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Determination of Drying Kinetics of Tunceli Garlic with Microwave Drying Technique

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ABSTRACT

In this study, drying kinetics of 4 mm-thick slices of Tunceli garlic (*Allium tuncelianum*) was investigated by using microwave technique at an interval of 90-600 W microwave output power. Ten mathematical models were used to represent the experimental data in this study. The determination of coefficient (R^2), root mean square error (*RMSE*), chi-square (χ^2) and percentage error (*E%*) values that show compatibility to these models were determined. The determination of coefficient (R^2) values were found to vary at an interval of 0.9440-0.9993. The Midilli et al model was determined to be the best model that represents the experimental data. It was seen that drying rate increases with the increase in microwave output power (*P*) and decreases with the increase in sample mass (*m*). Effective diffusion coefficients (D_{eff}) and drying rate constants (*k*) were determined for different sample masses at microwave output power of 90 W. Activation energies for both effective diffusion coefficients and drying rate constants were determined by using an Arrhenius type exponential equation. Activation energies from effective diffusion coefficients and drying rate constants were found as 3.85 W g^{-1} and 3.99 W g^{-1} respectively.

Keywords: Tunceli garlic; Thin-layer drying; Microwave drying

Tunceli Sarımsağının Mikrodalga Kurutma Tekniği ile Kuruma Kinetiğinin Belirlenmesi

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ÖZET

Bu çalışmada, mikrodalga tekniği kullanılarak 90-600 W mikrodalga çıkış gücü aralığında 4 mm kalınlıktaki Tunceli sarımsağı (*Allium tuncelianum*) dilimlerinin kuruma kinetiği incelenmiştir. Deneysel verileri temsil etmek için on adet matematiksel model kullanılmıştır. Bu modellere uygunluğu gösteren determinasyon katsayısı (R^2), ortalama hata kareleri karekökü (root mean square error, *RMSE*), ki- kare (χ^2) ve yüzde hata (*% E*) değerleri belirlenmiştir. Determinasyon katsayısı (R^2) değerlerinin 0.9440-0.9993 aralığında değiştiği görülmüştür. Midilli et al modeli deneysel verileri temsil eden en iyi model olarak belirlenmiştir. Mikrodalga çıkış gücündeki (*P*) artma ile kuruma hızı artarken örnek kütlesindeki (*m*) artma ile kuruma hızının azaldığı görülmüştür. Farklı örnek kütleleri için etkin difüzyon katsayıları (D_{eff}) ve kuruma hız sabitleri (*k*) 90 W mikrodalga çıkış gücünde belirlenmiştir. Hem kuruma hız sabitleri hem de etkin difüzyon katsayıları için Arrhenius tipi exponansiyel bir eşitlik kullanılarak aktivasyon enerjisi belirlenmiştir. Etkin difüzyon katsayılarından ve kuruma hız sabitlerinden aktivasyon enerjileri sırasıyla 3.85 W g^{-1} ve 3.99 W g^{-1} olarak belirlenmiştir.

Anahtar Kelimeler: Tunceli sarımsağı; İnce tabaka kurutma; Mikrodalga kurutma

1. Introduction

Allium tuncelianum, whose original name is *Allium macrochaetum* Boiss and Haussk subsp. *tuncelianum* Kollmann, is an endemic plant that grows in Tunceli (Turkey) and its environs, especially in the counties of Ovacık, Pülümür, Hozat and Pertek. For this reason, it is called "Tunceli garlic" or "Ovacık garlic" in the region (Ipek et al 2008). The most prominent features of Tunceli garlic that distinguish it from other garlic species are that it is single-cloved and yields seeds by flowering. It is an economically valuable plant and people in the region depend on it for their livelihoods. Various projects are carried out by the Ministry of Food, Agriculture and Livestock in order to grow and market Tunceli garlic. It loses its aroma and taste in a short time if it is not stored under suitable conditions.

Drying can be described in simple terms as removing water from a wet/moist material. However, drying is a complex process of heat and mass transfer between the moist material and its environment (Midilli et al 2002). Drying can be said to be one of the oldest methods of increasing the durability of food items and consuming them later. Drying is the best method in terms of preserving their vitamin potential, appearance, taste, advantage in packaging due to a reduction in size and the improvement in storing and transportation of food products (Doymaz 2013).

