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Microwave effect on drying behavior and quality parameters of green tea leaves

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ABSTRACT

This study aims to investigate the effect of microwave on drying behavior and quality parameters of green tea leaves experimentally and to perform mathematical modeling of microwave drying of green tea leaves. For this purpose, experiments were performed at 100 W, 300 W, 600 W and 800 W microwave powers and the mass loss and drying time were measured. Depending on the measured parameters, dimensionless moisture ratio, moisture content, mass shrinkage ratio, and drying rate were estimated. The quality parameters such as water extract, cellulose, total ash, caffeine, and total polyphenol were also determined. Furthermore, the best thin layer drying curve equation was obtained by using mathematical modeling for microwave drying of green tea leaves. As a result, improved Midilli-Kucuk model was determined as the best drying curve equation that describes the drying behavior of green tea leaves at all microwave power levels adopted. Also, it was determined that the highest water extract is 35.44% at 300 W, the highest caffeine is 1.93% at 800 W, the highest polyphenol is 11.20% at 300 W, the lowest total ash is 5.95% at 800 W, and the lowest cellulose is 17.79% at 300 W. It was observed that green tea leaves retain their natural color in its best at 800 W.

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1. INTRODUCTION

Drying is the removal of water from the product, and it is one of the traditional and the most common methods used for the preservation of foods [1]. The main purpose of the drying process is to ensure longer storage periods by removing the water from the product, reduce transportation costs by minimizing product weight [2-4]. However, during the drying period structure of food strongly changes depending on temperature, drying time, and water activity [5, 6]. On the other hand, the smell, color, and taste of the food deteriorate due to improper drying process [4]. Also, drying process highly affects the quality of the product [7, 8]. Sun drying and hot air drying methods are commonly used for drying of products. Natural drying has many disadvantages due to failure to achieve quality standards, contamination problems, and long drying times [9]. The hot air drying method also has problems such as non-standard product quality, low process efficiency, long drying time, and high operating costs [10]. In order to eliminate these existing problems in sun drying and hot air drying and to obtain higher quality products, researchers have been developed new drying processes [11]. One of these methods is microwave drying providing uniform energy and high thermal conductivity to the inside of the product, energy saving, shorter drying time, sanitation, and high quality of the final product [12-14] because water molecules quickly absorb microwave energy and evaporate rapidly [14]. In microwave drying, heat is produced very intensively in the whole material volume because of the intermolecular friction and high microwave frequency [10] and since the heating starts from the center of the material, drying time is shorter than conventional drying [15].

Thin-layer drying characteristics such as moisture ratio, moisture content, drying rate, drying time, and effective moisture diffusivity and modeling of mint leaves and basil were studied by Özbek and Dadali [12] and Demirhan and Özbek [2], respectively, in microwave drying system at 180, 360, 540, 720 and 900 W power levels. They found out that drying time decreases with increasing of microwave power and Midilli-Kucuk and logarithmic models are the best models for mint leaves and basil, respectively. The effect of enzyme inactivation was investigated by Huang *et al.* [16] on the quality of green tea for microwave and oven drying processes. They determined that vitamin C content, absorbance of extracts, chlorophyll content, and sensory quality of the green tea are higher for microwave drying than oven drying. Also, they obtained that the preservation qualities of green tea are greatly enhanced by microwave drying.

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Dong *et al.* [14] studied the effects of microwave drying on the contents of functional constituents such as total flavonoids, chlorogenic acid, aucubin and geniposidic acid of Eucommia ulmoides flower tea and compared with pan baking drying and oven ventilation baking drying. They observed that the functional components were preserved at the maximum level and in the scope of sensory quality it has intact shape, green color, fresh taste and unique Eucommia aroma of the tea liquor in the microwave drying method. Alibaş [17] performed a study on drying characteristics, mathematical modeling, and quality parameters of microwave drying of grapevine leaves. Alibas (modified Midilli-Kucuk) model was determined as the best thin layer drying curve equation and the best results in terms of color and ascorbic acid values were obtained at 15 Wg^{-1} microwave power density. Drying characteristics and quality parameters of grated carrots were studied by Arikan *et al.* [18] for microwave drying technique. They determined that drying time and specific energy consumption are significantly saved for a pulse ratio of 3.0 and the microwave power level of 2.23 Wg^{-1} and obtained better physical (color and texture) and sensory attributes when compared with the convective drying method. Shortened the drying time, better vitamin C content and color of the product, and lower energy consumption were obtained by Lechtanska *et al.* [10] for convective drying assisted with microwave of green pepper compared to convective drying. Şimşek *et al.* [19] investigated drying behavior and performed mathematical modeling of microwave drying of kiwi, mint, and apricot at microwave powers of 100 W, 300 W, 450 W, 600 W, 700 W, and 800 W. The best suitable drying models were determined as Midilli-Kucuk for kiwi, Midilli-Kucuk for mint leaves and modified page for apricot. They observed that drying time significantly decreases with increasing microwave power. Soysal *et al.* [9] performed a study on mathematical modelling, drying kinetics, and energy aspects for microwave drying of parsley leaves. Midilli-Kucuk model was determined as the best thin layer drying curve equation. They pointed out that when material load increases drying efficiency significantly rises and specific energy consumption considerable decrease. Ganesapillai *et al.* [20] studied the drying kinetics of plaster of Paris in microwave drying system for 180 W, 360 W, and 540 W and determined Midilli-Kucuk drying curve equation as the best drying model. Sarimeseli [21] investigated the effect of microwave on effective moisture diffusivity, color parameters and rehydration characteristics of coriander leaves and performed mathematical modeling. Midilli-Kucuk model was found out as the best suitable drying model. It was determined that there is no significant difference in the color parameters of fresh and dried samples and that they are independent of microwave power. Al-Harahsheh *et al.* [13] carried out a study on the microwave drying of tomato pomace and the effect of osmotic dehydration. They found out that the microwave drying process decreases drying time and increases drying rate with rising microwave power and NaCl concentration of osmotic solution.

