990
8	a=-125.624 k=0.1489 b=0.99	0.9937	0.0324	9.9064	a=-256.2496 k=0.1488 b=0.9953	0.9916	0.0374	13.9309	a=-0.0434 k=2.1292 b=0.0031	0.9708	0.0613	37.6202
9	a=-9.409 k=0.0068 g=0.01	0.9764	0.0627	41.7883	a=-19.601 k=0.0102 g=0.0119	0.9778	0.0607	38.1720	a=1.168 k=0.0079 g=1.3025	0.9936	0.0286	8.3235
10	a=0.999 k=0.005 n=1.878 b=-0.000392	0.9999	0.004	0.1392	a=0.998 k=0.0058 n=1.826 b=-0.0013	0.9998	0.0061	0.3617	a=0.9999 k=0.0017 n=1.259 b=-0.0000715	0.9999	0.0034	0.2252

No	300 W				300 W-50 °C				Freeze			
	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )
1	a=1.112 k=0.1143	0.9334	0.1091	121.978	a=1.0957 k=0.1226	0.9345	0.1096	120.4116	a=0.9997k= 0.0061	0.9921	0.0273	7.1467
2	k=0.1038	0.9168	0.1129	130.4408	k=0.1126	0.9209	0.1099	121.2001	k=0.0068	0.9921	0.0264	15.0520
3	k=0.0115 n=1.943	0.9995	0.0097	0.8553	k=0.0157 n=1.878	0.9990	0.0135	1.5265	k=0.0047 n=1.050	0.9929	0.0260	6.5001
4	a=1.689 k=0.0505 c=-0.6246	0.9750	0.0732	54.9694	a=2.048 k=0.0414 c=-1.0021	0.9838	0.0608	36.1810	a=1.077 k=0.0048 c=-0.1055	0.9979	0.0148	2.2303
5	a=-9.036 k <sub>0</sub> =0.028 b=10.1165 k <sub>1</sub> =0.0337	0.9756	0.0486	67.3199	a=-0.482 k <sub>0</sub> =6.4244 b=1.482 k <sub>1</sub> =0.1619	0.9805	0.0772	59.5606	a=-0.638 k <sub>0</sub> =0.0061 b=0.3615 k <sub>1</sub> =0.0062	0.9921	0.0295	8.2794
6	a=0.00010996 k=943.7622	0.9168	0.122	152.2412	a=0.0002 k=485.6445	0.9208	0.1204	145.5623	a=1.471 k=0.0072	0.9935	0.0248	5.9454
7	a=-0.0716 b=0.0011	0.9727	0.0698	50.8667	a=-0.0745 b=-0.00097098	0.9820	0.0574	32.3509	a=-0.0045 b=0.00000543	0.9860	0.0364	15.4982
8	a=-30.3088 k=0.2566 b=0.9585	0.9945	0.0343	12.1374	a=-30.7159 k=0.2739 b=0.9606	0.9931	0.0398	15.5223	a=1.0019 k=0.0058 b=-1.3749	0.9978	0.0149	2.0436
9	a=-19.625 k=0.0909 g=0.0916	0.9189	0.1319	177.9509	a=-28.823 k=0.2749 g=0.2634	0.9931	0.0398	15.5727	a=0.999 k=0.0061 g=0.7577	0.9921	0.0283	7.6923
10	a=0.9951 k=0.0104 n=1.992 b=0.0005013	0.9996	0.0107	1.0596	a=0.9958 k=0.0165 n=1.833 b=-0.0013	0.9994	0.0137	1.3131	a=0.9987 k=0.0111 n=0.844 b=-0.000315	0.9995	0.0071	0.4730