Such drying methods as contact drying, convective drying, radiative drying, freeze drying and osmotic drying are used to dry vegetables, fruits and cereal products. (Yagcioglu et al 1999). Microwave drying has an important place among radiative drying methods. Microwaves are generally used as heat sources due to their fast heating capabilities. Microwave drying has gained popularity as an alternative drying method in the food industry in recent years (Cui et al 2004). Due to the fact that the inner temperature of the food that is dried with microwave is greater than its surface temperature, a more dynamic moisture transfer compared to convective drying is achieved (Torringa et al 2001; Wang & Sheng 2006). Compared to the traditional and conventional hot air drying methods, microwave drying method has such advantages as homogenous energy distribution, high thermal conductivity, conservation of energy, a smaller area of drying, a shorter drying time and preservation of food items from enzymatic decay (Decareau 1992; Rhen & Chen 1998; Schiffmann 2001).

Microwave drying of various agricultural products was investigated by various researchers; for example, potato (Bouraout et al 1994), soybean (Adu & Otten 1994), white bean (Adu & Otten 1996), grape (Tulasidas et al 1997), apple (Feng & Tang 1998), carrot (Lin et al 1998; Litvin et al 1998), banana (Maskan 2000), kiwi (Maskan 2001), parsley (Soysal 2004), spinach (Ozkan et al 2007), grapevine leaves (Alibaş 2012). Related to garlic drying, different drying methods were reported in the literature (Madamba et al 1996; Sablani et al 2007; Babetto et al 2011; Thuwapanichayanan et al 2014). Microwave drying for garlic clove was also investigated in some studies (Sharma & Prasad 2001; Sharma & Prasad 2006; Figiel 2009).

The aim of this study is to investigate the drying kinetics of Tunceli garlic in a microwave oven at different microwave power levels and different amounts of the garlic and to apply the chosen thin layer drying models. This will be the first study investigating drying behavior of Tunceli garlic. This study is also original due to using microwave drying which is recently used as an alternative drying method in the food industry for Tunceli garlic.

2. Material and Methods

2.1. Material

Tunceli garlic (*Allium tuncelianum*) samples used in this study were obtained from a Tunceli-based and licensed producer, who grows garlic in a natural-like medium. Dirt and plant residues of the garlic samples were cleaned off and stored unpeeled at 4±0.5 °C in a refrigerator. Moisture determination device with a halogen lamp (AND MX50, Japan) was used to determine the initial moisture content of the garlic samples. The moisture content of the garlic samples was found to be 1.42 kg_{water} kg_{dm}^{-1}. The deviation among the five measurement results was ±2%.

2.2. The experimental set-up and method

In the garlic drying experiments, a domestic microwave oven with a maximum output power of 800 W and a frequency of 2450 MHz (SIEMENS HF12G240, Germany) was used. This microwave oven was modified by attaching 0.01 g sensitive digital scales to the oven and a pendulum to the scales (Figure 1). The teflon (PTFE) string attached to the pendulum was dangled into the oven whose internal dimensions were 194 mm (H) x 290 mm (W) x 300 mm (D). A teflon dish (diameter of 120 mm and depth of 5 mm) attached to the teflon string was used to place the garlic samples in microwave oven. Changes in mass were monitored periodically with a chronometer.

Garlic was peeled before each drying experiment and sliced 4±0.5 mm thick. Garlic slices placed in the teflon dish were dried at 90, 180, 360 and 600 W microwave output powers until their ultimate moisture content of 0.05 kg_{water} kg_{dm}^{-1}. Drying experiments were realized in duplicate.

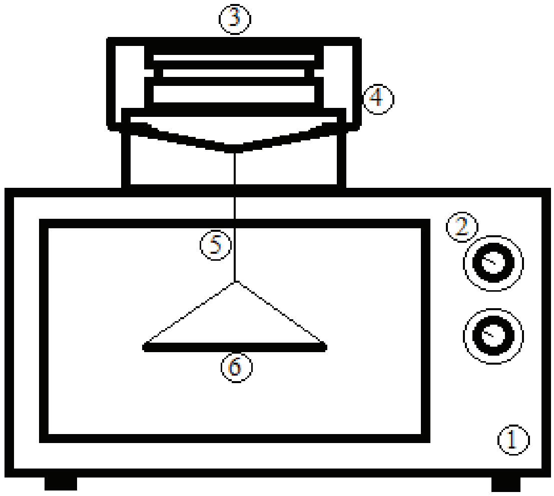

Figure 1- Microwave drying experimental setup. 1, microwave oven; 2, power and time set; 3, electronic balance; 4, pendulum hanger; 5, PP pendulum rope; 6, PTFE plate

