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Research Article

STUDY OF DRYING CHARACTERISTICS AND ENERGY EFFICIENCY ON WHITE MULBERRY UNDER MICROWAVE OVEN

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ABSTRACT
Characteristics of thin layer microwave drying of white mulberry were evaluated in a laboratory scale microwave dryer. The drying experiments were carried out at 200, 300, 400 and 500 W. In this study, measured values were compared with predicted values obtained from Midilli's thin layer drying semi-empirical equation. Highest value of R^2 and the lowest values of χ^2 and RMSE for white mulberry samples at different powers are obtained as 0.9996, 0.00003 and 0.00593 respectively. Within the range of microwave power values, 200–500 W, effective moisture diffusivities were found to be 1.43×10^{-6} to 4.88×10^{-6} m^2/s. The microwave power dependence of the effective diffusivity coefficient followed an Arrhenius-type relationship. The activation energy for the moisture diffusion was determined to be 8.922 W/g. The highest energy efficiency was recorded for the samples dried at 500W and lowest at 200 W.

Keywords: *Microwave Drying, Energy Efficiency, Moisture Diffusivity, Activation Energy*

INTRODUCTION
Food drying is a most important process for preserving agricultural products since it has a great effect on the quality of the dried products. Most cereals, vegetables and fruits can be preserved after drying. The major objective in drying agricultural products is the reduction of the moisture content to a level, which allows safe storage over an extended period. Mulberry trees are extensively grown (e.g. Southern Europe, India) for their leaves as food and fruits. There are three kinds of mulberry: white mulberry (Morus alba L.), black mulberry (Morus nigra L.), and red mulberry (Morus rubra L.). White mulberry originated in Western Asia, red mulberry in North and South America, and black mulberry is from Southern Russia. The fruits of white mulberries are often harvested by spreading a sheet on the ground and shaking the limbs. They have a high level of moisture content at harvest. 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 pekmez, juices, paste, marmalade and wine production (Maskan *et al*., 1998). The drying time of the convective technique can be shortened by using higher temperatures which increase moisture diffusivity (Maroulis *et al*., 1995) and by cutting the material into small pieces (Madamba *et al*., 1996). Increased drying temperature entails higher costs and may cause biochemical changes that degrade the dried product quality; whereas subdividing the material is an additional process that results, especially under industrial conditions, in mass losses and lowering of the product quality (Watada *et al.*, 1996). The drying time can be greatly reduced (Sharma *et al*., 2004) and the quality of finished product insured (Yongsawatdigul *et al*., 1996) by applying the microwave energy to the dried material. Furthermore, commonly used hot air techniques are limited by high energy consumption, long drying times, low energy efficiency and high costs, which is not desirable for the food industry. Due to these difficulties, more rapid, safe and controllable drying methods are required. Also, it is necessary to dry the product with minimum cost, energy and time. In microwave drying, drying time is shortened due to quick absorption of energy by water molecules, causes rapid evaporation of water, resulting in high drying rates of the food. One of the most important aspects of drying technology is the modeling of the drying process. There are various studies at the research level about drying of vegetables. For example; Bakal *et al*., (2012) and Senadeera *et al*., (2003) reported that the page model best described the drying behavior of potato. As little research has been performed effect of microwave power on energy consumption and drying

efficiency in microwave drying method (McMinn *et al*., 2003), the present research is focused on this issue. The aim of this study was to (i) describe the influence of microwave output power on drying kinetics and energy efficiency, and (ii) compare the measured findings obtained during the drying of white mulberry with the predicted values obtained with Midilli's semi-empirical equation for the purpose of simulation and scaling up of the process.

MATERIALS AND METHODS

White mulberry samples were purchased from a local market, in Tehran, Iran, and were stored in the refrigerator at temperature of 4±1°C until the experiments were carried out. Samples were washed with tap water, and then samples with mean length of 10 mm were selected. The initial moisture content of the samples found about 78.5±1.5% (w.b.), and was determined by drying in an air convection oven at 103±1 °C till the weight did not change any more (Hatamipour *et al*., 2007). A domestic microwave oven (M945, Samsung Electronics Ins) with maximum output of 1000 W at 2450MHz was used for the drying experiments. The oven has a fan for air flow in drying chamber and cooling of magnetron. The moisture from drying chamber was removed with this fan by passing it through the openings on the right side of the oven wall to the outer atmosphere. The microwave dryer was operated by a control terminal which could control both microwave power level and emission time. Experiments were performed at four microwave powers of 200, 300, 400 and 500 W. The moisture losses of samples were recorded at 30s intervals during the drying process by a digital balance (GF-600, A & D, Japan) and an accuracy of ±0.01 g. For measuring the weight of the samples during experimentation without taking them out of the oven, the tray with sample was suspended on the balance with a nylon wire through a ventilation hole in the center of chamber ceiling. Drying was carried out until the final moisture content reaches to a level less than 4% (w.b.) (Krokida *et al*., 2003). All measurements were carried out in triplicate.
The moisture ratio (MR) was calculated using the following equation:

