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FADIME BEGÜM TEPE[1]
TOLGA KAĞAN TEPE[1]
AYTEN EKINCI[2]

[1]Department of Food Technology, Şebinkarahisar Vocational School of Technical Science, Giresun University, Giresun, Turkey

[2]Department of Food Technology, Denizli Vocational School of Technical Science, Pamukkale University, Denizli, Turkey

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DRYING KINETICS AND ENERGY EFFICIENCY OF MICROWAVE-DRIED LEMON SLICES

Article Highlights

- Microwave lemon drying at various microwave powers fitted to Page model
- The drying rate increased, and drying time decreased with the increase of microwave power
- Effective moisture diffusivity increased with the increase of microwave power
- The higher the cumulative energy efficiency, the lower the specific energy consumption

Abstract

In the current study, lemon slices were dried at various microwave powers (120, 350, 460, 600, and 700 W) to determine drying characteristics and energy efficiency. Drying rate and time were significantly affected by the increase in microwave power. The lowest and highest drying times were 8 and 54 minutes at 700 and 120 W, respectively. As microwave power increased, drying rate increased, and drying time decreased. Besides, the most suitable model to describe microwave drying curves of the lemon slice was obtained as the Page model. The values of D_{eff} *of the dried lemon slices were calculated between* $3.61x10^{-9}$ *and* $3.41x10^{-8}$ m^2s^{-1}. *The* E_a *of the lemon slices drying, calculated using* D_{eff}, *and the rate constant obtained from the Page model were 4.39* Wg^{-1} *and 6.04* Wg^{-1}, *respectively. Additionally, the higher the cumulative energy efficiency, the lower the specific energy consumption. The lowest specific energy consumption and the highest energy efficiency were calculated at 460 W. The 460 W drying power was the best power with 11 min of drying time, the highest energy efficiency, and the lowest specific energy consumption.*

Keywords: lemon slices, drying characteristics, microwave drying, effective diffusion, energy efficiency.

Lemon (*Citrus limon* L.) is a fruit that contains high water content and is rich in nutritional compounds such as flavonoids and ascorbic acid. On the other hand, lemon is quite attractive due to its flavor and color [1–3]. Therefore, lemon is generally consumed as a beverage following fresh fruit consumption; however, the drying process improves novel products such as dried-lemon slices or flakes [2,4,5]. On the other hand, Darvishi *et al.* [1] have also stated high relative metabolic activity of lemon, resulting from increased water content and proceed after harvest and cause deterioration and economic loss.

Many factors associated with food spoilage result from high water content since high water content is one of the main requirements for microbiological activity, chemical reactions, and physical alterations in a pre- or post-harvest period of many plant-based foods [3, 5, 6]. The drying process, one of the most preferred conservation methods, aims to prevent microbiological activity, provide long shelf-life, and reduce undesirable physical and chemical changes by removing water content and activity [7–11]. In addition to benefits in terms of food quality, drying provides lower packing, transportation, and storage costs because of a reduction in weight and volume [6].

The main drying mechanisms are surface diffusion

Correspondence: T.K. Tepe, Department of Food Technology, Şebinkarahisar Vocational School of Technical Science, Giresun University, Giresun, Turkey.
E-mail: tolga.kagan.tepe@gmail.com
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or liquid diffusion on porous surfaces, liquid or vapor diffusion due to moisture concentration differences in granular and porous foods, and capillary movements due to surface forces. The primary diffusion mechanism, which determines the drying rate, is a function of moisture content and the structure of the foods [12]. Drying could generally be divided into constant- and falling-rate periods [13]. A constant rate period is associated with a saturated surface, which means adequate moisture transfer from interior parts of foods to the surface. On the contrary, insufficient moisture transfer from the interior to the surface begins to be observed in the falling rate period when a critical moisture level is reached after the constant rate period. It indicates that the moisture transfer rate to the surface is less than the evaporation rate, decreasing the drying rate [12,13].

