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# Mathematical Modeling and Drying Characteristics Investigation of Black Mulberry Dried by Microwave Method

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**ABSTRACT**

In this study, microwave drying characteristics of black mulberry were studied at microwave power levels of 90, 180 and 360 W. Obtained experimental drying results were applied to seven mathematical models of Aghbashlo *et al*., Henderson and Pabis, Jena and Das, Logaritmic, Midilli and Kucuk, Page and Weibull. The best model was selected as Midilli and Kucuk based on the highest coefficient of determination ($R^2$) (0.994861–90 W, 0.999824–180 W, 0.998747–360 W) and the lowest $\chi^2$ (0.-000575–90 W, 0.000027–180 W, 0.000255–360 W) and Root Mean Square Error (RMSE) (0.022427–90 W, 0.004275–180 W, 0.011899–360 W) values compared to other models. According to drying times, the best drying condition was seen on 360 W power. The effective moisture diffusivity ($D_{eff}$) values were calculated using the Fick's second law's spherical coordinate approximation and were found between $4.79 \times 10^{-8}$ and $2.60 \times 10^{-7}$ $m^2/s$. The activation energy ($E_a$) was calculated using modified form of Arrhenius equation and found as 13.15 kW/kg.

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**KEYWORDS**
Activation energy; black mulberry; drying; effective moisture diffusivity; microwave

## Introduction

Mulberry has been cultivated in the Northern hemisphere for centuries on account of its wide use for many purposes (Maskan and Gogus, 1998). Three mulberry trees are extensively grown (e.g. southern Europe, India) for their leaves as foods for silkworms. Their fruits can be eaten raw or dried. There are three kinds of mulberry: Red mulberry (*Morus rubra* L.), white mulberry (*Morus alba* L.) and black mulberry (*Morus nigra* L.). White mulberry originated in Western Asia, red mulberry in North and South America and black mulberry is from Southern Russia. Black mulberries have commonly been used in traditional Chinese medicine to treat diabetes, hypertension, anemia and arthritis (Chen et al., 2017). Mulberry fruit have high moisture level 62.20% to 74.62% therefore this fruit is regarded highly perishable (Ali et al.,

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2016). Because of the short season and the sensitivity to storage, drying is often used as a preservation method. In addition, mulberry is used in mulberry molasses, juices, paste, marmalade and wine production (Akbulut and Durmus, 2009).

Drying is an important food-processing technique and is one of the oldest methods of food preservation. The most popular and efficient way to preserve food by reducing its moisture content is convective drying (Izli et al., 2014). However, the relatively long drying time, high temperatures used and high velocities of the drying airflow are serious drawbacks of this method (Kipcak, 2017). Microwave drying is an alternative method with several advantages such as uniform energy delivery, high thermal conductivity to the interior of the material, better space utilization, sanitation, energy savings, precise process control and fast start-up and shutdown conditions (Maskan, 2000).

Recently, microwave drying has attracted popularity as an alternative method for drying several food products such as fruits, vegetables and dairy products were also studied. By researchers, banana (Maskan, 2000), white mulberry (Darvishi et al., 2014; Evin, 2011), black mulberry (Zojaji et al., 2016), carrot (Pu et al., 2016), nut seed (da Silva et al., 2016), blueberry (Zielinska and Markowski, 2016), apple slices (Zarein et al., 2015) and jujube (Fang et al., 2011) were studied along by a microwave method. As it is given in the literature studies, there is only a single study available about microwave drying of black mulberry with the high microwave (200–500 W) power levels. Hence, in this study, we aimed to investigate how the low level of microwave radiation (90–360 W) affects on the drying characteristics of black mulberry, which mathematical model best fits the experimental drying data. In addition, it is aimed to calculate the effective moisture diffusivity ($D_{eff}$) and activation energy ($E_a$) values.