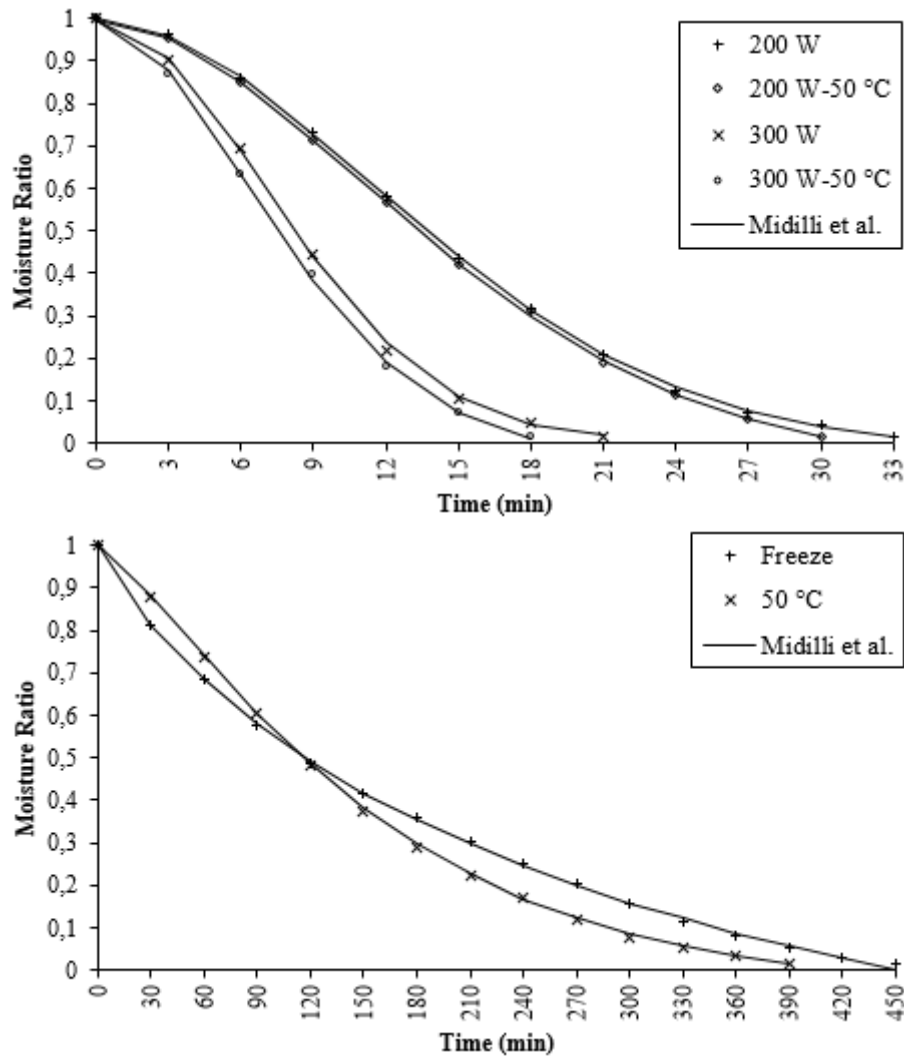


Figure 3. Comparative evaluation of experimental moisture content variations in nectarine samples subjected to different drying methods using the Midilli et al. model

Şekil 3. Midilli vd. modeli kullanılarak farklı kurutma yöntemlerine tabi tutulan nektarin numunelerindeki deneysel nem içeriği değişimlerinin karşılaştırmalı değerlendirmesi

show that the model follows the experimentally obtained moisture content quite well throughout all drying processes. As a result of the researches in the literature, it is seen that the mean regression coefficient of Midilli et al. equation is the highest and the chi-square value is the lowest compared to other models in Taşkın (2020) freeze drying of black chokeberry (*Aronia melanocarpa* L.) and Ganesapillai et al. (2011) banana drying studies with microwave, convective and combined microwave-convective methods. These results were in parallel with the results of this study.