Convective or hot air drying is the most frequently used method despite high energy consumption, long drying time, and nutritional losses based on drying temperature and time [10,14–16]. Due to these disadvantages, improving novel applicable techniques, which enable to shorten drying time, consume low energy, and preserve nutritional composition, have become a requirement. Microwave drying is of many advantages in comparison to convective drying. In microwave drying, a water vapor pressure gradient occurs between the surface of the food and its interior due to microwave-induced volumetric heating [17]. Thus, the drying rate increases with the increment in evaporation rate. Additionally, higher microwave powers enable more water vapor pressure gradient and an evaporation rate because more energy is supplied [18]. Furthermore, microwave application during the drying process can be an alternative method to reduce falling rate time [19]. Besides, it was stated that the microwave heating process provided desirable structural modifications, such as lower shrinkage [12]. On the other hand, recent developments in low-cost microwave sources have made microwave drying more attractive [15,20].

The drying kinetics of foods are generally determined by using thin-layer drying models. Thin-layer drying models are mathematical modeling that predicts drying behavior and appropriate drying conditions. Thus, the drying process can be designed and optimized [21].

Although many papers on drying various foods are current in the literature, the drying kinetics of microwave-dried lemon slices are limited. On the other hand, no data on the energy efficiency of microwave drying of lemon slices was published to the best of our knowledge. Therefore, it is hard to claim that microwave energy efficiency shows similar behavior in foods. Therefore, microwave energy efficiency must be investigated in trend foods such as lemon in terms of drying technology. Thus, processes may be efficient in an energy-saving-food quality preserving combination. Therefore, this study aims a) to determine the best fitting equation for microwave drying of lemon slices, b) to compare the impact of different microwave powers on drying time, drying rate, and adequate moisture diffusivity, and c) to calculate energy efficiency in terms of cumulative energy efficiency and specific energy consumption.

MATERIAL AND METHODS

Sample preparation

Fresh lemons were provided from a local market in İstanbul, a province in Turkey. Initially, fresh lemons were washed to remove foreign materials and cut into 6±0.5 mm slice thickness. Then, the initial moisture content of fresh lemons was determined at 105 °C in a drying oven until the sample weight achieved a constant value (%86.89±0.31).

Drying experiment

A microwave oven (Arçelik MD 574, Turkey), with 700 W output at 2450 GHz, was used for drying experiments. Microwave drying was performed at 700, 600, 460, 350, and 120 W levels. For each drying experiment, 70 g of samples were weighted on a glass plate and placed in the microwave oven. The intermittent on/off timing drying process was carried out 20 s on/10 s off [16,22,23]. Glass plate was weighted at the end of each 30 s for determination of moisture loss during drying. The weight measurement was carried out with a digital weight measure with 0.01 g precision. The drying experiments continued until the moisture content of samples achieved 7% on a wet basis. All drying experiments were performed in triplicate.

Mathematical modeling of drying data

Thin-layer drying modeling of drying is a necessary procedure to design the best drying conditions. Therefore, the thin-layer drying models, the most used mathematical equations in the drying process, are listed in Table 1. These equations provide essential information about drying temperature and time [16].

Eq. (1) was used for the calculation of the moisture ratio (MR) of lemon slices;

$$MR = (M_t - M_e)/(M_i - M_e) \tag{1}$$

where MR represents moisture ratio (dimensionless), M_i, M_t, and M_e are the initial moisture content, moisture content at any time, and equilibrium moisture content of samples, respectively. Compared to M_t and M_i, M_e was ignored due to its very small value, according to those reports by researchers [15,24]. All moisture content was indicated on dry matter (g g^{-1} dry matter).

Eq. (2) was used for the determination of drying rate (*DR*);

$$DR = \left(M_{t+\Delta t} - M_t\right) / \Delta t \tag{2}$$

where $M_{t+\Delta t}$ represents the moisture content at time difference, Δt is the difference of time between two measuring points.

Root mean square error (RMSE), determination coefficient (R^2), and reduced chi-square (χ^2) were the statistical parameters that explain the relationship between predicted and experimental data of lemon slices dried at various microwave powers. It is required to be the lower values of χ^2 and RMSE together with a high value of R^2 for the determination of the best equation predicting experimental data. The RMSE (Eq. 3) and Chi-Square (χ^2) (Eq. 4) values were calculated as follows;

$$RMSE = \left[\frac{1}{N}\sum_{i=0}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=0}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N-n} \tag{4}$$

$MR_{pre,i}$ is the predicted *MR* of mathematical models, $MR_{exp,i}$ is the experimental *MR*, *N* and *n* are the number of observation data and constants of thin-layer drying models [16,25]. All calculations of statistical parameters were determined with SPSS (ver. 22), and the lemon slices drying process modeling was determined using MATLAB (ver. 8.6) curve fitting toolbox.