## Materials and Methods

### *Materials*

Fresh black mulberry (*Morus nigra* L.), which is produced by Kerevitaş (Kerevitaş Industry and Commerce Inc., Bursa, Turkey) was purchased from a local market in Istanbul, Turkey in April 2017 and were kept in a refrigerator (1050 T model; Arcelik, Eskisehir, Turkey) at a temperature of −16°C for 1 week. Before the experiments, black mulberries were taken from the refrigerator and waited in a desiccator to reach the room temperature equilibrium. The initial moisture content of mulberry samples was determined by AOAC (1995) method by using an oven at 105°C. Three parallel experiments were conducted for the determination of initial moisture

content and the average values are calculated as 90.73%, wet basis (9.787 kg water/kg dry matter, dry basis).

### Microwave Drying Procedure

For the microwave drying a domestic microwave oven was used (HMT72G420, Robert Bosch Hausgerate GmbH, Munich, Germany), which has a generated 800 W maximum intermittent output power hence the equipment delivers the set microwave power in the particular time of process with the frequency of 2450 MHz. Microwave power level can be controlled by the control panel of equipment. Three different microwave power levels of 90, 180 and 360 W were used for the drying of black mulberry. Approximately 15.82 ± 0.15 g of black mulberry, which has an average radius of 1.90 ± 0.10 cm was weighted using a digital balance (Mettler-Toledo AG, Grefensee, Switzerland, model BB3000). The drying process was continued with the weighing time interval of 1 min until the final moisture contents decreased to 0.31 ± 0.01 kg water/kg dry matter. At the moisture content below 0.31 ± 0.01 kg water/kg dry matter the black mulberries were burned.

### Mathematical Modeling

In order to apply mathematical models, the moisture content (M), moisture ratio (MR) and drying rate (DR) of samples were calculated using the Equations (1)–(3) (Ismail and Kocabay, 2018a; Kipcak, 2017):

$$M = \frac{m_w}{m_d} \tag{1}$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{3}$$

In these equations $m_w$ and $m_d$ represent the weight (kg) of water content and dry content, respectively. t is the time (min), $M_i$, $M_e$, $M_t$ *and* $M_{t+dt}$ are initial moisture content, equilibrium moisture content, moisture content at t and $t + dt$ (kg water/kg dry matter), respectively. As the $M_e$ is very small compared to $M_0$ and $M_t$ values, the $M_e$ can be neglected and $MR$ can be expressed as $M_t/M_i$ (Ashtiani et al., 2018; Ismail et al., 2017; Ismail and Kocabay, 2018b; Izli et al., 2014).

**Table 1.** Mathematical drying models used for the microwave drying of black mulberry.

| Model | Equation |
|---|---|
| Aghbashlo *et al.* | $MR = exp(-k_1 \times t1 + k_2 \times t)$ |
| Henderson and Pabis | $MR = a \times exp(-k \times t)$ |
| Jena and Das | $MR = a \times exp(-k \times t + b \times \sqrt{t}) + c$ |
| Logarithmic | $MR = a \times exp(-k \times t) + c$ |
| Midilli and Kucuk | $MR = a \times exp(-k \times t^n) + b \times t$ |
| Page | $MR = exp(-k \times t^n)$ |
| Weibull | $MR = exp\left[-\left(\frac{t}{b}\right)^a\right]$ |

### *Statistical Calculations*

Measured experimental data were fitted by using Statistica 8.0.550 (StatSoft Inc., USA) software package, to seven mathematical models that are given in Table 1.

Model parameters were calculated by using a non-linear regression procedure based on the Levenberg-Marquardt algorithm. The coefficient of determination ($R^2$), reduced chi-square ($\chi^2$) and root-mean-square error ($RMSE$) is calculated for the experimental and predicted values and are given in (4), (5) and (6):

$$R^2 = 1 - \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N} (MR_{exp,i} - (1n) \sum_{i=1}^{N} MR_{pre,i})} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{5}$$

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} \left(MR_{pre,i} - MR_{exp,i}\right)^2\right)^{1/2} \tag{6}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are experimental and predicted dimensionless moisture ratios, respectively. $N$ is the number of observations, $z$ is the number of constants in the models. Better quality of fit is expected with higher $R^2$ values and the lower $\chi^2$ and $RMSE$ values (Akbulut and Durmus, 2009; Darvishi et al., 2014; Doymaz et al., 2015; Kipcak, 2017; Kipcak and Ismail, 2018).