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

Where, MR is the moisture ratio (dimensionless); M_t, M_e and M_0 are the moisture content at any time, the equilibrium moisture content, the initial moisture content (kg [H2O]/kg dry mater), respectively. The values of M_e are relatively small compared to M_t and M_0, hence the error involved in the simplification by assuming that M_e is equal to zero is negligible. The Midilli's model is an empirical modification of the simple exponential model to overcome its shortcomings. It was successfully used to describe the drying characteristics of a variety of biological materials. Therefore, the semi-empirical Midilli's equation (Eq. (2)) was used to describe the thin layer drying kinetics of samples (Aghbashlo *et al*., 2009):

$$MR = \frac{M_t}{M_0} = a\exp(-kt^n) + bt \qquad (2)$$

Where, k is the drying constant (1/min); a and b are constant coefficients and n is the dimensionless exponent. Statistical test using the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were calculated to evaluate the goodness of fit of each model. The reduced χ^2 and RMSE were calculated according to the following equation (Zarein *et al*., 2013):

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N - z} \qquad (3)$$

$$RMSE = \left(\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}\right)^{0.5} \qquad (4)$$

Where, MR_{exp} is the experimental dimensionless moisture ratio, MR_{pre} is the predicted dimensionless moisture ratio by Midilli model, N is the number of experimental data points, and z is the number of

parameters in model. The model is said to be good if R^2 value is high and, χ^2 and RMSE values are low (Zarein *et al*., 2015).
Drying rate was defined as:

$$DR = \frac{X_{t+\Delta t} - X_t}{\Delta t} \quad (5)$$

where $M_{t+\Delta t}$ is moisture content at time t+Δt (kg [H2O]/kg dry mater), t is the time (min) and DR is the drying rate (kg [H2O]/kg dry mater.min). Fick's second law of diffusion equation, symbolized as a mass-diffusion equation for drying agricultural products in a falling rate period, is shown in the following equation:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \quad (6)$$

By using appropriate initial and boundary conditions, Crank (Crank, 1975) gave the analytical solutions for various geometries and the solution for slab object with constant diffusivity is given as:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{4L^2}\right) \quad (7)$$

Where, D_{eff} is the effective diffusivity (m^2/s), and L is the L is the half-thickness of samples (m), n is a positive integer.
For long drying times, only the first term (n= 0) in the series expansion of the above equation can give good estimate of the solution, which is expressed in logarithmic forms as follows:

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

The diffusion coefficients are typically determined by plotting experimental drying data in terms of ln (MR) versus drying time (t), because the plot gives a straight line with a slope as $\pi^2 D_{eff}/4L^2$ (Ozbek *et al*., 2007). In as much as temperature is not precisely measurable inside the microwave drier, the activation energy is found as modified from the revised Arrhenius equation. In this method it is assumed as related to effective moisture diffusion and the ratio of microwave output power to sample weight (m/p) instead of to air temperature. Then Equation (9) can be effectively used as follows (Soysal *et al*., 2006):

$$D_{eff} = D_0 \exp\left(-\frac{E_a m}{P}\right) \quad (9)$$

Where, E_a is the activation energy (W/g), m is the mass of raw sample (g), D_0 is the pre-exponential factor (m^2/s) and P is the microwave power (W).
The microwave drying efficiency was calculated as the ratio of heat energy utilized for evaporating water from the sample to the heat supplied by the dryer (Darvishi and Zarein, 2012).

$$\eta = \frac{m_w \times \lambda_w}{P \times t} \quad (10)$$

Where, η is the microwave-convective drying efficiency (%); P is the microwave power (W); m_w is the mass of evaporated water (kg), and λ_w is the latent heat of vaporization of water (2257 kJ/kg).

RESULTS AND DISCUSSION

The moisture content versus drying time curves for microwave drying of white mulberry samples as affected by various microwave powers are shown in Figure 1. The time required to dry white mulberry samples from initial moisture content of 78.5±1.5% (w.b.) to the final moisture content of 4±1% (w.b.) was 24.5, 14, 10.5 and 7 min at 200, 300, 400 and 500 W, respectively. Drying microwave power had an important effect on drying time.
The results indicated that mass transfer within the sample was more rapidly 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 characteristic microwave volumetric heating.