Determination of the effective moisture diffusivity and activation energy in microwave drying

Fick's second law was used to determine the effective moisture diffusivity as suggested by papers on drying foods [1, 8, 16]. Crank [26] proposed Fick's second law for infinite slab objects with constant moisture diffusivity as Eq. (5).

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-(2n-1)\pi^2\frac{D_{eff}t}{4L^2}\right) \tag{5}$$

The effective moisture diffusivity (D_{eff}) was calculated with Eq. (5), as lemon slices were assumed to be infinite slab material. In Eq. (5), D_{eff} represents the effective moisture diffusivity (m^2 s^{-1}), and *L* is the half-thickness of the initial size of the sample before drying (m). For simplicity, Eq. (5) can be further simplified to only the first term of the series; thus, Eq. (5) is written in a logarithmic form as given below Eq.(6) [1,16];

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}D_{eff}t\right) \tag{6}$$

After the natural logarithm of *MR* versus drying time (Eq. 6), the plot gives a straight line with a slope as follows Eq. (7) [16,24];

$$Slope = -\frac{\pi^2}{4L^2}D_{eff} \tag{7}$$

Temperature cannot be precisely measured in the microwave dryer, and the reason for this Arrhenius equation was modified as suggested by Özbek and Dadali [27] as given below Eq. (8);

$$D_{eff} = D_0\exp\left(-\frac{E_a m}{P}\right) \tag{8}$$

where *m* is the initial sample weight, *P* represents microwave output power, E_a is the activation energy (W g^{-1}), and D_0 is the pre-exponential constant (m^2 s^{-1}) [15,16]. After the transformation of Eq. (8), the new equation is obtained:

$$\ln D_{eff} = \ln D_0 - \frac{E_a m}{P} \tag{9}$$

Natural logarithm of D_{eff} versus the ratio of microwave power to sample weight gives a straight line with a slope representing the E_a.

The second equation for calculation of the E_a is given in Eq. (10) as used by Darvishi *et al.* [1] and Demiray *et al.* [16]. Following the data evaluation, the kinetic rate constant (*k*) dependence on the ratio of microwave output power to sample weight was represented with an exponential Eq. (10).

$$k = k_0\exp(-\frac{E_a m}{P}) \tag{10}$$

If the natural logarithm of *k* versus the ratio of microwave output power to sample weight gives a straight line with a slope representing the E_a.

$$\ln k = \ln k_0 - \frac{E_a m}{P} \tag{11}$$

Determination of energy efficiency of microwave drying

To calculate the drying efficiency of microwave (η_d), the required energy to evaporate water from the lemon slices to the energy supplied by the microwave dryer was used [22]. In this context, Eq. (12) was used for calculation;

$$\eta_d = \frac{m_w\lambda_w}{Pt_{on}}100 \tag{12}$$

where m_w is the amount of evaporated water from the lemon samples in kg, *P* (W) is the power supplied by the microwave dryer, λ_w is the latent heat for vaporization of water (2257 kJ kg^{-1}), and t_{on} (s) is the time when the microwave irradiation is on.

Soysal *et al.* [22] and Beaudry *et al.* [23] proposed specific energy consumption as another equation to calculate the energy efficiency of the microwave dryer. Specific energy consumption was determined by using Eq. (13)

$$Q_s = \frac{t_{on}\ P\ 10^{-6}}{m_w}100 \qquad (13)$$

where Q_s is the specific energy consumption required to evaporate a unit mass of water from the product in MJ kg^{-1} water.

RESULTS AND DISCUSSION

Effect of the microwave power on drying rate and time

The variations of moisture content, *MR*, and *DR* of lemon slices dried at various microwave power were presented in Fig. 1.

