THE EFFECT OF MICROWAVE OUTPUT POWER ON DRYING KINETICS OF YOGHURT AND MATHEMATICAL MODELING OF DRYING CURVES

A.N. YÜKSEL

Alanya HEP University, Faculty of Art and Design, Department of Gastronomy and Culinary Arts, 07400, Antalya Turkey. Email: yukselaysenur88@gmail.com

***Abstract*— The objectives of this study were to investigate the effects of microwave output powers on drying kinetics of yoghurt, selecting the best fitted thin-layer model to characterize the drying behavior of yoghurt and determination of the activation energy and effective diffusivity. In order to achieve these objectives, low-fat yoghurt was dried by using domestic microwave oven at different microwave output powers (100, 180 and 300 W). The average drying rates were determined as 1.49, 4.43 and 7.90 g H_2O m^{-2} s^{-1} for microwave output powers of 100, 180 and 300 W, respectively. The effective moisture diffusivities were determined as 3.30 x 10^{-9}, 6.62 x 10^{-9} and 1.15 x 10^{-8} m^2 s^{-1} for 100, 180 and 300 W, respectively. The Ea of yoghurt was found as 3.62 W g-1. Midilli and others model was selected as best fitted model due to the highest values of R^2 and low values of χ^2, RMSE and RSS.**

***Keywords*— yoghurt, microwave drying, modeling, activation energy, effective moisture diffusivity.**

I. INTRODUCTION

Yoghurt is a fermented dairy product which is produced by lactic acid fermentation of milk. It is very rich in nutrients like, proteins, B vitamins, folate, niacin, magnesium and zinc. Besides, proteins contain essential amino acids for human health (Mckinley, 2005). Yoghurt has many varieties in terms of texture (e.g. set, liquid, strained), fat contents (e.g. whole-fat, low-fat) and flavor (e.g. fruit, natural). It can be consumed as a part of meal or a snack. However, yoghurt has short shelf-life (1 day at 25 °C and 5 days at 7°C) (Kumar and Mishra, 2004) because of its high moisture content and nutrients which is an optimum environment for microbiological growth. Therefore, to remove excess of water content by sun-drying or straining is used to prolong the shelf-life of yoghurt (Hayaloglu *et al*., 2007).

The most common drying methods for foods are sun-drying and hot-air drying (e.g. tray or tunnel drying). However, there are disadvantages such as longer drying times and inability to handle larger amounts which will increase the cost of processes. These disadvantages are not desirable for food industry. On the other hand, microwave drying is an alternative method with uniform energy distribution and shorter drying times (Dadali *et al*., 2007a) .

Different drying methods were applied to yoghurt such as freeze, spray, hot-air and microwave-vacuum and foam-mat (Koc *et al*., 2014, Malik and Sharma, 2019, Hayaloglu *et al*., 2007, Balkir *et al*., 2011, Bielecka and Majkowska, 2000, Kumar and Mishra, 2004, Lao *et al*., 2019, Kim and Bhowmik, 1994). In the study of Hayaloglu *et al*. (2007), strained yoghurt was dried with tray dryer at 40, 45 and 50°C with various air velocities. The drying curves were fitted in nine different drying models and also effective moisture diffusivity and activation energy were determined. As a result, Midilli and others model was found as best fitted model and also, they concluded that increase in temperature resulted an increase in diffusivity values. In another study, the effective moisture diffusivities of microwave-vacuum drying of yoghurt determined by the methods of regular regime and the slopes of the drying curves were compared by Kim and Bhowmik (1995). Preconcentrated yoghurt was dried at temperatures between 30-50 °C, 250 W and 10 mm Hg. They concluded that the method of slopes of drying curve was useful for estimation of effective moisture diffusivity of yoghurt.

However, no studies were found about investigation of microwave output power on drying kinetics of yoghurt. Therefore, in this study, it was aimed to determine the effect of microwave output power on drying behavior of yoghurt, to calculate the effective moisture diffusivity and the activation energy of yoghurt and to select a best model for characterization of microwave drying of yoghurt.