### *Effective Moisture Diffusivity Calculation*

During the drying of the food, a complex process that takes place is called diffusion. Drying characteristics of foods can be described by the Fick's diffusion equation at the falling-rate period. Black mulberries are in the form of spherical shape and the Fick's second law of diffusion for spherical object can be defined as:

$$\frac{\partial M}{\partial t} = \left[D_{eff}(\ \ M)\right] \tag{7}$$

where $D_{eff}$ is the effective moisture diffusivity ($m^2/s$) and $M$ is the moisture content. By using appropriate initial and boundary conditions Crank (1979) gave the analytical solution to Equation 7 for object with spherical geometry by making the assumptions of uniform initial moisture content, internal moisture movement as the main resistance, negligible external resistance to heat and mass transfer, a constant effective diffusion coefficient. Then, the equation is given in (8):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}exp\left(-n\pi^2 D_{eff}\times\frac{t}{r^2}\right) \tag{8}$$

where t is the drying time (s) and r is the radius of the spherical object (m). To be able to determine the effective moisture diffusivity, Equation (8) may be simplified to a linear logarithmic form:

$$MR = \frac{6}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}t}{r^2}\right) \tag{9}$$

$D_{eff}$ can easily be calculated from the plot of $ln\ (MR)$ versus t, which gave a straight plot. From the slope of this plot, $D_{eff}$ can be calculated.

### Activation Energy Calculation

For the microwave method since the temperature is not directly measurable quantity during drying process a modified form of Arrhenius equation used for the relationship between the effective diffusivity and the microwave power level to a sample weight (Darvishi et al., 2014).

$$D_{eff} = D_0 exp\left(\frac{-E_a m}{P}\right) \tag{10}$$

where $D_0$ is the pre-exponential factor ($m^2/s$), $E_a$ is the activation energy (W/kg), $P$ is the microwave power level (W) and m is the sample weight (kg).

## Results and Discussion

### Drying Curves

In Figure 1, the effect of microwave power level on the moisture content of black mulberries is given. As seen in Figure 1, increasing the microwave power level had a significant decrease in the drying time of black mulberry. The drying time required to dry the black mulberries is found as 42, 12 and 8 min for the microwave power levels 90, 180 and 360 W, respectively.

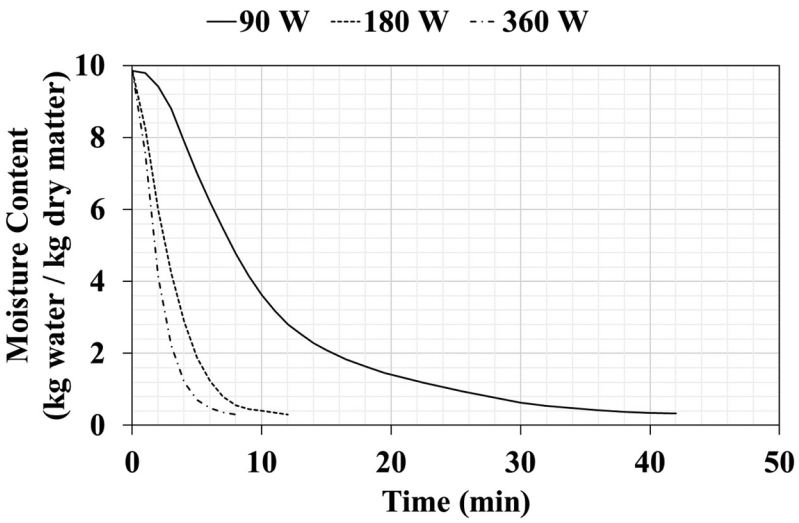



**Figure 1.** Drying curve of black mulberry with respect to drying time and microwave power level.

The average time of drying decreased 5.25 times as microwave power level increased 4 times from 90 to 360 W. This indicates that mass transfer within the sample was more rapid during higher microwave power heating because more heat was generated within the sample creating a large vapor pressure difference between the center and the surface of the product due to the characteristic microwave volumetric heating (Evin, 2011). Similar observations were reported in the literature for microwave drying method of agricultural products (Darvishi et al., 2014; Evin, 2011).