### Effective moisture diffusivities

The effective moisture diffusivity ( $D_{eff}$ ) of dried nectarine slices was determined using the slope method, based on Eq. (5). A linear regression was performed by plotting the natural logarithm of the moisture ratio ( $\ln(MR)$ ) against drying time using the experimental data. The resulting effective moisture diffusivity values, illustrated in Figure 4, ranged from  $3.978 \times 10^{-8}$  to  $10.625 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ . These values fall within the general range reported for food materials ( $10^{-11}$ – $10^{-6} \text{ m}^2 \text{ s}^{-1}$ ), as noted by Horuz et al. (2017). Upon evaluation of the data, the highest  $D_{eff}$  values were recorded for the microwave–convective drying method, followed in descending order by microwave, hot air,

and freeze-drying methods. A higher effective diffusion coefficient ( $D_{eff}$ ) enables an increase in moisture transfer rate in agricultural products, thereby allowing the target final moisture content to be reached in a shorter time. On the other hand, the lower  $D_{eff}$  values observed in conventional methods such as freeze-drying and hot air drying indicate that these methods have slower drying rates and limited moisture transfer. As drying temperature and microwave power level increase, the kinetic energy of water molecules rises, promoting moisture diffusion; therefore, an increase in  $D_{eff}$  values is observed (Yildiz & İzli, 2019). Similar findings were reported by Alaei and Chayjan (2025), who used microwave-hot air dehydration for nectarine chips production and found that  $D_{eff}$  values increased when microwave power was increased. Miraei Ashtiani et al. (2018) The results of this study show that the  $D_{eff}$  value in the hybrid microwave-hot air drying technique is significantly higher than that in the hot air drying method. Additionally, Caliskan and Dirim (2017) found that the  $D_{eff}$  value in convective drying was higher than the  $D_{eff}$  values obtained in the freeze-drying method in their study on the drying of pumpkin slices. These studies are consistent with the results of our study.

### **Color parameters**

Color serves as a key quality indicator in fruits and vegetables during drying, playing a vital role in shaping consumer preferences and overall product acceptability; hence, maintaining color integrity should be prioritized throughout postharvest processing stages (Liu et al., 2021). Table 3 shows the CIELAB color parameters for the nectarine slices, in the fresh form and after drying with different conditions. The values for the  $L_o^*$ ,  $a_o^*$  and  $b_o^*$  coordinates of the fresh nectarine were  $63.40 \pm 0.580$ ,  $22.37 \pm 0.123$ , and  $58.46 \pm 0.389$ , respectively.  $L^*$ ,  $b^*$  and  $C$  values decreased with the effect of drying. When  $L^*$  values were analyzed, the closest value to the fresh product was observed in freeze-dried products. There was no statistical difference between the  $L^*$  value of the samples dried at 200 W and the samples dried at 200 W-50 °C ( $p > 0.05$ ). The same was true for the samples dried at 300 W and 300 W-50 °C. The  $L^*$  values of the samples dried with hot air were higher than those dried with microwave and microwave-hot air methods. This may be due to the high drying temperatures and long processing times involved in hot air drying (İlter et al., 2018). While no statistical difference was observed between the  $a^*$  values of the samples dried with Fresh, 200W-50 °C, and 50 °C ( $p > 0.05$ ), a decrease was detected in the  $a^*$  values of the products obtained from the other treatments. When the  $b^*$  values were examined, the closest value to the fresh product was observed in the hot air method. It was determined that the  $b^*$  values of microwave and microwave convective methods were lower than the hot air method. The decrease in  $b^*$  values indicates a loss of yellowness in the dried fruit, while the increase in  $a^*$  values reflects a shift towards a redder hue. These color changes may be attributed to pigment degradation or non-enzymatic Maillard browning. Demirel and Ismail (2017) found that  $L^*$ ,  $a^*$ , and  $b^*$  values of products dried with 50 °C hot air were higher than microwave and microwave method in nectarine drying studies. This is in parallel with the results of our study. Chroma ( $C$ ) represents the saturation or vividness of color, with higher values corresponding to greater color intensity as perceived by the human eye. When the results were analyzed, the lowest  $C$  value was observed in 200W and 300W-50 °C samples. It was determined that the negative effect of microwave and microwave-hot air method on the color saturation of the product was higher than the other methods. İzli et al. (2018). obtained similar results to ours in their studies on pineapple drying. It has been reported that products dried using the hot air method have higher Chroma values and therefore more vibrant colours compared to those dried using microwave and freeze-drying methods. The Chroma values obtained in parallel with  $b$  and  $a$  values indicate that microwave application may cause greater colour loss compared to other methods due to pigment degradation or non-enzymatic Maillard reactions. The hue angle values of the samples ranged from  $73.81^\circ \pm 0.120$  to  $63.01^\circ \pm 0.301$ , indicating a noticeable shift in color tonality from yellowish hues towards more orange-red tones. This reduction in hue angle may be attributed to thermal degradation of natural pigments such as carotenoids or polyphenols, as well as the occurrence of non-enzymatic browning reactions during the drying process. The total color difference ( $\Delta E$ ) represents a composite metric derived from individual color parameters—namely lightness