Şekil 1- Mikrodal kurutma deney düzeneği 1, mikrodalga fırın; 2, güç ve zaman ayar düğmeleri; 3, elektronik terazi; 4, sarkaç tutucu; 5, PP sarkaç ipi; 6, PTFE tabak

2.3. Modeling of microwave drying curves

Mathematical models to represent the thin layer drying behaviors of food products and agricultural products were developed by many researchers. Ten mathematical models in the literature were used in this study (Table 1). The dimensionless moisture ratio (*MR*) in these models is calculated with the Equation 1 and 2.

$$MR=\frac{M_{C_t} - M_{C_e}}{M_{C_0} - M_{C_e}} \quad (1)$$

$$MC=\frac{w_t - w_d}{w_d} \quad (2)$$

Where; w_t (kg) and w_d, masses of the garlic samples (kg) at any time of drying and at the end of drying, respectively; M_{C_0} and M_{C_t}, moisture contents of the garlic samples (kg_{water} kg_{dm}^{-1}) in the beginning and at any time of drying, respectively; M_{C_e}, equilibrium moisture content (kg_{water} kg_{dm}^{-1}). It has been regarded as the moisture content at the end of drying in the microwave drying (Ren & Chen 1998; Altan & Maskan 2005).

Drying rate of the garlic slices (DR ($kg_{water}\ kg_{dm}^{-1}\ min^{-1}$)) was calculated with the Equation 3.

$$DR=\frac{M_{C_{t+dt}} - M_{C_t}}{dt} \tag{3}$$

Where; dt, period between two consecutive measurements (min).

The constants of the mathematical models were determined by doing regression analysis. Regression analyses were done with STATISTICA data analysis program (version 10). The consistency between the moisture ratios that were determined experimentally and calculated from the mathematical model was determined by using statistical parameters, i.e. determination of coefficient (R^2), chi-square (χ^2), root mean square error (*RMSE*), and percentage error (*E%*). Small χ^2 and *RMSE* values and high R^2 values show that the model was more suitable (Yaldız & Ertekin 2001; Midilli & Küçük 2003).

The *E*% values smaller than 10% were acceptable (Park et al 2002; Mohapatra & Rao 2005). The values of χ^2, *RMSE* and *E*% were calculated with the Equations 4, 5 and 6.

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

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (MR_{exp,\,i} - MR_{pre,\,i})^2}{N}} \tag{5}$$

$$E\% = \frac{100}{N} \sum_{i=1}^{N} \frac{|MR_{exp,\,i} - MR_{pre,\,i}|}{MR_{exp,\,i}} \tag{6}$$

Where; $MR_{exp,\,i}$, experimental moisture ratio at *i* th observation; $MR_{pre,\,i}$, predicted moisture ratio for this observation; *N,* number of observations and *z*, number of constants in the model.

2.4. Diffusion of moisture

Removal of moisture from the solid matter during drying was diffusion-controlled. The effective diffusion coefficient for the garlic slices was determined by using Fick's diffusion equation. The effective diffusion coefficient was calculated with the Equation 7 (Crank 1975).

$$MR=\frac{M_{C_t} - M_{C_e}}{M_{C_0} - M_{C_e}} = \frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-(2i+1)^2 \cdot \frac{\pi^2 \cdot D_{eff}}{4 \cdot L^2} \cdot t\right) \tag{7}$$

Where; t, time (s); L, half-thickness of garlic slice (m); D_{eff}, effective diffusion coefficient ($m^2\ s^{-1}$). For long drying periods Equation 7 can be written as Equation 8 (i.e. for i= 0) (Lopez et al 2000).

$$MR=\frac{M_{C_t} - M_{C_e}}{M_{C_0} - M_{C_e}} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 \cdot D_{eff}}{4 \cdot L^2} \cdot t\right) \tag{8}$$

Table 1- Thin-layer drying models applied to Tunceli garlic microwave drying curves

Çizelge 1- Uygulanan ince tabaka kuruma modelleri

Model no	*Model name*	*Model equation*	*Reference*
1	Page	$MR = exp(-kt^n)$	Arslan & Özcan (2010)
2	Henderson & Pabis	$MR = a\ exp(-k\ t)$	Yagcıoglu et al (1999)
3	Logarithmic	$MR = a\ exp(-k\ t) + c$	Yaldız & Ertekin (2001)
4	Midilli et al	$MR = a\ exp(-k\ t^n) + b\ t$	Midilli et al (2002)
5	Weibull Distribution	$MR = a - b\ exp(-(k\ t^n))$	Corzo et al (2008)
6	Two Term Exponential	$MR = a\ exp(-k\ t) + (1-a)\ exp(-k\ a\ t)$	Yaldız & Ertekin (2001)
7	Two-Term	$MR = a\ exp(-k_0\ t) + b\ exp(-k_1\ t)$	Arslan & Özcan (2010)
8	Simplified Fick's Diffusion	$MR = a\ exp(-c\ (t/L^2))$	Diamante & Munro (1991)
9	Diffusion Approach	$MR = a\ exp(-k\ t) + (1-a)\ exp(-k\ b\ t)$	Doymaz (2013)
10	Wang & Singh	$MR = 1 + a\ t + b\ t^2$	Eştürk & Soysal (2010)