### *Drying Rate Curves*

The characteristics of drying rate curves (drying rate versus moisture content) of black mulberry samples using the three MW power levels are presented in Figure 2. The drying rates increased with the increasing microwave power levels. The drying rate reached its maximum values at a higher MW power level. The moisture removal inside the black mulberry slices was higher at high microwave power levels, because the migration of moisture to the surface and the evaporation rate from surface to air slows down with decreasing the moisture in the product, the drying rate clearly decreases. If the curves in Figure 2 are analyzed, these curves occurred in the falling rate period of the drying process after a short warm-up period. Also, no constant rate period was observed in these curves. This situation shows that diffusion was domain physical mechanism governing moisture movement in drying process. These results are in agreement with the observations of earlier researchers on mulberry and other fruits (Abolhasani and Ansarifar, 2015; Evin, 2011; Xie et al., 2018).

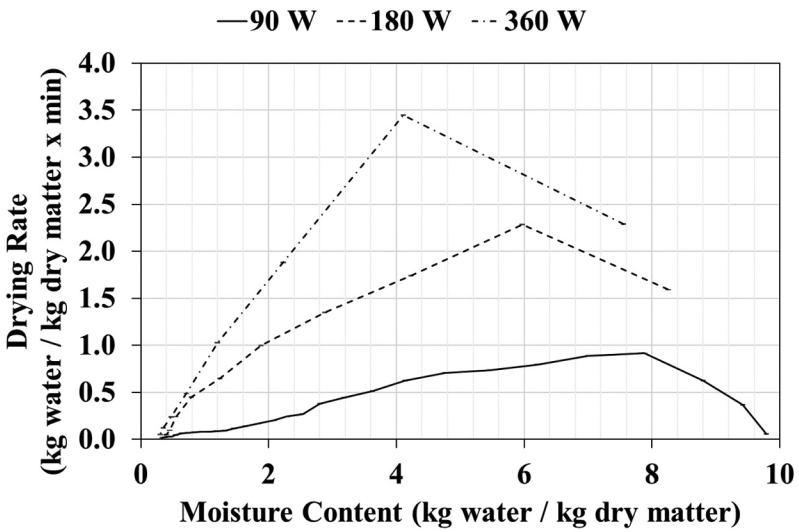



**Figure 2.** Drying rate curve of black mulberry with respect to moisture content and microwave power level.

### *Modeling and Statistical Evaluation Results*

The mathematical modeling results are given in Table 2. The highest $R^2$ values were found in the Midilli and Kucuk model with the values of 0.994861, 0.999824 and 0.998747 at the microwave power levels 90, 180 and 360 W, respectively. The lowest $R^2$ values were found at 90 W in the model of Aghbashlo *et al.* with a value of 0.979267. For both in 180 and 360 W, the lowest $R^2$ values were found in the model of Henderson and Pabis with the values of 0.988380 and 0.982049, respectively. The lowest $\chi^2$ values were found in the Midilli and Kucuk model with the values of 0.000575, 0.000027 and 0.000255 at the microwave power levels 90, 180 and 360 W, respectively. In parallel to the $\chi^2$ values the lowest RMSE values were found in the Midilli and Kucuk model with the values of 0.022427, 0.004275 and 0.011899 at the microwave power levels 90, 180 and 360 W, respectively. Among these seven mathematical models, Midilli and Kucuk model best fits the experimental drying data with the highest $R^2$ and lowest $\chi^2$ and RMSE values. The plot of the experimental and predicted values is given in Figure 3. Since the data were on the 45° line, it can be said that the predicted values were in good agreement with the experimental drying values. Also, Midilli and Kucuk model was reported as the best model in the literature for describing drying curves of white mulberry (Abolhasani and Ansarifar, 2015; Karaaslan et al., 2017)