( $L^*$ ), redness ( $a^*$ ), and yellowness ( $b^*$ )—and serves as an indicator of the extent of color changes occurring in food materials during the drying process. Microwave-hot air and microwave-dried samples exhibited significantly higher final total color difference ( $\Delta E$ ) values compared to those subjected to hot air drying, indicating a greater degree of color degradation (Guiné & Barroca, 2012). This suggests that microwave drying led to more pronounced visual alterations, often resulting in a brownish appearance in the dried products. The lowest  $\Delta E$  value of the freeze-dried sample can probably be explained by the fact that the drying process was carried out at a lower temperature and therefore the pigments in the sample were less degraded. This contributed to better preservation of the color and appearance characteristics of the product. The results of our study showed parallels with the results of Horuz and Maskan (2015) and Sun et al. (2022).

Table 3. Color values of the fresh and dried nectarine slices

Çizelge 3. Taze ve kurutulmuş nektarin dilimlerinin renk değerleri

Product	$L^*$	$a^*$	$b^*$	$C$	$h^\circ$	$\Delta E$
Fresh	63.40±0.580 <sup>a</sup>	22.37±0.123 <sup>a</sup>	58.46±0.389 <sup>a</sup>	62.59±0.372 <sup>a</sup>	69.09±0.153 <sup>b</sup>	-
200W	42.47±0.085 <sup>d</sup>	15.50±0.055 <sup>c</sup>	35.39±0.335 <sup>e</sup>	38.64±0.292 <sup>e</sup>	66.37±0.255 <sup>bc</sup>	31.89±0.271 <sup>d</sup>
200W-50 °C	41.96±0.798 <sup>d</sup>	20.72±0.171 <sup>a</sup>	40.63±0.727 <sup>d</sup>	45.60±0.707 <sup>d</sup>	63.01±0.301 <sup>d</sup>	27.95±0.555 <sup>c</sup>
300W	40.13±3.276 <sup>e</sup>	18.01±0.420 <sup>b</sup>	41.41±0.700 <sup>d</sup>	45.15±0.803 <sup>d</sup>	66.53±0.191 <sup>bc</sup>	29.21±3.040 <sup>c</sup>
300W-50 °C	40.79±0.471 <sup>de</sup>	16.95±1.477 <sup>bc</sup>	34.36±0.993 <sup>f</sup>	38.50±2.000 <sup>e</sup>	64.02±3.371 <sup>cd</sup>	33.72±1.228 <sup>e</sup>
50 °C	50.76±0.112 <sup>c</sup>	20.26±0.075 <sup>a</sup>	53.24±0.845 <sup>b</sup>	56.97±0.775 <sup>b</sup>	69.20±0.350 <sup>b</sup>	13.85±0.393 <sup>b</sup>
Freeze	60.19±0.385 <sup>b</sup>	15.21±0.092 <sup>c</sup>	52.29±0.594 <sup>c</sup>	54.45±0.590 <sup>c</sup>	73.81±0.120 <sup>a</sup>	9.99±0.385 <sup>a</sup>

\*<sup>a-f</sup> Alphabets in the same column not have the same superscript are significantly different ( $p<0.05$ ).