Okur *et al.* [8] performed a study on drying kinetics, mathematical modeling and quality parameters of swirling flow fluidized bed infrared drying of green tea leaves. They found out that drying time highly decreases, and drying rate rises when the infrared power increases. Parabolic, Wang and Singh, Aghbashlo et al., Parabolic, Balbay and Sahin, and Alibas (Modified Midilli-Kucuk) were determined as the best model for 1000 W, 750 W, 500 W, 250 W, and 100 W of infrared power, respectively. Maximum water extract, caffeine, and total polyphenol were obtained as 44.04% at 500 W, 1.91% at 750 W, and 4.30% at 1000 W, respectively. The lowest total ash and cellulose are determined as 4.48 at 500 W and 15.73 at 250 W, respectively.

Although a few studies were separately performed on the quality parameters and mathematical modeling of microwave drying of green tea in the literature there is no comprehensive study including drying kinetics, mathematical modeling, and quality parameters of green tea leaves dried in microwave dryer. For this purpose, depending on drying time mass losses were measured for 100 W, 300 W, 600 W, 800 W microwave powers. Moisture content, dimensionless moisture ratio, drying rate, and mass shrinkage rate were estimated. Also, water extract, cellulose, caffeine, total ash, and total polyphenol were determined for dried green tea samples. Also, 24 drying models and seven evaluation criteria were used for mathematical modeling.

2. MATERIAL AND METHODS

2.1. Material

Figure 1 shows green tea leaves collected in September from Ambarlık town, Rize, Türkiye. The experiments were carried out in the IDEA-L Innovation laboratory of the Mechanical Engineering Department of Recep Tayyip Erdoğan University.

Fig. 1. Green tea leaves.

2.2. Experimental Setup

The flow chart of the microwave drying system is given in Figure 2. Samsung ME711K model microwave oven and microwave power values of 100 W, 300 W, 600 W, and 800 W were used in experiments. The weight of the product was measured by using TEM brand ETEKOTER+LCD/00/00 precision scale with 1 g precision. Humidity and temperature were measured by EMKO Pronem Mini PMI-P. Electrical panel including EMKO brand ESM-3723 digital humidity and temperature controller was produced to read the temperature and humidity.

Fifty grams of products were used for microwave drying experiments and their weight were measured in 10 minute periods, 5 minute periods, 1 minute periods and 1 minute periods for 100 W, 300 W, 600 W, and 800 W power, respectively. Data acquisition time was determined according to the preliminary experiments and data were recorded in a shorter time interval at microwave powers where the drying rate was high.