II. METHODS

A. Microwave drying of yoghurt

Yoghurt with low-fat was purchased from a local market in Antalya, Turkey. The drying process were performed by domestic microwave oven (GW73E, Samsung, South Korea) at microwave output powers of 100, 180 and 300W. The total amount of yoghurt was 50.00±0.20 g for each drying experiment. Yoghurt samples were placed as a slab with 5 mm of thickness. The plate was placed at the center of the microwave tray; thus, homogenous distribution of waves was provided during drying process. The samples were removed from microwave oven in every 30 seconds and weighed. Drying were completed when the moisture contents of yoghurt samples were below 10 % (wet basis, w.b.).

B. Drying kinetics of microwave drying of yoghurt

Drying rate ($\boldsymbol{R}$) of yoghurt was determined by using Eq. (1), where $\boldsymbol{R}$ is the drying rate (g H_2O m^{-2} s^{-1}); $\boldsymbol{G}$ is the

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weight of dry solid (g); $\boldsymbol{A}$ is the drying area (m^2); $\boldsymbol{X_t}$ is the moisture content at specific time (g g^{-1} dry solid) and $\boldsymbol{t}$ is time (s).

$$R=-\frac{G}{A}\times\left(\frac{X_{t+1}-X_t}{t_{t+1}-t_t}\right) \quad (1)$$

C. Modelling of thin-layer drying curves

Firstly, moisture ratio (MR) was calculated by using Eq. (2), where X_t is the moisture content at chosen time of drying, X_0 is the initial moisture content and X_e is the equilibrium moisture content (g H_2O g^{-1} dry solid (DS)).

$$MR=\frac{X_t-X_e}{X_0-X_e} \quad (2)$$

Then, MR values of microwave drying data at 100, 180 and 300W were fitted three thin-layer models using non-linear least squares regression analysis by using Sigma Plot software (Erkrath, Germany) as Midilli and others (Midilli *et al.*, 2002), Wang and Singh (Wang and Singh, 1978) and Page (Madamba *et al.*, 1996) (Table 1).

D. Correlation coefficients and error analysis

The goodness of fit of presented models to experimental drying data was evaluated by using the correlation coefficient (R^2), the reduced chi-square (χ^2), root mean square error ($RMSE$) (Wang *et al.*, 2007) and residual sum of squares (RSS) (McMinn, 2006). RSS, $RMSE$ and χ^2 can be determined by using Eqs. (3), (4) and (5), respectively; where $MR_{exp,i}$ is the experimental moisture ratio; $MR_{pre,i}$ is the predicted moisture ratio; N is the number of experimental data points and n_p is the number of parameters in model.

$$RSS=\sum_{i=1}^{N}(MR_{exp,\,i}-MR_{pred,i})^2 \quad (3)$$

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,\,i}-MR_{pred,i})^2} \quad (4)$$

$$\chi^2=\frac{\sum_{i=1}^{N}(MR_{exp,i}-MR_{pred,i})^2}{N-n_p} \quad (5)$$

E. Calculation of effective moisture diffusivities

It was reported that drying behavior of biological products can be described by Fick's diffusion equation if the drying occurs in falling rate period (Wang *et al.*, 2007). Simplified version (first term of the diffusion series) can be used for long drying periods and slab geometry in one dimension could Eq. (6), where $\boldsymbol{D_{eff}}$ is the diffusion coefficient (m^2 s^{-1}); $\boldsymbol{t}$ is the drying time (s) and $\boldsymbol{L}$ is the half thickness of sample (m). Assuming that there are constant diffusivity and uniform moisture distribution, and volume change (shrinkage) is negligible (Crank, 1975).

$$\boldsymbol{MR}=\frac{\mathbf{8}}{\boldsymbol{\pi}}\boldsymbol{exp}\left(\frac{-\boldsymbol{D_{eff}\pi^2 t}}{\boldsymbol{4L^2}}\right) \quad (6)$$

F. Estimation of activation energy

The relation between the effective diffusivity and activation energy with the ratio of the microwave output power to sample amount was represented with an Arrhenius type exponential model by (Dadali *et al.*, 2007b). Where P is microwave output power (W) and m is the mass of raw sample (g) (Eq. 7).

$$D_{eff}=D_0\exp\left(-\frac{Ea\,m}{P}\right) \quad (7)$$

Table 1. Thin-layer drying models

Model Name	Model	Reference
Page	$MR=\exp(-k\cdot t^n)$	(Madamba *et al.*, 1996)
Midilli and others	$MR=a\exp(-k\cdot t^n)+bt$	(Midilli *et al.*, 2002)
Wang and Singh	$MR=1+a\cdot t+b\cdot t^2$	(Wang and Singh, 1978)

k is the drying constant, a, b and n are the parameters.