### Rehydration capacity values

Rehydration is often considered an indicator of structural damage incurred by the material as a result of the drying process. Higher rehydration ratio values are associated with superior product quality, as they reflect a closer resemblance of the rehydrated sample to its fresh counterpart (Dev et al., 2011). Figure 4 shows the rehydration capacity values of nectarine slices dried by different methods using a constant rehydration temperature. Rehydration capacity values ranged between 3.2125 and 2.2355 and the highest value was observed in freeze dried samples. The rehydration capacity values obtained from freeze drying method were found to be higher than hot air method. The underlying reason may be that exposure to elevated temperatures during drying leads to irreversible cellular disintegration and structural damage. Similar to our study, Jia et al. (2019) and Argyropoulos et al. (2011) found that the rehydration values of freeze-dried products were higher than hot air dried samples in persimmon and mushroom drying studies. No significant difference was observed in the rehydration capacity values of nectarine samples by increasing the microwave power from 200 W to 300 W in microwave and microwave-hot air method ( $p>0.05$ ). Unlike the results of our study, Miraei Ashtiani et al. (2018) found that the rehydration values of nectarine samples dried with hot air and hot air-microwave methods were lower than the samples dried with hot air-microwave methods. This may be due to the different air temperatures and microwave power used in the experiments.

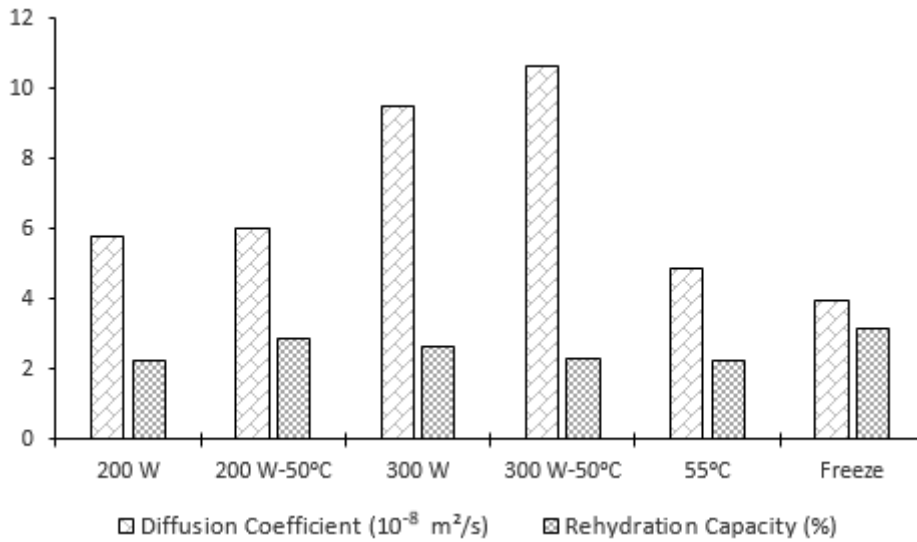


Figure 4. Rehydration capacity and effective moisture diffusion values of nectarine samples dried by different drying methods

Şekil 4. Farklı kurutma yöntemleri ile kurutulmuş nektarin örneklerinin rehidrasyon kapasitesi ve etkin nem difüzyon değerleri