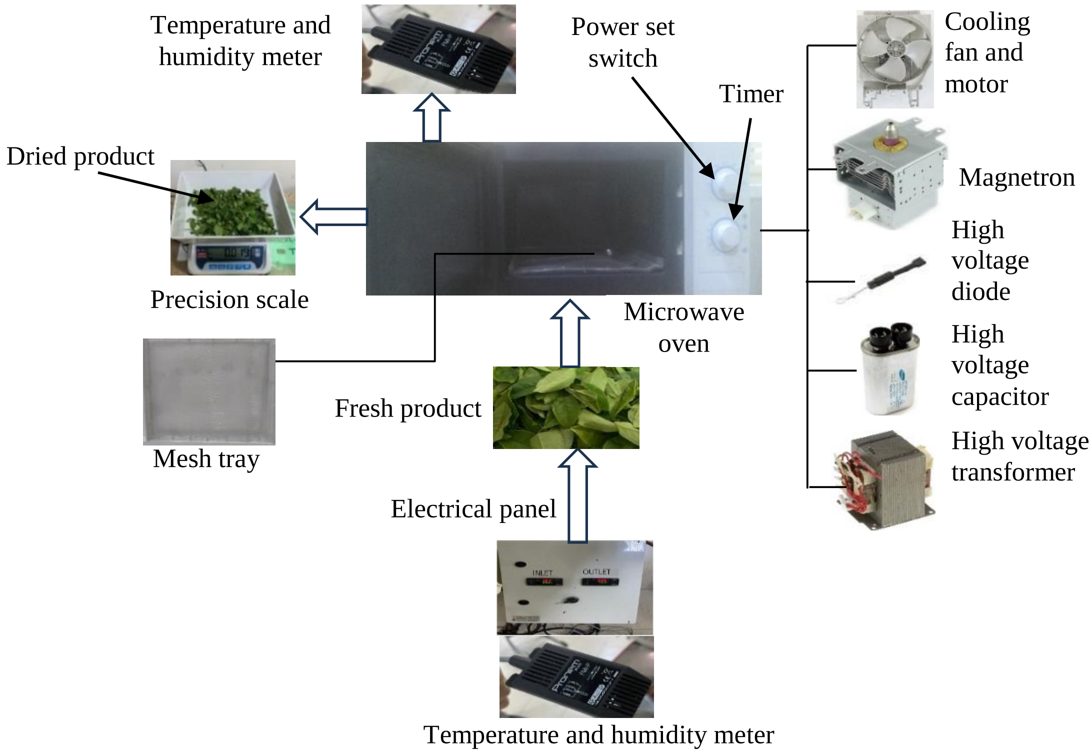

Fig. 2. Flow chart of the microwave drying system.

2.3. Mathematical Modeling

Mathematical modeling is used to estimate the drying time and to analyze the drying process [22, 23]. To estimate the drying time thin-layer drying models are widely used because of their simple and easy use [24].

The empirical and drying constants in thin layer drying models were estimated and these models were compared to experimental data for each microwave power. Twenty-four thin layer drying curve equations shown in Table 1 were considered to determine the best model [22, 23, 25].

To decide the best drying curve equation seven evaluation criteria given in Table 2 [22, 23, 25, 27, 28] were taken into account and the highest values (closest to 1) of the correlation coefficient (r), the coefficient of determination (R^2) and adjusted R^2 ($\bar{R}^2$) and the lowest values (closest to 0) of the reduced chi-square (χ^2), the root mean square error (RMSE), the reduced sum square error (RSSE) and the mean bias error (MBE) were determined.

Dimensionless moisture ratio, moisture content, mass shrinkage ratio, and drying rate are given in Equations (1), (2), (3) and (4), respectively [22, 25-28].

Dimensionless moisture ratio: $MR = \frac{M_t - M_e}{M_i - M_e}$ (1)

Moisture content; $MC(\%) = \frac{M_t - M_e}{M_i}$ (2)

Mass shrinkage ratio: $S_{mr} = \frac{M_t}{M_i}$ (3)

Drying rate: $DR = -\frac{dM}{dt} = -\frac{M_{t+dt} - M_t}{dt}$ (4)

2.4. Quality Parameters

Water extract, cellulose, caffeine, total ash, and total polyphenol of green the product dried in a microwave dryer were chosen as quality parameters and were analyzed in General Directorate of Tea Enterprises (ÇAYKUR), Rize, Türkiye. TS ISO 9768/T1, TS ISO 15598, TS 1564, TS ISO 10727, and ISO 14502-2 standard [29], respectively.

2.5. Experimental Errors and Uncertainty Analysis

Errors highly affect the accuracy in experiments, and they can arise from the operator, structure of the experimental setup and measuring tools. Environmental conditions, test planning, observation, data reading, and device may cause uncertainties and errors in experiments [26].

Total error rate in a measurement with *n* independent variables are given in Equations (36) - (38).

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (36)$$

$$\frac{W_R}{R} = \left[\left(\frac{w_1}{x_1}\right)^2 + \left(\frac{w_2}{x_2}\right)^2 + \left(\frac{w_3}{x_3}\right)^2 + \cdots + \left(\frac{w_n}{x_n}\right)^2\right]^{1/2} \quad (37)$$

(a_1) Error due to mass, power and time measurements during experiments = $\pm$ 1g, $\pm$ 0,5W, $\pm$ 0.001min.

(a_2) Error caused by reading of mass, power and time = $\pm$ 0.01g, $\pm$ 0.005W, $\pm$ 0.00001min.

$$W_R = [(a_1)^2 + (a_2)^2 + ..]^{1/2} = \%1.5 \quad (38)$$

Table 1. Thin-layer drying-curve equations.