The Equation 8 can be written in logarithmic form as in Equation 9.

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 \cdot D_{eff}}{4 \cdot L^2} \cdot t\right) \quad (9)$$

Experimental *ln (MR)* values and drying time can be transferred onto a graph and the effective diffusion coefficient is calculated from the slope (Equation 10) of line obtained from the graph.

$$Slope = \frac{\pi^2 \cdot D_{eff}}{4 \cdot L^2} \quad (10)$$

2.5. Effect of sample mass

In microwave technique, the influence time of the microwave power that was applied depends on the sample mass. There is no known study in the literature that shows the effect of sample mass on Tunceli garlic's drying kinetics with microwave. In this study, the drying kinetics of garlic samples with sample mass ranging from 11 to 44 g were investigated at 90 W constant microwave output power.

In order to determine the relationship between the effective diffusion coefficient and proportion of sample mass to microwave output power, Arrhenius type exponential model (Equation 11) proposed by Dadalı et al (2007a) was used.

$$D_{eff} = D_0 \, exp\left(-\frac{E_a \, m}{P}\right) \quad (11)$$

Where; D_{eff} effective diffusion coefficient (m^2 s^{-1}); D_0, pre-exponential factor (m^2 s^{-1}); E_a, activation energy (W g^{-1}); *m*, sample mass (g) and *P*, microwave output power (W).

According to the drying rate constant data, the activation energy was determined using the Arrhenius type exponential model (Dadalı et al 2007b) in Equation 12.

$$k = k_0 \, exp\left(-\frac{E_a \, m}{P}\right) \quad (12)$$

Where; k, drying rate constant (min^{-1}); k_0, pre-exponential factor (min^{-1}); E_a, activation energy (W g^{-1}); *m*, sample mass (g) and *P*, microwave output power (W).

3. Results and Discussions

3.1. Drying kinetics

Garlic samples were dried at 90, 180, 360 and 600 W microwave output powers in order to determine the effect of microwave output power on drying characteristics of Tunceli garlic. The change of the moisture ratio with drying times at different microwave output powers was shown in Figure 2. It was seen that drying time decreased with an increase in microwave output power. It was reached the moisture content of 0.05 kg_{water} kg_{dm}^{-1} after periods of 32, 11, 5.5 and 4 minutes at 90, 180, 360 and 600 W microwave output powers respectively. It took about 25 minutes to decrease the moisture content of fresh garlic (*Allium sativum* L.) slices (4 mm thickness) from 1.9 to 0.1 kg_{water} kg_{dm}^{-1} under vacuum-microwave drying conditions at 240 W microwave output power (Figiel 2009).

The change in drying rates with moisture ratios at different microwave output powers was shown in Figure 3. The zone between 1.0 and 0.88 for moisture ratio at 90 W microwave output power was the pre-heating period. The falling rate period was seen after the moisture ratio of 0.88. The falling rate periods for the 180, 360 and 600 W microwave output powers started around the 0.85, 0.81 and 0.82 moisture ratios, respectively. Similarly, drying rate was decreased with the decrease in the moisture content of garlic during drying. This showed that the dominant physical mechanism in moisture removal from garlic was diffusion. The results are compatible with Sharma & Prasad (2001) for garlic, Dadalı et al (2007b) for okra and Arslan & Özcan (2010) for onion.

3.2. Evaluation of mathematical models

The model constants regarding the ten mathematical models that were used to represent the drying behaviors of garlic samples were given in Table 2. The drying rate constant (*k*) increased with the increase in microwave output power in all of the drying models.