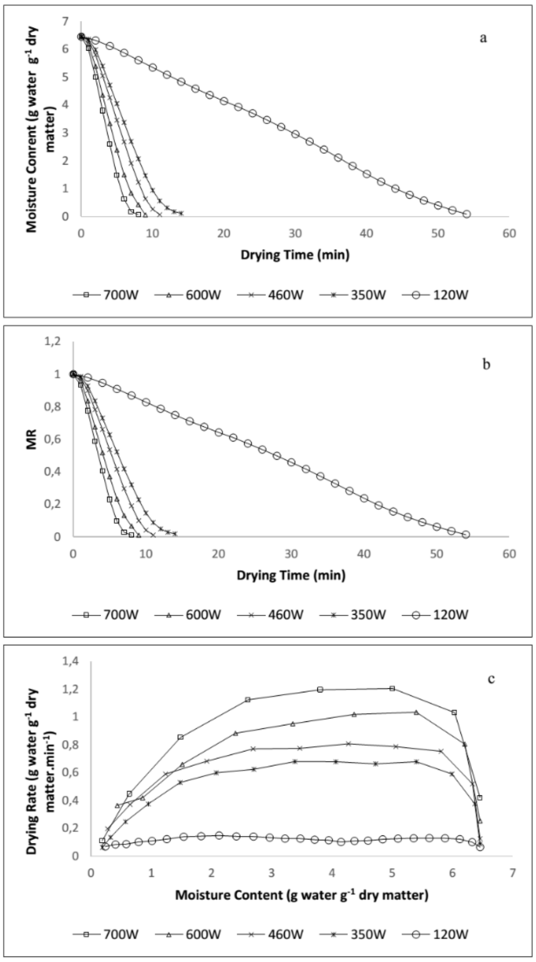

Figure 1. Variation of moisture content (a), MR (b), and DR (c) of lemon slices at various microwave powers.

As seen in Fig. 1, the drying rate increased with microwave power increment. It is a fact that microwave output power has a crucial effect on drying time and drying rate. It was determined that the moisture content of lemon slices reached 7% moisture content (*WB*) at the end of 8, 9, 11, 14, and 54 min at 700, 600, 460, 350, and 120 W, respectively. Likewise, Yogurtcu [28], Demiray *et al.* [16], Zarein *et al.* [15], Polatcı and Taşova [29] have reported increment in the drying rate of various foods based on increasing microwave power which results in a reduction in drying time. In conclusion, more drying rate and lower drying time can be obtained at higher microwave powers due to more heat generation in the sample leading higher evaporation rate [12]. In the initial period of the drying process, a higher drying rate was observed because of high moisture content, which leads to higher microwave absorption. However, despite a higher drying rate at the beginning of the drying process, a falling drying rate period was observed based on the decrement in the moisture content oncoming period. This result was in good accordance with those reported by Aghilinategh *et al.* [30], Çelen *et al.* [31], Azimi-Nejadian and Hoseini [32], and Tepe and Tepe [12]. As presented in Fig. 1, microwave drying consists of three stages. The first is the warming-up stage at the beginning of the drying process. After warming up, rapid drying and falling rate stages follow the first one.

Fitting of microwave drying curves

The thin layer drying models (Table 1) fit the *MR* data of lemon slices dried at various microwave powers.

Table 1. Thin-Layer drying models for microwave drying of lemon slices

Model name	Model	References
Logarithmic	$a\exp(-kt) + c$	[12]
Lewis	$\exp(-kt)$	
Henderson and Pabis	$a\exp(-kt)$	
Page	$\exp(-kt^n)$	
Parabolic	$a + bt + ct^2$	
Wang and Sing	$1 + at + bt^2$	

* *a*, *k*, *n*, *b*, and *c* are constants of mathematical models.