No	Model name	Model equation	Eq. No
1	Newton (Lewis, Exponential, Single exponential)	$MR = exp(-kt)$	(5)
2	Page	$MR = exp(-kt^n)$	(6)
3	Modified Page	$MR = exp(-(kt)^n)$	(7)
4	Modified Page-I	$MR = exp((-kt)^n)$	(8)
5	Modified Page-II	$MR = exp\left(-c\left(\frac{t}{L^2}\right)^n\right)$	(9)
6	Henderson and Pabis (Single term)	$MR = a\,exp(-kt)$	(10)
7	Logarithmic (Asymptotic) Yagcioglu et al.	$MR = a\,exp(-kt) + c$	(11)
8	Midilli-Kucuk	$MR = a\,exp(-kt^n) + bt$	(12)
9	Demir et al.	$MR = a\,exp(-kt)^n + b$	(13)
10	Two-Term	$MR = a\,exp(-k_0t) + b\,exp(-k_1t)$	(14)
11	Two-Term Exponential	$MR = a\,exp(-kt) + (1-a)\,exp(-kat)$	(15)
12	Verma et al. (Modified Two-Term Exponential)	$MR = a\,exp(-kt) + (1-a)\,exp(-gt)$	(16)
13	Approximation of Diffusion (Diffusion approach)	$MR = a\,exp(-kt) + (1-a)\,exp(-kbt)$	(17)
14	Modified Henderson and Pabis (Three Term Exponential)	$MR = a\,exp(-kt) + b\,exp(-gt) + c\,exp(-ht)$	(18)
15	Thompson	$t = a\,ln(MR) + b(ln(MR))^2$	(19)
16	Wang and Singh	$MR = 1 + at + bt^2$	(20)
17	Hii et al.	$MR = a\,exp(-kt^n) + c\,exp(-gt^n)$	(21)
18	Simplified Fick's diffusion (SFFD)	$MR = a\,exp\left(-c\left(\frac{t}{L^2}\right)\right)$	(22)
19	Weibull	$MR = exp\left(-\left(\frac{t}{a}\right)^b\right)$	(23)
20	Aghbashlo et al.	$MR = exp\left(-\frac{k_1t}{1+k_2t}\right)$	(24)
21	Parabolic	$MR = a + bt + ct^2$	(25)
22	Balbay and Şahin	$MR = (1-a)\,exp(-kt^n) + b$	(26)
23	Alibas (Modified Midilli-Kucuk)	$M_R = a\,exp(-kt^n) + bt + g$	(27)
24	Improved Midilli-Kucuk	$MR = a\,exp(-k_1t^n) - exp(-k_2t^n) - bt^n$	(28)

Table 2. Evaluation criteria of thin-layer drying curve-equations.

No	Evaluation parameters	Equation	Eq. No
1	Correlation coefficient	$r = \frac{N\sum_{i=1}^{N}(MR_{pre,i})(MR_{exp,i}) - (\sum_{i=1}^{N} MR_{pre,i})(\sum_{i=1}^{N} MR_{exp,i})}{\sqrt{\left(N\sum_{i=1}^{N} MR_{pre,i}^2 - (\sum_{i=1}^{N} MR_{pre,i})^2\right)\left(N\sum_{i=1}^{N} MR_{exp,i}^2 - (\sum_{i=1}^{N} MR_{exp,i})^2\right)}}$	(29)
2	Coefficient of determination	$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{1}^{n}(MR_{exp,i} - MR_{avg})^2}$	(30)
3	Adjusted R²	$\bar{R}^2 = 1 - (1 - R^2)\frac{N-1}{N-k-1}$	(31)
4	Reduced chi-square	$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n}$	(32)
5	Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}}$	(33)
6	Reduced sum square error	$RSSE = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{cal,i})^2}{N}$	(34)
7	Mean bias error	$MBE = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})}{N}$	(35)

4. RESULTS AND DISCUSSION

To obtain the drying characteristics of green tea leaves in microwave dryer and perform mathematical modeling 50 g of product and 100 W, 300 W, 600 W, and 800 W microwave power levels were used. Moisture content, mass shrinkage rate, dimensionless moisture ratio, and drying rate were estimated based on drying time and mass losses, and mathematical modeling was performed by using 24 drying curve equations and seven evaluation criteria. Also, water extract, cellulose, total ash, caffeine, and polyphenol were analyzed in ÇAYKUR, Rize, Türkiye.

In the microwave drying experiments ambient temperature ranged from 19.1 ºC to 20 ºC and outlet temperatures changed from 20.2 ºC to 21.5 ºC for 100 W, from 22.1 ºC to 25 ºC for 300 W, from 23.6 ºC to 26.5 ºC for 600 W, and from 23.3 ºC to 28 ºC for 800 W. Uncertainty analysis was performed and the total error was estimated at 1.5% and therefore these errors did not affect the results.

The highest moisture loss and small color and shape changes occurred during the initial drying period. As seen in Table 3-6, the maximum color change was observed at 100 W microwave power during the middle and last drying periods, and it was seen that the color change decreased as the microwave power increased. However, it was observed that there is almost no color change on the product at 800 W microwave power. As the effect time of the microwave on the product decreases the color change decreases. Also, it was obtained that the minimum moisture loss occurred at last drying period. Drying time was obtained as 80, 20, 5 and 4 minutes for 100 W to 800 W microwave powers, respectively.

Twenty-four thin-layer models and seven evaluation criteria were used for mathematical modeling of microwave drying of green tea leaves. The best model was determined by considering the closest values to 1 of the *r*, R^2 and $\bar{R}^2$ and the closest values to 0 of the χ^2, RMSE, RSSE, and MBE. As seen in Table 7, the best model was determined as Improved Midilli-Kucuk model for microwave powers of 100 W, 300 W, 600 W, and 800 W. The best drying curve equations are presented in Table 3-6 for each microwave power.