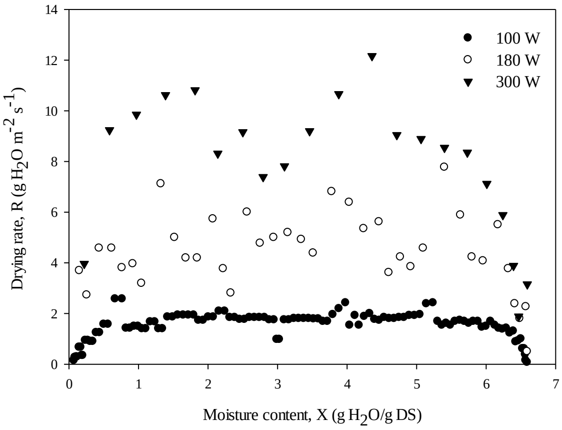

Fig. 1. Drying rates of yoghurt at different microwave output powers.

III. RESULTS

A. Drying kinetics of yoghurt

The initial moisture content of yoghurt was 6.59 dry basis (d. b.) (g H_2O/g DS) and it was dried to 0.04 (d. b.) (g H_2O/g DS) by using three different levels of microwave output powers. Drying was completed when the moisture content of yoghurt was below 10 % (w.b), which is a safe level for dried products to avoid from microbiological spoilage (Tze *et al.*, 2012). The average drying rates were determined as 1.49, 4.43 and 7.90 g H_2O m^{-2} s^{-1} for microwave output powers of 100, 180 and 300 W, respectively. Increase in output power caused an increase in drying rate. Drying rate was almost 3 times higher for increasing power from 100 to 180 W, where almost 2 times higher for increasing power from 180 to 300 W. Similar effects can be seen for drying times. Drying time decreased 66.67 % with increasing microwave power from 100 to 180 W and 81.98 % from 100 to 300 W. Wang *et al.* (2007) observed the similar behavior for drying of fresh and pre-treated apple pomace by using microwave. The speeding of drying process can occur because of the penetration of microwave energy into the sample and creation of vapor pressure difference between the center and the surface of the sample (Chayjan *et al.*, 2015). Drying rates of yoghurt at different microwave output powers are illustrated in Fig. 1. It can be stated that during microwave drying of yoghurt, three periods were observed: warming-up, constant rate and falling rate periods. Similar observations were reported by Bal *et al.* (2010) for microwave drying of bamboo shoot slices and McMinn (2006) for microwave drying of lactose powder. In addition, in the study of Soysal (2004), after warming-up pe riod, a long constant rate and then falling rate period were

Table 2. Effective moisture diffusivities and activation energy of microwave dried yoghurt.

Microwave Output Power	Effective Diffusivity($m^2\ s^{-1}$)	Activation Energy (E_a)
100 W	3.30×10^{-9}	
180 W	6.62×10^{-9}	3.62 W g^{-1}
300 W	1.15×10^{-8}	

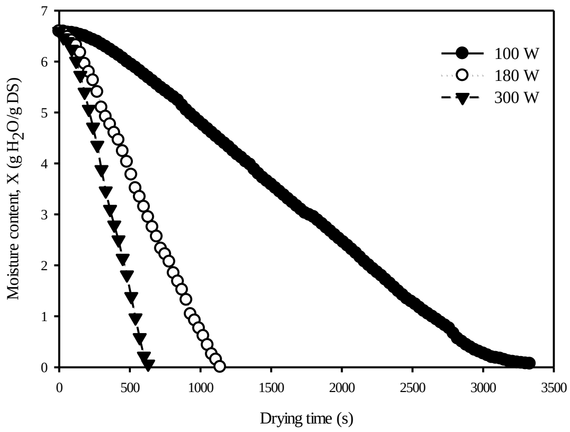

Fig. 2. Variation of moisture content with drying time during drying of yoghurt at different microwave output powers.

observed for microwave drying of parsley. Besides, it can be seen also in Fig. 2. that the drying curves were getting steeper, this behavior indicated increase in drying rate (Bal *et al*., 2010, Yüksel *et al*., 2018).