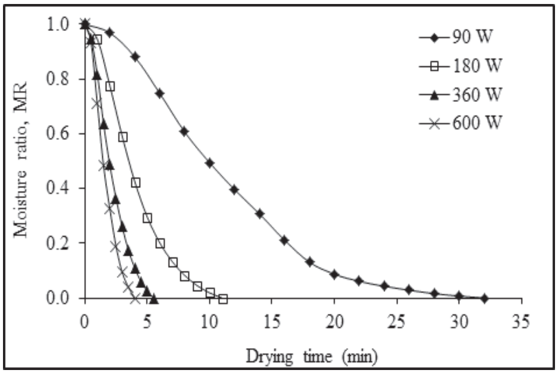

Figure 2- The relationship between the moisture ratio and drying time at different microwave output power

Şekil 2- Farklı mikrodalga çıkış güçlerinde kuruma süresi ile nem oranı arasındaki ilişki

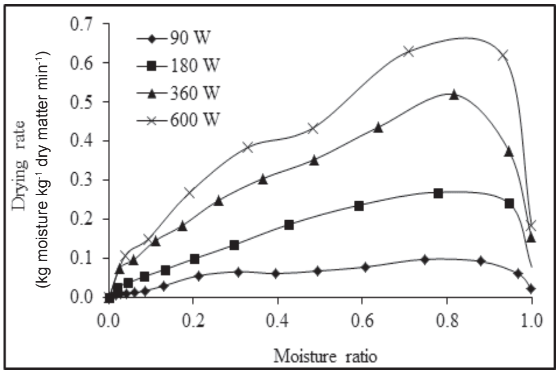

Figure 3- Drying curves for Tunceli garlic versus moisture ratio at different microwave output power

Şekil 3- Farklı mikrodalga çıkış güçlerinde nem oranı ile kuruma hızılarının değişimi

The results of statistical evaluation, which was an indicator of the compatibility between experimental results and the models used, were displayed in Table 3. The model which has the highest R^2 and lowest *RMSE*, χ^2 and *E%* values is chosen as the best suitable one (Wang et al 2007; Doymaz & İsmail 2011; Doymaz 2013). The Weibull Distribution model was the most compatible model according to the *RMSE* values obtained at 90 W microwave output power. According to χ^2 and *E*% values, the Page model showed a better compatibility: however, the values of R^2, *RMSE*, χ^2 and *E*% were quite close to each other in the Page, Midilli et al and Weibull Distribution models.

The Midilli et al model was clearly seen to be the most compatible model at 180, 360 and 600 W microwave output powers. Figure 4 shows the relationship between the experimental moisture ratios obtained at 90 W microwave output power and the moisture ratios obtained from the drying models used in this study.

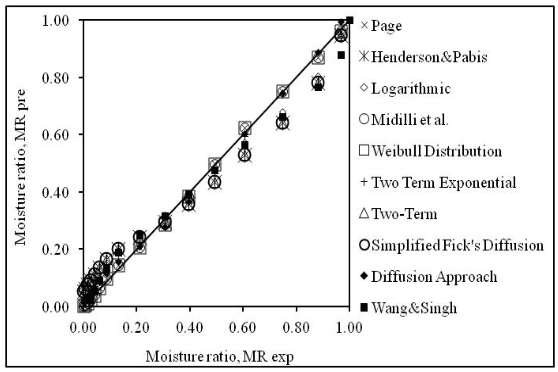

Figure 4- Predicted moisture ratio from mathematical models versus experimental moisture ratio for 90 W microwave output power

Şekil 4- 90 W mikrodalga çıkış gücü için deneysel nem oranına karşı matematiksel modellerden elde edilen nem oranını değişimi

3.3. The effect of sample mass on microwave drying kinetics of garlic

The change with time in moisture contents of garlic samples with different masses was seen in Figure 5. Drying time increased with an increase in sample mass. For example, while it was taken 14.5 minutes for the moisture content of 22 g of sample mass to drop from 1.40 to 0.05 $kg_{water}\ kg_{dm}^{-1}$, the same amount of moisture content change in 33 g of sample mass was taken 25 minutes. The change in drying rate with time for different sample masses at 90 W microwave output power was displayed in Figure 6. It was clearly seen that

Table 2- Constants and coefficients of thin-layer drying models for 33 grams of samples at different microwave output powers

Çizelge 2- Farklı mikrodalga çıkış güçlerinde 33 gram örnek için kuruma modellerine ait sabitler ve katsayılar