The best five models were determined by using r, R^2, $\bar{R}^2$, χ^2, RMSE, RSSE, and MBE and ordered from higher accuracy to lower accuracy in Table 7 for 100 W, 300 W, 600 W and 800 W microwave power values.

Model constants are affected by microwave power that creates microwave, which directly targets the water molecules in the green tea leaves, generates heat directly, and increases the ambient temperature. Because of these physical phenomena drying time and dimensionless moisture ratio decrease with increasing microwave power. As seen in Figure 3, maximum moisture loss was observed during the initial drying period at each microwave power. At the mid-drying period, moisture loss is higher than the last drying period and lower than the initial drying period. It was observed that moisture loss was quite low at the last drying period. Drying time diminishes as the microwave power increases. Drying time determined as 80, 20, 5, and 4 minutes for 100 W, 300 W, 600 W, and 800 W microwave powers, respectively. It was concluded that increasing of microwave power considerably decreases drying time.

Water extract, cellulose, caffeine, total ash, and total polyphenol of product dried in a microwave dryer were analyzed in ÇAYKUR, Rize, Türkiye. The water extract, which is an indicator of the quality of the dried green tea leaves, varies from 27.66% to 35.44%. Thea *et al.* [30] reported that the water extract in green tea changes from 32.7% to 48.7%. The water extract in green tea should be at least 32% [29, 31]. As seen in Table 8, the highest water extract was obtained as 35.4% at 300 W microwave power. This value was determined as 44. % in swirling flow fluidized bed infrared drying system at 500 W infrared power for green tea leaves [8]. As shown in Table 8, water extract was determined as 26.77%, 28.07%, and 29.07% (on dry basis, g/g) at 100 W, 600 W, and 800 W microwave powers, respectively.

Table 3. Photos and the best model for 100 W power.

Improved Midilli-Kucuk		
$MR = 2.000\exp(0.007369t^{1.088451}) - \exp(-0.013777t^{1.088451}) - 0.038866t^{1.088451}$		
		
0th minute	40th minute	80th minute

Table 4. Photos and the best model for 300 W power.

Improved Midilli-Kucuk		
$MR = 2.000\exp(0.142448t^{0.6712}) - \exp(-0.938362t^{0.6712}) - 0.775823t^{0.6712}$		
		
0th minute	10th minute	20th minute

Table 5. Photos and the best model for 600 W power.

Improved Midilli-Kucuk		
$MR = 1.995\exp(-0.243681t^{1.81377}) - \exp(-0.330039t^{1.81377}) - 0.00181t^{1.81377}$		
		
0th minute	3rd minute	5th minute

Table 6. Photos and the best model for 800 W power.

Improved Midilli-Kucuk		
$MR = 2.000\exp(0.172632t^{1.259356}) - \exp(-0.183083t^{1.259356}) - 0.877462t^{1.259356}$		
		
0th minute	2nd minute	4th minute

Table 7. Evaluation criteria values.

Model Name	*Power*	*r*	R^2	χ^2	$\bar{R}^2$	*RMSE*	*RSSE*	*MBE*
Improved Midilli-Kucuk		**0.99877**	**0.99876**	**0.00068**	**0.99669**	**0.01739**	**0.00030**	**0.00158**
Weibull		0.99455	0.99401	0.00188	0.99201	0.03821	0.00146	0.01163
Wang and Singh	100 W	0.99479	0.99299	0.00220	0.99066	0.04133	0.00171	0.01866
Modified Page		0.99431	0.99398	0.00189	0.99197	0.03830	0.00147	0.00927
Modified Page-II		0.99449	0.99397	0.00220	0.99036	0.03833	0.00147	0.01109
Improved Midilli-Kucuk		**1.00000**	**1.00000**	**-**	**1.00000**	**0.00003**	**0.00000**	**0.00000**
Weibull		0.99984	0.99970	0.00010	0.99941	0.00767	0.00006	0.00260
Modified Page-II	300 W	0.99984	0.99969	0.00015	0.99877	0.00779	0.00006	0.00251
Modified Page		0.99984	0.99970	0.00010	0.99941	0.00767	0.00006	0.00253
Page		0.99946	0.99871	0.00042	0.99743	0.01595	0.00025	0.00165
Improved Midilli-Kucuk		**0.99908**	**0.99886**	**0.00161**	**-**	**0.01636**	**0.00027**	**0.00038**
Midilli-Kucuk		0.99902	0.99878	0.00086	0.99392	0.01693	0.00029	0.00004
Alibas (Modified Midilli-Kucuk)	600 W	0.99876	0.99846	0.00217	-	0.01902	0.00036	0.00013
Hii et al.		0.99860	0.99803	0.00278	-	0.02154	0.00046	0.00489
Modified Page		0.99854	0.99793	0.00073	0.99656	0.02207	0.00049	0.00722
Improved Midilli-Kucuk		**1.00000**	**1.00000**	**0.00000**	**1.00000**	**0.00001**	**0.00000**	**0.00001**
Aghbashlo et al.		0.99972	0.99933	0.00022	0.99865	0.01146	0.00013	0.00269
Balbay and Şahin	800 W	0.99818	0.99714	0.00278	-	0.02359	0.00056	0.00027
Midilli-Kucuk		0.99809	0.99701	0.00291	-	0.02415	0.00058	0.00032
Weibull		0.99779	0.99614	0.00125	0.99228	0.02743	0.00075	0.00739