The statistical parameters and determination coefficient are given in Table 2. To select the best equation for microwave drying curves of lemon slices, RMSE, χ^2, and R^2 were compared. Among the thin layer models, the highest values of R^2 and the lowest values of RMSE and χ^2 were obtained from the Page model, meaning the Page model gave the best fitting to microwave dried lemon slices. This result showed similarity with findings reported for microwave drying of onion slices, lemon slices, apple slices, and okra [16,28,33,34]. On the other hand, Darvishi *et al.* [1]

Table 2. The values of the thin-layer drying model's constants, RMSE, chi-square, and R^2 for microwave drying of lemon slices

Model	Drying Method, W	Model Constants			χ^2	RMSE	R^2
Lewis	120	k= 0.0303			0.003129	0.0969	0.9058
	350	k= 0.1372			0.009568	0.1220	0.8900
	460	k= 0.1591			0.013300	0.1275	0.8808
	600	k= 0.2035			0.014208	0.1192	0.8978
	700	k= 0.2511			0.017325	0.1241	0.8980
Page	120	k= 0.0024	n= 1.742		0.000517	0.0387	0.9856
	350	k= 0.0174	n= 2.032		0.000099	0.0120	0.9990
	460	k= 0.0221	n= 2.087		0.000276	0.0175	0.9979
	600	k= 0.0428	n= 1.978		0.000171	0.0124	0.9990
	700	k= 0.0564	n= 2.044		0.000294	0.0151	0.9987
Henderson and Pabis	120	k= 0.0349	a= 1.130		0.002459	0.0843	0.9313
	350	k= 0.1607	a= 1.172		0.007531	0.1043	0.9254
	460	k= 0.1855	a= 1.160		0.011451	0.1128	0.9151
	600	k= 0.2323	a= 1.141		0.013195	0.1083	0.9251
	700	k= 0.2823	a= 1.132		0.017600	0.1170	0.9207
Logaritmic	120	k= 0.0357	a= 1.117	c= 0.0143	0.002676	0.0862	0.9281
	350	k= 0.1658	a= 1.155	c= 0.0189	0.008731	0.1079	0.9201
	460	k= 0.1890	a= 1.149	c= 0.0116	0.013174	0.1148	0.9120
	600	k= 0.2362	a= 1.131	c= 0.0103	0.015613	0.1102	0.9224
	700	k= 0.2876	a= 1.121	c= 0.0111	0.021348	0.1193	0.9175
Wang and Singh	120	a= -0.01748	b= -0.000027		0.000069	0.0141	0.9981
	350	a= -0.08424	b= 0.000571		0.002529	0.0605	0.9749
	460	a= -0.08865	b= -0.000719		0.002542	0.0532	0.9812
	600	a= -0.12250	b= 0.000722		0.003336	0.0545	0.9811
	700	a= -0.15810	b= 0.003239		0.005412	0.0649	0.9756
Parabolic	120	a= 1.017	b= -0.01874	c= -0.000008	0.000059	0.0128	0.9985
	350	a= 1.093	b= -0.10990	c= 0.002044	0.001803	0.0490	0.9848
	460	a= 1.073	b= -0.11400	c= 0.001121	0.002049	0.0453	0.9877
	600	a= 1.069	b= -0.15160	c= 0.003272	0.002927	0.0477	0.9873
	700	a= 1.073	b= -0.19250	c= 0.006580	0.005358	0.0598	0.9823

have reported that the Midilli *et al.* model was the best model for describing *MR* of microwave drying of lemon slices. Contrary to these studies, Mosa [35] has recommended the Lewis model as the best describing model of microwave drying of split lemons. Therefore, a comparison of predicted (Page model) and experimental *MR* of lemon slices at various microwave powers were presented in Fig. 2. The predicted and experimental *MR* values showed the straight line, meaning the suitability of the Page model in describing.

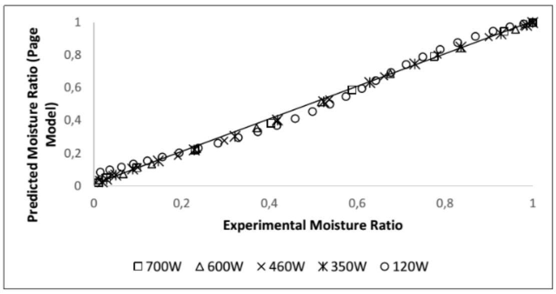

Figure 2. Comparison of predicted MR and experimental MR of lemon slices at different microwave powers.