Microwave output power (W)	*Model no*	*Constants and coefficients*			
90	1	k= 0.0124	n= 1.7472		
	2	k= 0.0971	a= 1.1518		
	3	k= 0.0629	a= 1.3362	c= -0.2350	
	4	k= 0.0133	n= 1.7193	a= 1.0058	b= -0.0001
	5	k= 0.0134	n= 1.7150	a= -0.0045	b= -1.0104
	6	k= 0.1429	a= 2.1718		
	7	k_0= 0.0971	k_1= 0.0971	a= 0.5670	b= 0.5848
	8	a= 1.1518	c= 0.3883		
	9	k= 0.1998	a= -22.9699	b= 0.9502	
	10	a= -0.0618	b= 0.0009		
180	1	k= 0.0824	n= 1.6642		
	2	k= 0.2591	a= 1.1248		
	3	k= 0.1611	a= 1.3500	c= -0.2705	
	4	k= 0.0890	n= 1.6213	a= 1.0137	b= -0.0003
	5	k= 0.0887	n= 1.6232	a= -0.0023	b= -1.0158
	6	k= 0.3902	a= 2.1578		
	7	k_0= 0.5551	k_1= 0.5050	a= -11.9115	b= 12.9084
	8	a= 1.1248	c= 1.0365		
	9	k= 0.2329	a= 0.8509	b= 1.0000	
	10	a= -0.1681	b= 0.0069		
360	1	k= 0.2149	n= 1.6990		
	2	k= 0.4694	a= 1.1282		
	3	k= 0.2414	a= 1.5141	c= -0.4424	
	4	k= 0.2250	n= 1.6157	a= 1.0101	b= -0.0044
	5	k= 0.2238	n= 1.6036	a= -0.0270	b= -1.0371
	6	k= 0.7052	a= 2.1524		
	7	k_0= 0.4694	k_1= 0.4694	a= 0.5751	b= 0.5530
	8	a= 1.1282	c= 1.8776		
	9	k= 0.4192	a= 0.8657	b= 1.0008	
	10	a= -0.2937	b= 0.0193		
600	1	k= 0.3316	n= 1.7991		
	2	k= 0.6218	a= 1.1192		
	3	k= 0.2901	a= 1.6204	c= -0.5525	
	4	k= 0.3419	n= 1.7194	a= 1.0122	b= -0.0047
	5	k= 0.3401	n= 1.7085	a= -0.0206	b= -1.0327
	6	k= 0.9731	a= 2.2225		
	7	k_0= 0.6217	k_1= 0.6218	a= 0.5582	b= 0.5611
	8	a= 1.1192	c= 2.4870		
	9	k= 0.1376	a= 8.2168	b= 0.7453	
	10	a= -0.3864	b= 0.0318		

Table 3- Statistical results obtained from different thin-layer drying models for various microwave output powers

Çizelge 3- Farklı kuruma modelleri için elde edilen istatistiksel sonuçlar

Microwave output power (W)	*Model no*	*Constants and coefficients*			
		R^2	*RMSE*	*χ^2*	*E%*
90	1	0.9993	9.3501 10^{-03}	9.9083 10^{-05}	5.92
	2	0.9568	7.3143 10^{-02}	6.0632 10^{-03}	123.22
	3	0.9814	4.7936 10^{-02}	2.7902 10^{-03}	63.07
	4	0.9993	9.0932 10^{-03}	1.0813 10^{-04}	6.24
	5	0.9993	9.0754 10^{-03}	1.0771 10^{-04}	6.48
	6	0.9952	2.4385 10^{-02}	6.7391 10^{-04}	49.52
	7	0.9568	7.3143 10^{-02}	6.9960 10^{-03}	123.23
	8	0.9568	7.3143 10^{-02}	6.0632 10^{-03}	123.23
	9	0.9971	1.8958 10^{-02}	4.3642 10^{-04}	35.81
	10	0.9812	4.8226 10^{-02}	2.6358 10^{-03}	43.85
180	1	0.9991	1.0377 10^{-02}	1.2923 10^{-04}	5.40
	2	0.9603	7.0045 10^{-02}	5.8876 10^{-03}	60.94
	3	0.9845	4.3808 10^{-02}	2.5588 10^{-03}	19.94
	4	0.9993	9.3211 10^{-03}	1.3033 10^{-04}	4.74
	5	0.9993	9.3555 10^{-03}	1.3129 10^{-04}	4.97
	6	0.9983	1.4673 10^{-02}	2.5836 10^{-04}	17.92
	7	0.9992	9.8835 10^{-03}	7.4652 10^{-04}	11.80
	8	0.9603	7.0045 10^{-02}	5.8876 10^{-03}	60.49
	9	0.9428	8.4070 10^{-02}	9.4236 10^{-03}	73.39
	10	0.9840	4.4506 10^{-02}	2.3769 10^{-03}	15.52
360	1	0.9991	1.0500 10^{-02}	1.3231 10^{-04}	6.28
	2	0.9547	7.4455 10^{-02}	6.6522 10^{-03}	53.91
	3	0.9876	3.8919 10^{-02}	2.0196 10^{-03}	14.62
	4	0.9995	8.0445 10^{-03}	9.7072 10^{-05}	2.04
	5	0.9995	8.1451 10^{-03}	9.9515 10^{-05}	2.14
	6	0.9958	2.2815 10^{-02}	6.1371 10^{-04}	20.56
	7	0.9547	7.4455 10^{-02}	8.3153 10^{-03}	53.91
	8	0.9547	7.4455 10^{-02}	6.6522 10^{-03}	53.91
	9	0.9351	8.9125 10^{-02}	1.0591 10^{-02}	64.23
	10	0.9851	4.2753 10^{-02}	2.1933 10^{-03}	13.66
600	1	0.9987	1.3281 10^{-02}	2.2677 10^{-04}	3.49
	2	0.9440	8.5584 10^{-02}	9.4174 10^{-03}	48.37
	3	0.9830	4.7226 10^{-02}	3.3455 10^{-03}	12.93
	4	0.9990	1.1607 10^{-02}	2.4248 10^{-04}	2.67
	5	0.9990	1.1646 10^{-02}	2.4415 10^{-04}	2.76
	6	0.9958	2.4053 10^{-02}	7.4384 10^{-04}	16.17
	7	0.9440	8.5584 10^{-02}	1.3184 10^{-02}	48.37
	8	0.9440	8.5584 10^{-02}	9.4174 10^{-03}	48.37
	9	0.9779	5.3751 10^{-02}	4.3337 10^{-03}	13.98
	10	0.9801	5.0972 10^{-02}	2.3405 10^{-03}	11.98