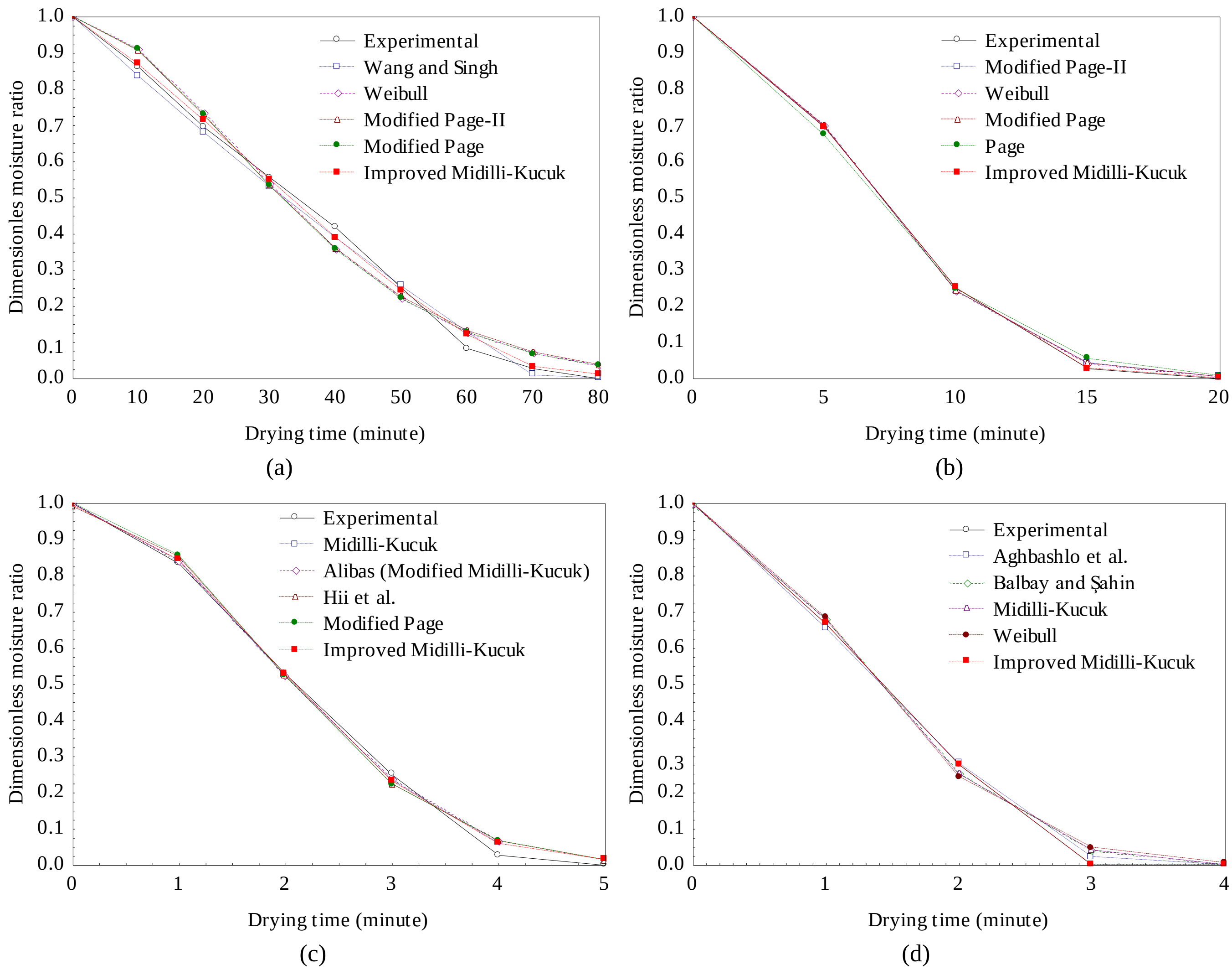

Fig. 3. Variation of MR with time, (a) 100 W, (b) 300 W, (c) 600 W, and (d) 800 W.

Total ash is one of the quality parameters of the dried green tea leaves and expected to be between 4 and 8% [29, 31]. As presented in Table 8, the lowest total ash was determined as 5.95% at 800 W microwave power. Okur *et al.* [8] determined the lowest total ash as 4.48% in swirling flow fluidized bed infrared drying at 500 W infrared power for green tea leaves. Also, total ash was obtained as 5.99%, 6%, and 6.35% at 600 W, 300 W, and 100 W microwave powers, respectively.