The effective moisture diffusivity and the activation energy

The values of effective moisture diffusivity and E_a were presented in Table 3. Effective moisture diffusivity of lemon slices ranged from 3.61 10^{-9} to 3.41 10^{-8} m^2 s^{-1}. Increment in microwave power resulted in an increment in effective diffusivity of moisture content of lemon slices. The increment of supplied energy could explain by the microwave dryer. Absorption of higher energy by water molecules at higher microwave powers increases the evaporation rate of water. Similar to this study, Darvishi *et al.* [1] have reported an increment in effective moisture diffusivity with the increasing microwave power during microwave drying of lemon slices. It was also stated that the D_{eff} values of lemon slices ranged from 1.87 10^{-8} to 3.95 10^{-8} m^2 s^{-1} by Darvishi *et al.* [1]. Likewise, effective moisture diffusivity has also been reported for drying apples and *Eriobotrya japonica* L. with different microwave powers [15,29].

The E_a of lemon slices was found in two different equations. The natural logarithm of the values of D_{eff} versus the ratio of microwave power to sample weight (Eq. 9) gives a straight line with a slope, and the slope represents the E_a. The E_a of lemon slices calculated by Eq. (9) was 4.39 W g^{-1}. The Arrhenius relation between the D_{eff} and the sample weight/microwave power is given in Fig. 3.

Drying rate constants of the best fitting Page model were used to calculate the E_a. The E_a of lemon slices was estimated by using Eq. (11). The values of E_a were calculated at 6.04 W g^{-1}. The Arrhenius type relation of k versus sample weight/microwave power is presented in Fig. 4.

Energy efficiency and specific energy consumption of microwave drying

Cumulative energy efficiency and specific energy consumption values for microwave drying of lemon slices were given in Table 3. While the highest cumulative energy efficiency value of 46.14% was calculated at the 460 W microwave, the lowest value of cumulative energy efficiency of 34.53% was obtained at 120 W microwave power. No mean differences were found between the cumulative energy efficiency values of 700 and 600 W ($p>0.05$). This result shows that the highest microwave power may not be selected as the correct drying power when investigating energy efficiency. As addressed above, drying time at 460 W was nearly the same as those at 600 W and 700 W.

However, the energy efficiency at 460 W was higher than those at 600 and 700 W. In that study, 460 W may be the best power option in light of this result.

Table 3. Effective moisture diffusivity, activation energy, pre-exponential constants, specific energy consumption and cumulative drying efficiency of microwave dried-lemon slices

Microwave Power, W	D_{eff} (m^2 s^{-1})	E_a (W g^{-1})	E_a (W g^{-1})	Q_s (MJ kg^{-1})	η_d (%)
120	3.61×10^{-9}	6.04^t	4.39^r	6.53^a (±0.05)	34.53^a (±0.02)
350	1.74×10^{-8}			5.57^b (±0.03)	40.48^b (±0.02)
460	2.18×10^{-8}			4.89^c (±0.03)	46.14^c (±0.02)
600	2.68×10^{-8}			5.44^d (±0.04)	41.46^d (±0.04)
700	3.41×10^{-8}			5.45^d (±0.04)	41.40^d (±0.02)

** The same letters within the same row are not significantly different at a probability ($p<0.05$). Values in parenthesis indicate standard deviation. ^{t} - the activation energy calculated using the equation $k=k_0 \exp(-E_a\ m\ P^{-1})$, where k values were obtained from Page model. ^{r} - the activation energy calculated by $D_{eff}=D_0 \exp(-E_a\ m\ P^{-1})$.*

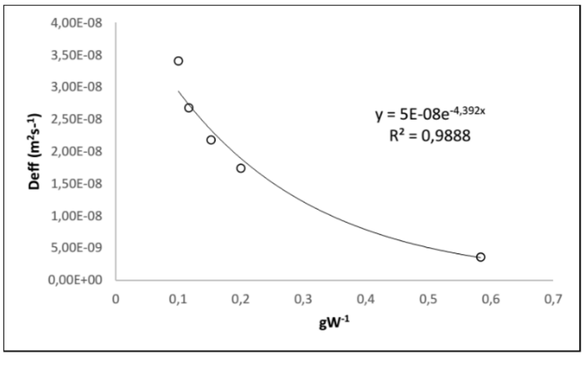

Figure 3. Arrhenius-type relation between D_{eff} and sample weight/microwave power

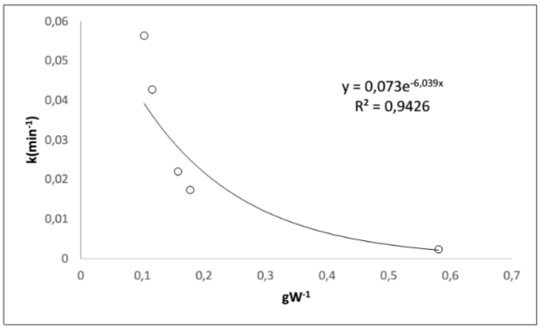

Figure 4. Arrhenius-type relation between the values of k (Page model) versus sample weight/microwave power.