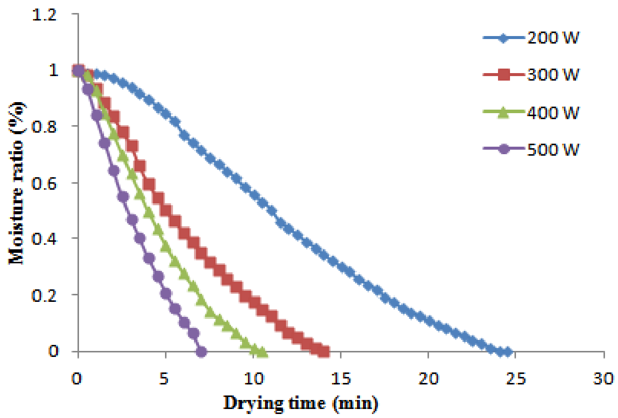

Figure 1: The Variation of the Moisture Content with Drying Time at Various Microwave Powers

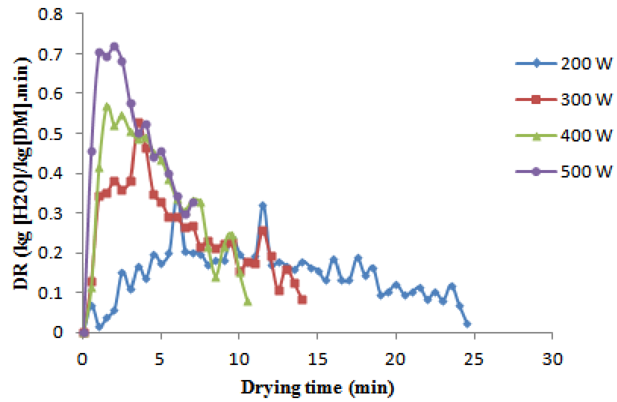

Figure 2: Variation of Drying Rate with Drying Time for White Mulberry

Figure 2 shows how the drying rate of white mulberry samples was changed with increased drying time under various drying conditions. The drying rates increased with the increasing microwave power levels. The maximum drying rates were approximately 0.342, 0.527, 0.568 and 0.719 kg [H2O]/kg dry mater min, when the microwave powers of 200, 300, 400 and 500W were applied, respectively. The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate.

The moisture content data obtained from the drying experiments was fitted to the Midilli model. The statistical results from the models such as R^2, χ^2 and RMSE values are shown in Table 1. As it is seen, the R^2, χ^2 and RMSE values range from 0.999 to 0.9996, 0.00003 to 0.00026 and 0.006714 to 0.01071, respectively.

Table 1: Results of Statistical Analysis on the Modeling (Midilli's Model) of Moisture Content and Drying Time for White Mulberry Samples

P (W)	Model Constants		R^2	χ^2	RMSE
200	a= 1.01	b= -0.003831	0.9996	0.00004	0.006714
	k=0.01101	n=1.682			
300	a= 1.017	b= -0.008218	0.999	0.00010	0.01071
	k=0.0808	n=1.244			
400	a=1.012	b=-0.0078	0.9977	0.00003	0.00593
	k=0.09	n=1.421			
500	a=1.007	b=-0.02494	0.9996	0.00026	0.00774
	k=0.1567	n=1.217			

The highest values of R^2 and the lowest values of χ^2 and RMSE indicate in the Midilli model a good fit. Based on the multiple regression analysis, the Midilli model, the constants and coefficients were as follows:

$$k = 0.0035\exp(0.0081P) \qquad R^2 = 0.805$$
$$n = 2.4608 - 0.0053P + 6 \times 10^{-6}P^2 \qquad R^2 = 0.64$$
$$a = 0.9834 + 0.0002P - 3 \times 10^{-7}P^2 \qquad R^2 = 0.864$$
$$b = -0.0242 + 0.0002P - 3 \times 10^{-7}P^2 \qquad R^2 = 0.905$$

Plots of calculated versus experimental dimensionless moisture content are shown in Figure 3. As can be observed in this figure, good agreement between the former variables is observed.