B. Effective moisture diffusivity and activation energy of yoghurt

In literature, no documentation was found about the investigation of the effective moisture diffusivity for microwave dried yoghurt. The effective moisture diffusivities of yoghurt were determined as 3.30×10^{-9}, 6.62×10^{-9} and 1.15×10^{-8} $m^2\ s^{-1}$ for 100, 180 and 300 W, respectively (Table 2). Increase in microwave output power resulted in increase in effective moisture diffusivity. Similar to these values, Omolola *et al*. (2014) determined the effective moisture diffusivities 4.89×10^{-10}, 1.09×10^{-10} and 1.69×10^{-9} $m^2\ s^{-1}$ at 100, 200 and 300 W for banana, respectively. In addition, for air dried strained yoghurt at 40, 45 and 50 °C, the effective diffusivities were observed in range of 9.5×10^{-10} - 1.3×10^{-9} $m^2\ s^{-1}$ (Hayaloglu *et al*., 2007). The values were in general range of 10^{-12} and 10^{-8} for food materials. Similar effective diffusivity values were reported for microwave drying of hawthorn fruit (Chayjan *et al*., 2015), spinach (Dadali *et al*., 2007a), purslane (Demirhan and Ozbek, 2010) and garlic (Ilter *et al*., 2018).

Activation energy of microwave drying of yoghurt was estimated by modification of Arrhenius equation. In this study, the activation energy (Ea) of yoghurt was found as 3.62 W g^{-1} (Table 2). In general, high values of Ea associated with the materials contain more bounded water and the removal of this water occurs from the structure of the product. On the other hand, yoghurt has high amount of free moisture and during the falling rate period this water was removed, thus low energy was required

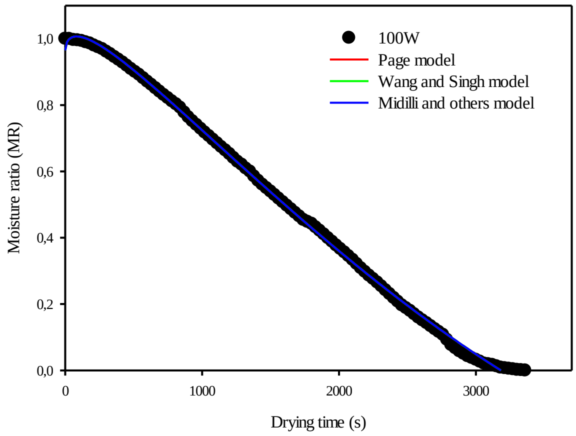

Fig. 3. Drying curves of yoghurt with the all fitted models dried at 100 W.

(Chayjan *et al*., 2015). Different results were observed for microwave dried okra (5.54 Wg^{-1}) (Dadali *et al*., 2007b), spinach (9.62 W g^{-1}) (Dadali *et al*., 2007a) and purslane (7.53 W g^{-1}) (Demirhan and Ozbek, 2010).

C. Model application

Three thin-layer drying models were fitted to experimental drying data of yoghurt. The best fitted model was determined according to four criteria: higher value of correlation coefficient and lower values of the reduced chi-square, the root mean square error and residual sum of squares. Model parameters were given in Table 3. For all applied methods and all microwave output powers, higher R^2 values were obtained (>0.99). However, the lowest values of $RMSE$, RSS and χ^2 were observed for Midilli and other model, while the highest R^2 values (0.999) were observed (Table 4). Chayjan *et al*. (2015) and Demirhan and Ozbek (2010) also determined Midilli and others model as the best fitted for microwave drying of hawthorn fruit and purslane, respectively. Moreover, Hayaloglu *et al*. (2007) observed Midilli and others model was best suited to describe the air drying behavior of strained yoghurt.

Moisture ratio against time for microwave drying of yoghurt, comparing experimental data with predicted thin layer models are given in Figs. 3-5. Validation of the best fitted model was made comparing the predicted and experimental values of moisture ratios in all the drying runs. The equations of $y = 0.0004 + 0.9991x$ (R^2=0.9991), $y = 0.0003 + 0.9994x$ (R^2=0.9995) and $y = 0.0007 + 0.9988x$ (R^2=0.9990) were determined from the straight line obtained with linear regression analysis for 100, 180 and 300 W, respectively. It was observed that accuracy of fitting the drying data into this model is very good for all the experimental microwave output powers.