Caffeine, which is one of the most important features that show the quality of green and black tea, is expected to be high. Caffeine content changes between 1.85% and 1.93% for green tea leaves dried in a microwave dryer. Thea *et al.* [30] reported that caffeine content varies between 1.1-2.8% in green tea. However, it was reported that the caffeine content should be at least 1.6% in green tea [29]. As shown in Table 8, the maximum caffeine was obtained as 1.93% at 800 W microwave power. This value was obtained as 1.91% for swirling flow fluidized bed infrared drying of green tea leaves at 750 W infrared power [8]. Also, caffeine content was found as 1.91% at 100 W and 1.85% at 300 W and 600 W microwave powers.

Cellulose is expected to be low in a quality green tea. As seen in Table 8, cellulose varies between 17.79% and 20.82%. Thea *et al.* [30] reported that cellulose varies between 1.8-20.5% in green tea. According to Turkish Food Codex [29] cellulose should be at most 16.5% in green tea. The lowest cellulose was obtained as 17.79% at 300 W microwave power. Okur *et al.* [8] reported that the lowest value of cellulose was determined as 15.73% in swirling flow fluidized bed infrared drying system at 250 W infrared power. Also, the cellulose was determined as 20.43% at 600 W, 20.79% at 100 W, and 20.82% at 800 W microwave powers, respectively.

Total polyphenol is the most important compounds that add flavor to tea [31]. As seen in Table 8, total polyphenol varies between 8.16% and 11.20% for green tea leaves dried in microwave drying system. According to Turkish Food Codex [29], the total polyphenol should be at least 11% in green tea. Yashin *et al.* [32] reported that the total polyphenol ranges from 21% to 33% in green tea. The highest polyphenol was determined as 11.2% at 300 W microwave power for green tea leaves dried in microwave dryer. Okur *et al.* [8] determined the highest total polyphenol as 4.30% in swirling flow fluidized bed infrared drying system at 1000 W infrared power. Also, total polyphenol is 8.16%, 10.5%, and 11% at 100 W, 800 W and 600 W, respectively.

Figure 4 presents the variation of drying rate estimated from Equation (4) with drying time for green tea leaves dried in a microwave dryer. The drying rate considerably increases by rising microwave power because microwave directly targets the water molecules in the green tea leaves, generates heat, and faster moisture transfer occurs from the green tea leaves. Energy is directly provided from the microwave source to green tea leaves for water evaporation. The maximum drying rate was calculated as 0.6 g water/minute at 20th, 50th and 60th minutes for 100 W, 3.2 g water/minute at 10th minute for 300 W, 11 g water/minute at 2nd minutes for 600 W and 14 g water/minute at 2nd minutes for 800 W microwave powers. Drying time was obtained as 80, 20, 5 and 4 minutes for microwave powers of 100 W, 300 W, 600 W and 800 W, respectively.

Table 8. Quality analysis results.

Analyzes	*Method*	*Power*	*Result, %*
Water extract (on dry basis) (g/g) (%)	TS ISO 9768/T1 November 2003	100 W	27.66
		300 W	35.44
		600 W	28.07
		800 W	29.07
Cellulose (on dry basis) (g/g) (%)	TS ISO 15598 March 2003	100 W	20.79
		300 W	17.79
		600 W	20.43
		800 W	20.82
Total ash (on dry basis) (g/g) (%)	TS 1564 March 2003	100 W	6.35
		300 W	6.00
		600 W	5.99
		800 W	5.95
Total polyphenol (on dry basis) (g/g)%	ISO 14502-2	100 W	8.16
		300 W	11.20
		600 W	11.00
		800 W	10.50
Caffeine (on dry basis) (g/g) (%)	TS ISO 10727	100 W	1.91
		300 W	1.85
		600 W	1.85
		800 W	1.93

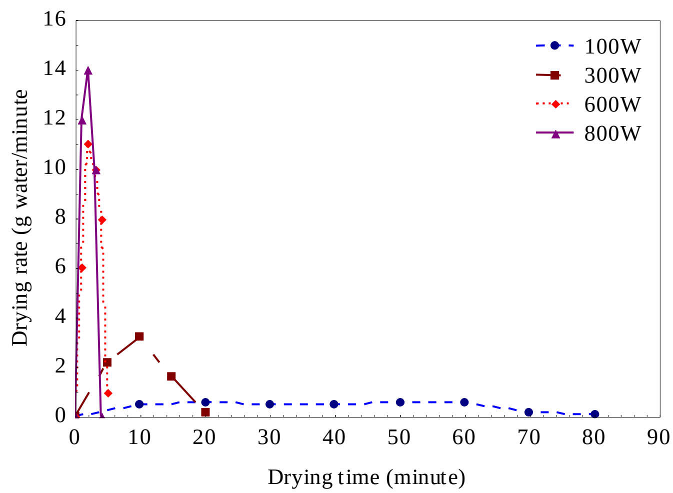

Fig. 4. The variation of drying rate with time.