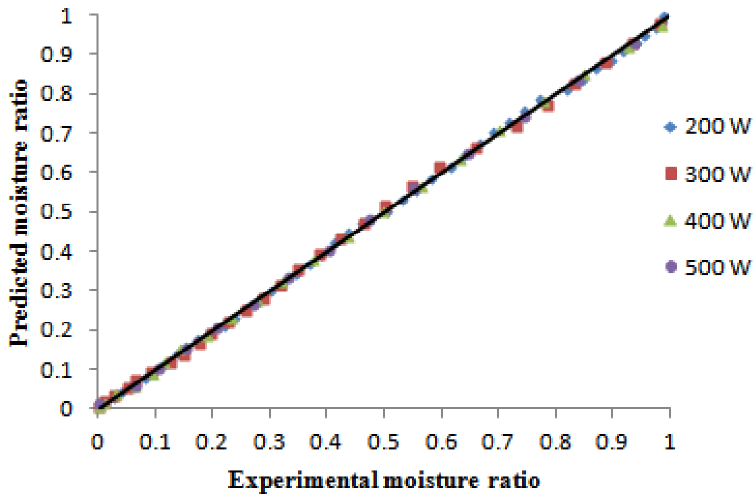

Figure 3: Comparison of Experimental and Calculated Dimensionless Moisture Content Values by the Midilli's Model

The determined values of D_{eff} for different microwave powers are given in Table 2. The values lie within the general range of 10^{-6}–10^{-11} m^2/s for food materials. It can be seen that the values of D_{eff} increased with increasing microwave power. This might be explained by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power.

Table 2: Effective Diffusivity Values for Microwave Drying of White Mulberry

P(W)	Effective Diffusivity $\times 10^{-6}$ (m^2/s)
200	1.43
300	2.62
400	3.71
500	4.88

The activation energy was calculated by plotting the natural logarithm of D_{eff} versus sample amount/power (m/P) as presented in Figure 4. The plot was found to be a straight line in the range of microwave power studied, indicating Arrhenius dependence. Then, the dependence of the effective diffusivity of white mulberry samples on the microwave power can be represented by the following equation:

$$D_{eff} = 1 \times 10^{-5} \exp\left(-8.922 \frac{m}{P}\right) \quad (11)$$

The activation energy for white mulberry samples was found to be 8.922 W/g.

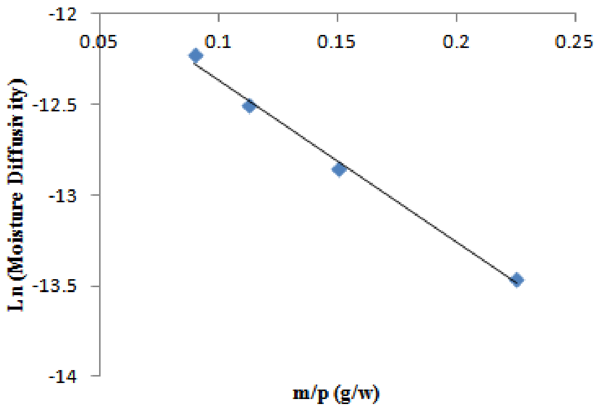

Figure 4: Arrhenius-Type Relationship the Values of Ln (D_{eff}) Versus Sample Amount/Power

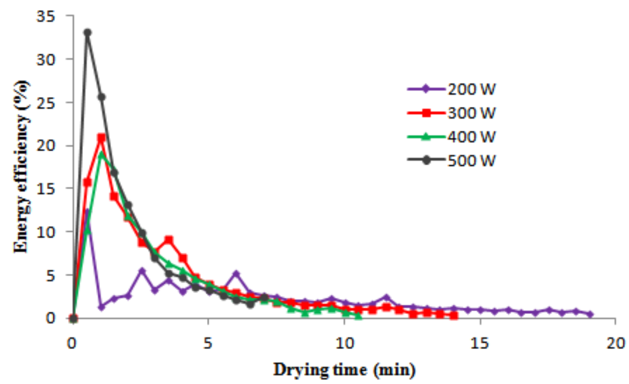

Figure 5: Energy Efficiency Versus Drying Time for Microwave Drying of White Mulberry Samples

Figure 5 shows the variation of energy efficiency whit drying time for microwave drying of white mulberry samples. The energy efficiency was very high during the initial phase of the drying which resulted in a higher absorption of microwave power. Following moisture reduction, the energy absorbed by the product decreased and reflected power increased. The best result with regard to energy efficiency was obtained from 500W microwave power levels among all microwave power. Average energy efficiency of white mulberry samples ranged from 32 to 53% for the output microwave power.

Conclusion

Characteristics of the microwave drying of white mulberry (with mean length samples of 10 mm) were determined. Microwave drying period of samples lasted between 24.5 and 7 min at the microwave powers at 200 and 500 W, respectively. The changes of moisture content have been described by using Midilli's model. We concluded that 500 W is the optimum microwave power level in the microwave drying of white mulberry with respect to drying time and energy efficiency. The values of effective diffusivity for microwave drying of white mulberry ranged from 1.43×10^{-6} to 4.88×10^{-6} m^2/s and activation energy was found 8.922 W/g. Energy efficiency increases with the increase of microwave drying power and moisture content.

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