IV. CONCLUSIONS

Microwave drying of yoghurt was carried out at 100, 180 and 300 W and drying behavior of yoghurt was investigated. Increase in microwave output power increased the drying rate, while decreased the drying time. It can be

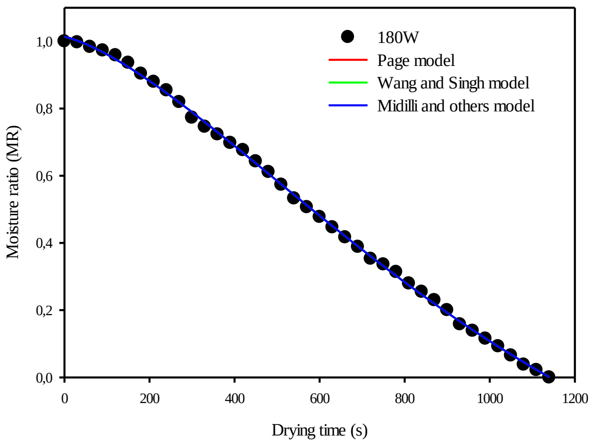

Fig. 4. Drying curves of yoghurt with the all fitted models dried at 180 W.

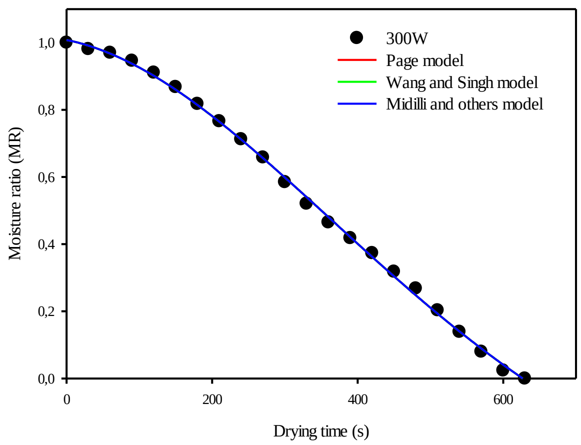

Fig. 5. Drying curves of yoghurt with the all fitted models dried at 300 W.

Table 3. Model parameters and statistical results

Drying model	Microwave output power (W)	*k*	*n*	*a*	*b*
Page	100	3.9670×10^{-7}	1.9528	-	-
	180	4.1262×10^{-6}	1.8982	-	-
	300	2.1613×10^{-6}	2.1749	-	-
Midilli and others	100	2.6750×10^{-6}	1.6466	1.0068	-6.4574×10^{-5}
	180	2.1761×10^{-5}	1.5676	1.0135	-2.3020×10^{-4}
	300	6.3363×10^{-6}	1.9047	1.0079	-4.1789×10^{-4}
Wang and Singh	100	-	-	-2.8363×10^{-4}	-1.2066×10^{-8}
	180	-	-	-7.5417×10^{-4}	-1.3929×10^{-7}
	300	-	-	-1.0017×10^{-3}	-1.0633×10^{-6}

Table 4. Statistical results of models.

Drying model	Microwave output power (W)	R^2	χ^2	*RMSE*	*RSS*
Page	100	0.992	0.0021	0.0453	0.0984
	180	0.993	0.0012	0.0327	0.0268
	300	0.992	0.0016	0.0371	0.0193
Midilli and others	100	**0.999**	0.0002	0.0150	0.0108
	180	**0.999**	0.0001	0.0092	0.0021
	300	**0.999**	0.0002	0.0134	0.0025
Wang and Singh	100	0.991	0.0023	0.0470	0.1058
	180	0.994	0.0011	0.0315	0.0248
	300	0.993	0.0014	0.0342	0.0164

stated that microwave oven can be used to dry food products including yoghurt in short times with high drying rates.

Effective moisture diffusivity values of microwave dried yoghurt were determined which were found in general range of food materials and the effective diffusivity values were between 3.30×10^{-9} and 1.15×10^{-8} m^2 s^{-1}. On the other hand, the activation energy was estimated relatively lower (3.62 W g^{-1}) than the values obtained in the literature, however, it can be due to the low amount of bounded water in low-fat yoghurt.

Mathematical modeling was also made by using three thin-layer drying models and the best fitted model to experimental data was evaluated with the high level of R^2, low level of RMSE, RSS and $\chi 2$. According to these values, Midilli and others model provided a good agreement between experimental and predicted moisture ratio values.

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