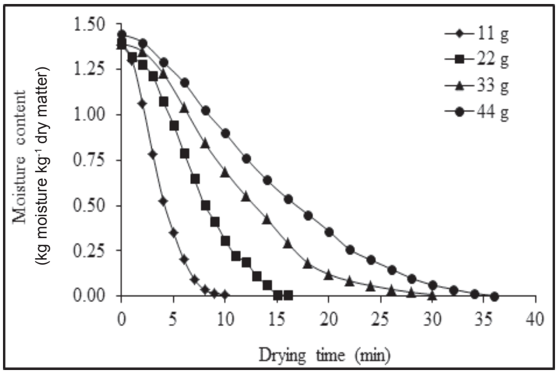

Figure 5- The relationship between moisture content of Tunceli garlic and drying time at various sample amounts for microwave output power of 90 W

Şekil 5- 90 W mikrodalga çıkış gücü için farklı örnek kütlelerinde kuruma zamanı ile nem içeriği arasındaki ilişki

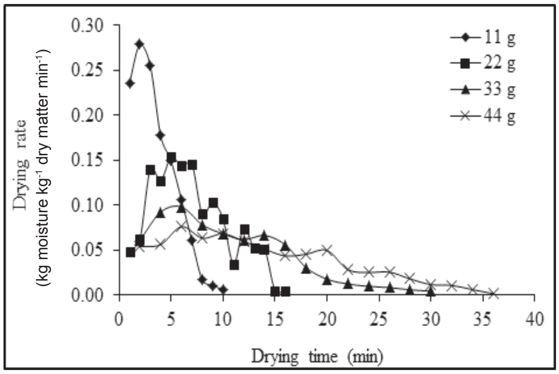

Figure 6- Drying curves for Tunceli garlic versus drying time at various sample amounts for microwave output power of 90 W

Şekil 6- 90 W mikrodalga çıkış gücü için farklı örnek kütlelerinde kuruma süresine karşı kuruma hızının değişimi

drying rate decreases with an increase in sample mass. The energy amount that was transferred per unit sample mass decreased from 8.18 to 2.05 W g^{-1} with an increase of sample mass from 11 to 44 g. As a result, while the amount of energy to remove unit of water mass in a less sample mass of garlic sample with the same amount of moisture content was high, less energy per mass was applied for a larger sample mass. For this reason, drying rate decreased with an increase in sample mass.

3.4. Determination of activation energy

3.4.1. The effect of sample mass on moisture diffusion

The change in the effective diffusion coefficients obtained from Equation 9 and Equation 10 at 90 W microwave output power for different sample masses with sample mass was seen in Figure 7. The effective diffusion coefficient decreased with an increase in sample mass. This observation is in agreement with microwave drying of okra (Dadalı et al 2007a). The values of D_0 and E_a were determined as 21.5 × 10^{-9} m^2 s^{-1} and 3.85 W g^{-1} respectively from the exponential model (Equation 11) with a R^2 value of 0.9783.