#### Energy efficiencies of drying methods

Table 4 shows the energy efficiency evaluations of nectarine samples dried by different drying methods. When the energy consumption values were analyzed, the highest value was determined in freeze drying method, followed by hot air method. In microwave drying method, increasing the power level decreased the energy consumption. This is attributed to the fact that drying processes performed at lower microwave power levels require longer durations, thereby resulting in higher energy consumption rates (Motevali et al., 2011). However, this was not statistically significant ( $p>0.05$ ). The same situation was determined for microwave-hot air and microwave methods. Although there were small differences in energy consumption between microwave method and microwave-hot air method, they were not statistically significant ( $p>0.05$ ). SEC values in the decreasing order were  $61.239 > 13.938 > 4.204 > 3.8941 > 3.746 > 3.584 \text{ kWh kg}^{-1}$  for the Freeze-dried,  $50^\circ\text{C}$ ,  $200 \text{ W-}50^\circ\text{C}$ ,  $300 \text{ W-}50^\circ\text{C}$ ,  $200 \text{ W}$ , and  $300 \text{ W}$ . As in the energy consumption values, the highest SEC values were obtained in freeze drying method, while there was no significant difference between the SEC values obtained from microwave-hot air and microwave methods ( $p>0.05$ ). A high SMER would indicate an efficient drying process with low-energy consumption. The larger SMER result indicates the higher energy efficient (Boateng et al., 2021). When the SMER values of the freeze drying, hot air, microwave-hot air and microwave drying methods were compared, a lowest SMER value was obtained for the freeze drying due to an energy consumption than the other methods. Considering the amount of moisture removed per hour, the moisture evaporation rate (MER) ranged from  $0.0009$  to  $0.226 \text{ kg h}^{-1}$ , with the highest MER value ( $0.226 \text{ kg h}^{-1}$ ) recorded under the  $300 \text{ W-}50^\circ\text{C}$  drying condition. This finding indicates that the  $300 \text{ W-}50^\circ\text{C}$  application facilitated the most significant moisture removal per unit time, thereby demonstrating that the microwave-hot air combination is the most energy-efficient drying method. While there is no significant difference between the hot air method and freeze drying method in terms of MER values ( $p>0.05$ ), the moisture removal rate of these methods is lower than the other methods. Boateng et al. (2021) found that the SMER and MER values of the products dried by freeze drying method were lower and SEC values were higher than hot air in the drying study of ginkgo seed by different methods. In addition, Altay et al. (2021) examined the efficiency of drying devices by drying purple bacillus with different methods (sun, freeze, convective, and microwave oven). While they determined the microwave oven  $>$  convective  $>$  freeze drying correlation between SMER and MER values, they

obtained Freeze drying > convective > microwave oven correlations in SEC values. The results of these two studies are in parallel with our study.

Table 4. Energy values of nectarine slices dried with different treatments

Çizelge 4. Farklı işlemlerle kurutulmuş nektarin dilimlerinin enerji değerleri

Drying processes	EC (kWh)	SEC (kWh/kg)	SMER (kg/kWh)	MER (kg/h)
200W	0.254±0.024 <sup>c</sup>	3.746±0.3540 <sup>c</sup>	0.269±0.0254 <sup>a</sup>	0.135±0.0140 <sup>c</sup>
200W-50 °C	0.285±0.004 <sup>c</sup>	4.204±0.0590 <sup>c</sup>	0.238±0.0033 <sup>b</sup>	0.137±0.0000 <sup>c</sup>
300W	0.243±0.015 <sup>c</sup>	3.584±0.2212 <sup>c</sup>	0.280±0.0173 <sup>a</sup>	0.189±0.0530 <sup>b</sup>
300W-50 °C	0.264±0.009 <sup>c</sup>	3.894±0.1327 <sup>c</sup>	0.257±0.0088 <sup>ab</sup>	0.226±0.0000 <sup>a</sup>
50 °C	0.945±0.029 <sup>b</sup>	13.938±0.4277 <sup>b</sup>	0.0719±0.0022 <sup>c</sup>	0.010±0.0004 <sup>d</sup>
Freeze-dried	4.152±0.215 <sup>a</sup>	61.239±3.1711 <sup>a</sup>	0.0164±0.0009 <sup>d</sup>	0.009±0.0003 <sup>d</sup>

\*<sup>a-d</sup> Alphabets in the same column not have the same superscript are significantly different (p<0.05).