The variation of moisture content calculated from Equation (2) depending on the drying time in microwave drying of green tea leaves was shown in Figure 5. It was observed that the moisture content diminishes with rising drying time. Also, it was seen that the drying time significantly decreases, and moisture loss highly increases by increasing microwave power. Because energy is directly transferred by microwave to the water molecules inside the green tea leaves and rapid moisture transfer occurs when microwave power increases.

Figure 6 gives the variation of the mass shrinkage ratio estimated from Equation (3) with drying time. The mass shrinkage ratio diminishes with the rising of drying time. Also, the mass shrinkage ratio considerably decreases with increasing microwave power. The final mass shrinkage ratio is estimated as 0.28 for each microwave power.

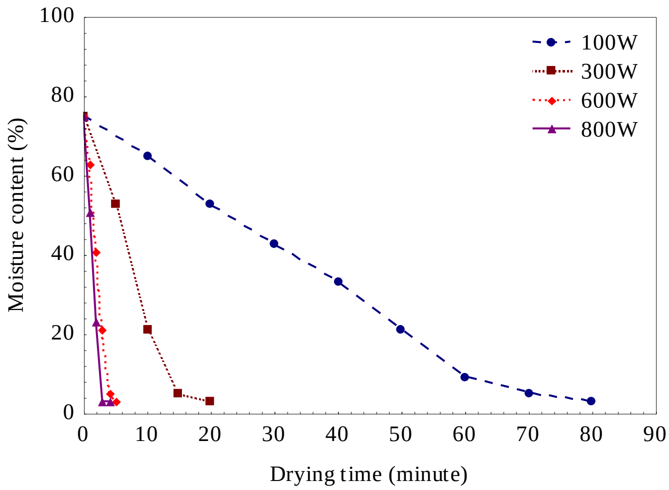

Fig. 5. The variation of moisture content with time.

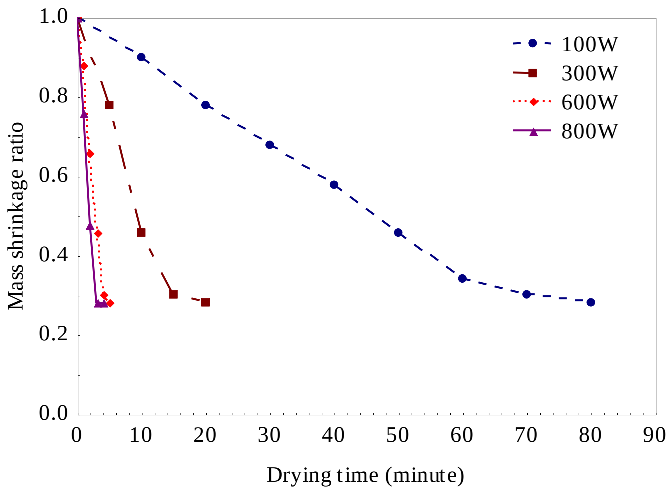

Fig. 6. The variation of mass shrinkage ratio depending on time.

4. CONCLUSION

Drying kinetics, mathematical modeling, and quality parameters of green tea leaves dried in microwave drying system were studied for microwave powers of 100 W, 300 W, 600 W, and 800W. Some important outcomes are given as follows;

- The most suitable drying model was found as improved Midilli-Kucuk model for all microwave power levels.
- Green tea leaves preserved their natural color best at 800 W.
- Mass shrinkage ratio and moisture content diminish, and drying rate rise with rising of microwave power.
- Drying time highly decreases as the microwave power rises.
- The highest water extract was found as 35.4% at 300 W.
- The highest caffeine was determined as 1.9% at 800 W.
- The minimum cellulose and total ash were obtained as 17.8% at 300 W and 6% at 800 W, respectively.
- The maximum total polyphenol was found as 11.2% at 300 W.

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Nomenclature

a, b, c, g, n	Empirical constants in models
c, g, h, k, k_0, k_1, k_2	Drying constants (1/min)
DR	Drying rate (g water/minute)
EF	Modeling efficiency (-)
MBE	Mean bias error
MC	Moisture content
MR	Dimensionless moisture ratio
S_{mr}	Mass shrinkage ratio
M_t	Product moisture on dry basis at "t" (g water/g dry solid)
M_{t+dt}	Product moisture on dry basis at "t+dt" (g water/g dry solid)
M_i	Initial product moisture on dry basis (g water/g dry solid)
M_e	Equilibrium or final product moisture on dry basis (g water/g dry solid)
N	Number of observations
n	Number of constants
P	Mean relative percentage error
r	Correlation coefficient
R^2	Coefficient of determination
$\bar{R}^2$	Adjusted R^2
RMSE	Root mean square error
RSSE	Reduced sum square error
SST	Total sum of squares
t	Time (minute)
W_R	Total error
$x_1, x_2, x_3, .., x_n$	Variables affecting measurement
$w_1, w_2, w_3, .., w_n$	Error rate regarding independent variables

Greek Symbols

χ^2	Reduced chi-square

Subscripts

avg	Average
exp	Experimental
pre	Predicted

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