**Table 2.** Estimated coefficients and statistical data obtained from different drying models.

| Model | Power (W) | 90 | 180 | 360 |
|---|---|---|---|---|
| Aghbashlo *et al.* | $k_1$ | 0.080859 | 0.231754 | 0.331667 |
| | $k_2$ | −0.008760 | −0.051388 | −0.087892 |
| | $R^2$ | 0.979267 | 0.994539 | 0.989358 |
| | $\chi^2$ | 0.002165 | 0.000679 | 0.001546 |
| | RMSE | 0.045047 | 0.023786 | 0.034674 |
| Henderson and Pabis | a | 1.111516 | 1.059674 | 1.050718 |
| | k | 0.102370 | 0.316468 | 0.465910 |
| | $R^2$ | 0.987718 | 0.988380 | 0.982049 |
| | $\chi^2$ | 0.001282 | 0.001445 | 0.002607 |
| | RMSE | 0.034671 | 0.034696 | 0.045033 |
| Jena and Das | a | 0.263136 | 0.135778 | 0.180185 |
| | k | 0.136284 | 0.448873 | 0.768826 |
| | b | 0.136956 | 0.278603 | 0.490279 |
| | c | 1.348466 | 1.996057 | 1.715152 |
| | $R^2$ | 0.993599 | 0.999259 | 0.998556 |
| | $\chi^2$ | 0.000716 | 0.000115 | 0.000294 |
| | RMSE | 0.025029 | 0.008764 | 0.012773 |
| Logarithmic | a | 1.105627 | 1.089267 | 1.079458 |
| | k | 0.105464 | 0.285770 | 0.424772 |
| | c | 0.011256 | −0.040939 | −0.036706 |
| | $R^2$ | 0.987953 | 0.990622 | 0.984034 |
| | $\chi^2$ | 0.001301 | 0.001295 | 0.002706 |
| | RMSE | 0.034338 | 0.031170 | 0.042471 |
| Midilli and Kucuk | a | 1.048504 | 1.002868 | 1.006003 |
| | k | 0.052193 | 0.193146 | 0.302429 |
| | n | 1.287934 | 1.363748 | 1.493400 |
| | b | 0.001403 | 0.002571 | 0.005034 |
| | $R^2$ | 0.994861 | 0.999824 | 0.998747 |
| | $\chi^2$ | 0.000575 | 0.000027 | 0.000255 |
| | RMSE | 0.022427 | 0.004275 | 0.011899 |
| Page | k | 0.050499 | 0.200656 | 0.310224 |
| | n | 1.246942 | 1.297331 | 1.385964 |
| | $R^2$ | 0.987340 | 0.998495 | 0.995710 |
| | $\chi^2$ | 0.001322 | 0.000187 | 0.000623 |
| | RMSE | 0.035200 | 0.012487 | 0.022016 |
| Weibull | b | 10.96278 | 3.448890 | 2.326834 |
| | a | 1.24694 | 1.297333 | 1.385969 |
| | $R^2$ | 0.987340 | 0.998495 | 0.995710 |
| | $\chi^2$ | 0.001322 | 0.000187 | 0.000623 |
| | RMSE | 0.035200 | 0.012487 | 0.022016 |

### *Effective Moisture Diffusivity Values*

In order to calculate the $D_{eff}$, ln(MR) values were plotted against drying time (s). Obtained straight-line equations for the different microwave power levels are given in (11), (12) and (13):

$$90W \rightarrow ln(MR) = -0.001459t - 0.056422\left(R^2 = 0.984309\right) \quad (11)$$

$$180W \rightarrow ln(MR) = -0.005448t - 0.021639(R^2 = 0.974170) \quad (12)$$

$$360W \rightarrow ln(MR) = -0.007934t - 0.006086\left(R^2 = 0.978982\right) \quad (13)$$