### Surface temperature of product

The surface temperatures of nectarine slices subjected to different drying methods are presented in Figure 5. In accordance with the fundamental principle of freeze-drying, the water content in the samples initially froze at sub-zero temperatures and subsequently underwent sublimation. During this process, the product temperature initially dropped to -20 °C and then exhibited a logarithmic increase throughout the drying period, ultimately reaching 15.15 °C. In hot air drying, the product temperature peaked at 42.65 °C, consistently remaining below the drying air temperature of 50 °C. This observation aligns with the findings of Shi et al. (2021). For samples treated with 200 W, 200 W–50 °C, 300 W, and 300 W–50 °C drying conditions, the corresponding surface temperatures were recorded as 97.7 °C, 96.25 °C, 99.8 °C, and 98.85 °C, respectively. These results demonstrate that increasing microwave power led to a corresponding increase in product surface temperature in both drying configurations. Moreover, the integration of microwave energy into the hot air drying process elevated the product temperature compared to hot air drying alone. Similar findings were reported by Varith et al. (2007) and Zhao et al. (2023), who noted that increased microwave power enhanced product surface temperature and that the incorporation of microwave energy into hot air drying further intensified this effect. Interestingly, the surface temperatures observed in treatments using solely microwave energy at both power levels were higher than those recorded in the microwave–hot air hybrid drying methods. This can be explained by the fact that the internal heat generated by microwave energy increases the vapour pressure within the porous structure, facilitating the transport of moisture towards the surface and its subsequent removal by evaporation with convective airflow; in some cases, evaporative cooling can also occur on the surface (Kumar & Karim, 2019). Cuccurullo et al. (2019) attributed this behavior to the advantages of the hybrid microwave–hot air heating system, which reduces temperature fluctuations by alleviating the non-uniform temperature distribution commonly associated with microwave drying alone. The same phenomenon is also mentioned by Wray and Ramaswamy (2015).