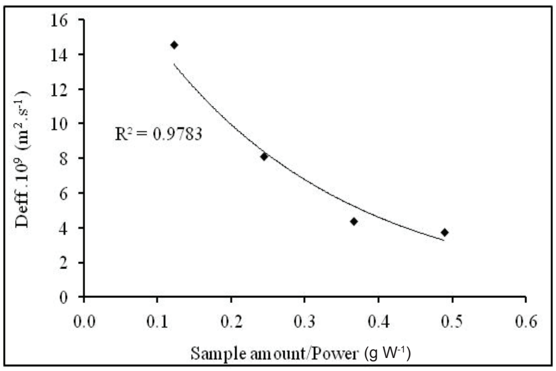

Figure 7- Relationship between D_{eff} and sample amount of Tunceli garlic for microwave output power of 90 W. ♦ estimated data, — model (Equation 11)

Şekil 7- 90 W mikrodalga çıkış gücü için örnek kütlesi ile D_{eff} arasındaki ilişki. ♦ hesaplanan veri, — model (Eşitlik 11)

3.4.2. The effect of sample mass on drying rate constant

The change in the drying rate constant for different sample masses at 90 W microwave output power was determined according to the Midilli et al model. The drying rate constant values obtained from this model and statistical evaluation results were displaced in Table 4. It was seen that the drying rate constant value decreased with an increase in sample amount. The values of R^2, χ^2 and E% values for the sample mass interval of 11-44 g changed as 0.9990-0.9997, 4.2615 × 10^{-5}-15.6298 × 10^{-5} and 6.66-19.35% respectively. High R^2 and low E% values showed that the applied model was suitable. The compatibility of the data for Equation 12 was seen in Figure 8. The values of R^2, k_0 and E_a were determined as 0.9706, 0.0596 min^{-1} and 3.99 W g^{-1}, respectively.

Table 4- Drying rate constants and statistical analysis of Midilli et al model at various sample amount of Tunceli garlic for microwave output power of 90 W

Çizelge 4- 90 W mikrodalga çıkış gücünde farklı örnek kütleleri için Midilli et al modeline gore kuruma hız sabitleri ve istatistiksel veriler

Sample amount (g)	*k (min^{-1})*	*R^2*	*RMSE*	*χ^2*	*E%*
11	0.0406	0.9997	6.2842 10^{-3}	5.9237 10^{-5}	8.73
22	0.0196	0.9990	11.0256 10^{-3}	15.6298 10^{-5}	19.35
33	0.0133	0.9993	9.3730 10^{-3}	11.7139 10^{-5}	6.66
44	0.0091	0.9997	5.8389 10^{-3}	4.2615 10^{-5}	7.07

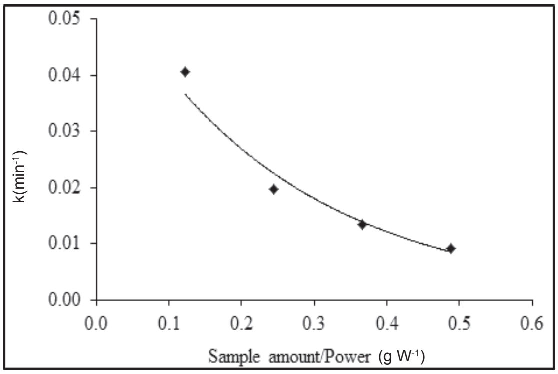

Figure 8- Relationship between drying rate constant, k, from Midilli at al model and sample amount of Tunceli garlic for microwave output power of 90 W. ♦ estimated data, — model (Equation 12)

Şekil 8- 90 W mikrodalga çıkış gücü için örnek kütlesi ile Midilli et al modelinden elde edilen kuruma hız sabiti, k, arasındai ilişki (Equation 12)

4. Conclusions

In the drying of Tunceli garlic with microwave, while drying rate increased with an increase in microwave power, it decreased with an increase in sample mass. It was seen that the Midilli et al model, one of the thin layer drying models used in this study, was the best fit model to the experimental results.

The effective diffusion coefficient (D_{eff}) and drying rate constant (k) values decreased with an increase in sample mass (m). The activation energy values calculated from the effective diffusion coefficient and the drying rate constant data were 3.85 W g^{-1} and 3.99 W g^{-1}, respectively and these values were very close. The findings obtained from this study showed that microwave technique was viable for the drying of sliced Tunceli garlic.

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