Using these equations, $D_{eff}$ values were calculated as $4.79 \times 10^{-8}$, $1.79 \times 10^{-7}$ and $2.60 \times 10^{-7}$ $m^2/s$ for the microwave power levels of 90, 180 and 360 W,

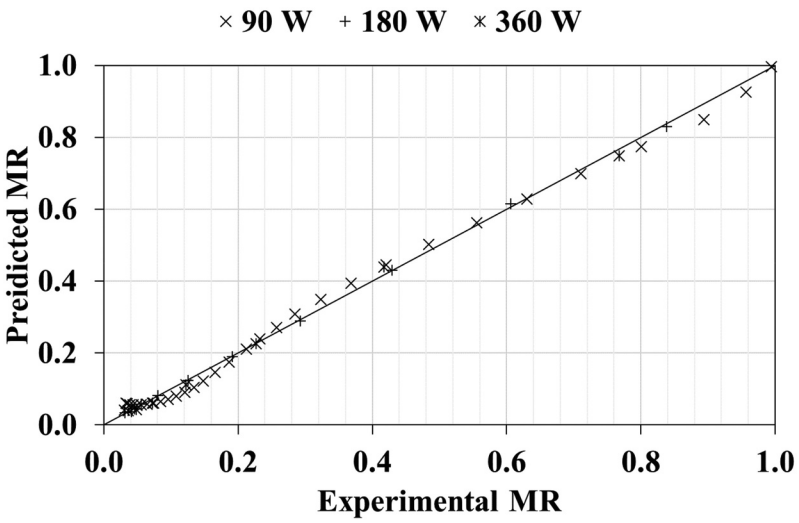



**Figure 3.** The plot of experimental and predicted MR values obtained from the model of Midilli and Kucuk.

respectively. The effect of different microwave power level on the $D_{eff}$ values was given in Figure 4. The highest value of $D_{eff}$ was found in 360 W and the lowest value of $D_{eff}$ was found in 90 W. The effect of different microwave power level on $D_{eff}$ can be given by the equation of (14):

$$D_{eff} = 1.06 \times 10^{-7} P - 5.02 \times 10^{-8} \left(R^2 = 0.9824\right) \quad (14)$$

It can be seen from Figure 4 that $D_{eff}$ values increased with increasing microwave power level. This might be explained by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture

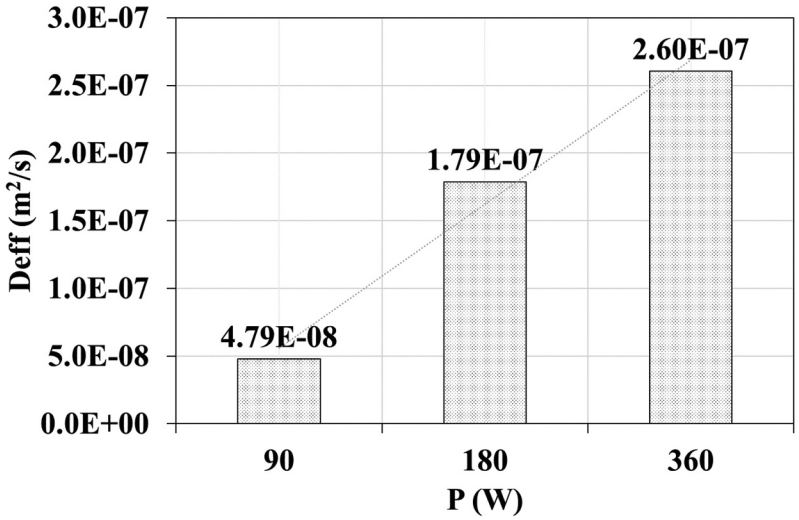



**Figure 4.** The effect of different microwave power level of the $D_{eff}$ values.

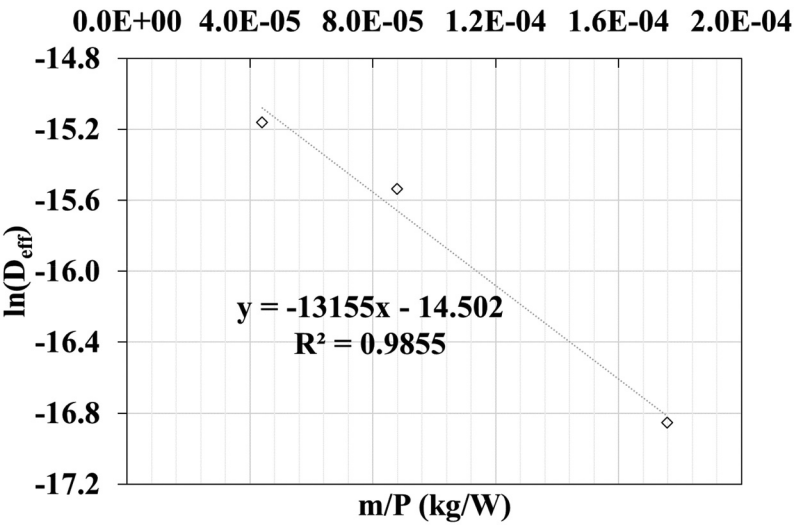



**Figure 5.** The plot of ln($D_{eff}$) against *m/P* (kg/W).

diffusivity when samples were dried at higher microwave power. These values fall within the range of $10^{-12}$ ⁻ $10^{-8}$ $m^2/s$, which is reported for most food materials (Zogzas et al., 1996). The resulted values of $D_{eff}$ are comparable to $1.06 \times 10^{-8}$ to $3.45 \times 10^{-8}$ mentioned for microwave drying white mulberry at 100–500 W (Darvishi *et al.*, 2014) and $0.45 \times 10^{-8}$ to $3.25 \times 10^{-8}$ $m^2/s$ for microwave drying white mulberry at 90–800 W (Evin, 2011).

### *Activation Energy*

In order to calculate the $E_a$ value of black mulberry, ln($D_{eff}$) values were plotted against *m/P* values and given in Figure 5. From the intercept and the slope of the straight-line $D_0$ and $E_a$ *can* be calculated. Obtained straight-line equation and exponential form of this straight-line equation are given in (15) and (16):

$$ln\left(D_{eff}\right) = -13155mP - 14.502\left(R^2 = 0.9801\right) \quad (15)$$

$$D_{eff} = 5.033 \times 10^{-7} exp(-13155mP) \quad (16)$$

From the equations, $D_0$ and $E_a$ are calculated as $5.033 \times 10^{-7}$ $m^2/s$ and 13.15 kW/kg, respectively. The $E_a$ value is higher than that corresponding to white mulberry (3.98 kW/kg) (Darvishi et al., 2014).

## Conclusion

Drying behavior and kinetics of black mulberry were investigated in a microwave oven at 90, 180 and 360 W microwave power. Drying operation

was finished when the moisture content reached to 0.31 kg water/kg dry matter from 9.787 kg water/kg dry matter (dry basis). Increase in microwave power increased drying rates and reduced drying time. For the short drying time, 360 W power level is the optimum power level. Only falling rate period was observed in the drying of black mulberry in microwave oven. Seven mathematical models were used for describing the drying kinetics of black mulberry. Midilli and Kucuk model gave the best fitting to the experimental data. Fick's second law was used for the determination of effective moisture diffusivity values. Average effective moisture diffusivity varies between $4.79 \times 10^{-8}$ and $2.60 \times 10^{-7}$ $m^2/s$ increasing with increase in microwave power. The activation energy ($E_a$) was calculated using modified form of Arrhenius equation and found as 13.15 kW/kg. It was concluded and recommended on the basis of mentioned facts that black mulberry fruit dried by using microwave dryer were found a good food drying technique on the basics of physicochemical and sensory evaluation. In the next studies, the mulberry fruit will be dried by combining microwave and other drying methods and the effect of drying conditions on the components of mulberry fruit will be examined.

## Disclosure Statement

The authors declare that they have no conflict of interest.

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