Soysal *et al.* [22] have reported that the value of cumulative energy efficiency of 75 g parsley sample dried at 900 W microwave power was 46.48%. On the other hand, the highest specific energy consumption was determined at 120 W microwave power as 6.53 MJ kg^{-1} water. On the contrary, the lowest value of specific energy consumption was obtained at 460 W microwave power as 4.89 MJ kg^{-1} water. Therefore, it can be seen that energy efficiency increased as specific energy consumption statistically decreased ($p<0.05$).

CONCLUSION

The effect of microwave powers on drying characteristics, energy efficiency, and specific energy consumption in microwave-dried lemon slices was investigated. The lemon slices' drying time and drying rate were significantly affected by the increment in microwave power. Higher microwave power reduces drying time and increment in drying rate. On the other hand, effective moisture diffusivity increased with microwave power. Effective moisture diffusivity of lemon slices ranged from $3.61x10^{-9}$ to $3.41x10^{-8}$ m^2 s^{-1}. The E_a of lemon slices was calculated with the exponential Arrhenius equation with D_{eff} and rate constant (k) obtained from the Page model as 4.39 W g^{-1} and 6.04 W g^{-1}, respectively. Page model suitably describes the curve of microwave drying of lemon slices. Additionally, energy efficiency is related to specific energy consumption. Energy efficiency increased as specific energy consumption decreased. Nowadays, food processes requiring energy, such as drying, should be designed by considering energy efficiency. In this study, 460 W was the best power with 11 min of drying time, the highest energy efficiency, and the lowest specific energy consumption. However, the highest microwave power may not always be the best option for the drying process.

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FADIME BEGÜM TEPE[1]
TOLGA KAĞAN TEPE[1]
AYTEN EKINCI[2]

[1]Department of Food Technology, Şebinkarahisar Vocational School of Technical Science, Giresun University, Giresun, Turkey

[2]Department of Food Technology, Denizli Vocational School of Technical Science, Pamukkale University, Denizli, Turkey

NAUČNI RAD

KINETIKA I ENERGETSKA EFIKASNOST MIKROTALASNOG SUŠENJA KRIŠKI LIMUNA

U ovoj studiji, kriške limuna su sušene u mikrotalasnoj pećnici pri različitim snagama (120, 350, 460, 600 i 700 W) da bi se utvrdile karakteristike sušenja i energetska efikasnost. Na brzinu i vreme sušenja značajno je uticalo povećanje snage mikrotalasne pećnice. Najniže i najveće vreme sušenja bilo je 8 min i 54 min na 700 W i 120 W, redom. Brzina sušenja se povećava, a vreme sušenja skraćuje sa povećanjem snage mikrotalasne pećnice. Najpogodniji model za opisivanje krivih mikrotalasnog sušenja kriški limuna je model Pejdža. Vrednosti D_{eff} *za kriške limuna su između* $3{,}61x10^{-9}$ *and* $3{,}41x10^{-8}$ m^2s^{-1}. E_a *sušenja kriški limuna, izračunata korišćenjem* D_{eff}*, i konstanta brzine iz modela Pejdža su 4.39* Wg^{-1} *and 6.04* Wg^{-1}*, redom. Pored toga, što je veća kumulativna energetska efikasnost, to je niža specifična potrošnja energije. Najmanja specifična potrošnja energije i najveća energetska efikasnost izračunate su za 460 W. Pri snazi od 460 W vreme sušenja je 11 min, energetska efikasnost je najveća, a specifična potrošnja energije najmanja.*

Ključne reči: kriške limuna, karakteristike sušenja, mikrotalasno sušenje, efektivna difuzija, energetska efikasnost.