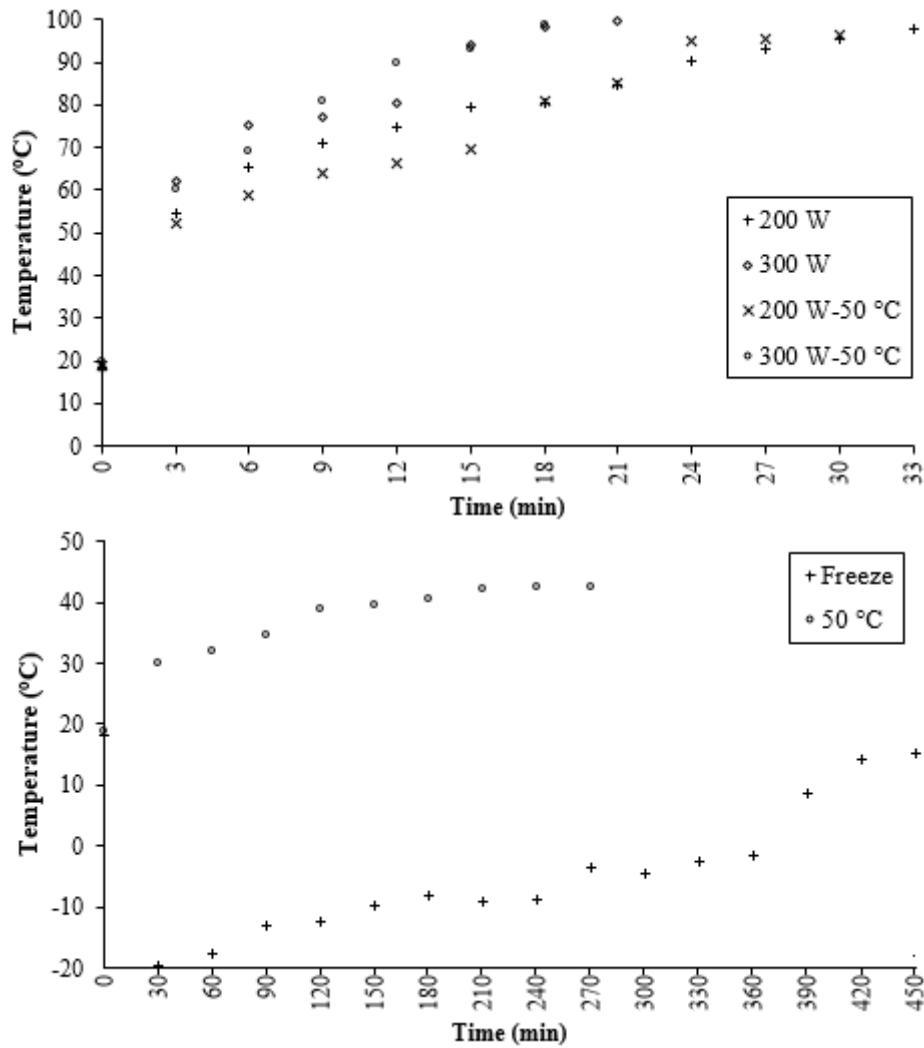


Figure 5. Surface temperature evaluation of nectarine slices dried using different drying techniques

Şekil 5. Farklı kurutma teknikleri kullanılarak kurutulan nektarin dilimlerinin yüzey sıcaklığının değerlendirilmesi

In conclusion, the present study investigated the drying behavior of nectarine slices using four distinct drying methods: microwave drying, hot air drying, a combined microwave-hot air system, and freeze-drying. For the drying experiments, two microwave power settings (200 W and 300 W) along with a fixed drying temperature of 50 °C were employed. Subsequently, various parameters including drying time, effective moisture diffusivity, drying kinetics modeling, color characteristics, rehydration ability, energy efficiency, and surface temperature were analyzed to assess the performance of each technique. The longest drying time was obtained in freeze drying method, followed by hot air, microwave-hot air combination method. Microwave-hot air>microwave>hot air>freeze drying relation was obtained between the effective moisture diffusion values. Comparing the statistical parameters of applied models, Midilli et al. model was found to be the best-fitting models in describing drying kinetics of the nectarine slices. The hot air drying treatment has a small effect on chroma of the product than the the other methods. Freeze-dried samples had the lowest  $\Delta E$  value and were the least affected by drying. It was determined that microwave-hot air and microwave power variation had no effect on rehydration capacity in microwave-hot air and microwave applications ( $p>0.05$ ). The lowest SMER (0.0164 kg kWh<sup>-1</sup>) and MER (0.0009 kg h<sup>-1</sup>) values, and the highest SEC (61.239 kWh kg<sup>-1</sup>) value were determined for the Freeze drying method. The surface temperatures of the products dried by microwave and microwave hot air combined methods were higher than the surface temperatures of the products dried by hot air and freeze drying. Although the total color change values of

freeze-dried products were the lowest, energy consumption was found to be high. With 300 W-50 °C applications, the energy consumption of dried nectarine products was found to be low and energy efficiency was high, while the high total color change was negative in terms of quality. In the future, there is a need to increase drying studies on consumer perception of dried nectarine using different microwave and temperature values.

#### STATEMENT OF CONFLICT OF INTEREST

The authors declare no conflict of interest for this study.

#### AUTHOR'S CONTRIBUTIONS

The contribution of the authors is equal

#### STATEMENT OF ETHICS CONSENT

Ethical approval is not applicable, because this article does not contain any studies with human or animal subjects.

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