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Keywords: microwave power, energy efficiency, moisture diffusivity, activation energy, banana samples.

I. Introduction

Banana is one of the most prevalently consumed fruits and is amply available in tropical countries. Banana is an excellent source of potassium. it can help cure an upset stomach by stimulating the production of mucus and cells in the stomach, thus creating a barrier between the stomach lining and the acids that cause upset stomachs and heartburn. Banana has antibiotic properties to help fight off infections and viruses [1]. The qualities of fresh banana deteriorate rapidly after harvesting [2-4]. Considerable amounts of this fruit is wasted due to the lack of efficient preservation methods that are unique to banana. One of the oldest methods of food preservation is drying [2]. The basic objective in drying food products is the removal of water from solids to a certain level at which microbial decadence is avoided. The major motives of dried food popularity are Longer shelf life and significant reduction in the volume of the product. Characteristics of conventional drying is: prolonged drying time, hot temperature, rapid drying and low energy efficiency which each one have Some disadvantages. Conventional drying may reduce the capacity of dried product , damage the **flavour, colour and nutrients,** vapourise volatile compounds, cause case-hardening and have low energy efficiency [5].Therefore, there has been a search for an alternative method of drying for years. MD (Microwave Drying) seems to be a suitable method to reduce the disadvantages. A number of studies have been conducted to improve microwave drying [6-10]. Microwave drying is caused by water vapour pressure differences between interior and surface regions, which provide a driving force for moisture transfer. Microwave drying results in a high thermal efficiency, no case hardening, shorter drying time, reduced costs and improved product quality compared to conventional hot air drying [11]. However, microwave drying will reduce the product's quality if not properly applied [12]. Researchers have shown that applying the energy in decreasing rate or at low moisture content for finish drying results in a higher quality of product [13]. Medeni investigated banana samples drying using convection (60°C at 1.45 m/s), microwave (350, 490 and 700 W power) and convection followed by microwave (at 350 W, 4.3 mm thick sample) finish drying. The drying of banana slices took place in the falling rate drying period with convection drying taking the longest time. Higher drying rates were observed with the higher power level. Microwave finish drying reduced the convection drying time by about 64.3%. A physical model was employed to fit the experimental data and gave good fit for all experimental runs except microwave finish data. Microwave finish dried banana was lighter in colour and had the highest rehydration value [14]. Although the textural property improved at high temperature, the product color was brown as manifested by the low L- and hue values in particular at the drying temperature of 100 °C [12].

The drying time of the convective technique can be shortened by using higher temperatures which increase moisture diffusivity [15] and by cutting the material into small pieces [16]. The drying time can be greatly reduced [17] and the quality of finished product insured [18] by applying the microwave energy to the dried material. Furthermore, commonly used hot air techniques are limited by high energy consumption,

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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. [19] and Senadeera et al. [20] reported that the Page model best described the drying behaviour of potato. As little research has been performed effect of microwave power on energy consumption and drying efficiency in microwave drying method [21], 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 banana samples with the predicted values obtained with Midilli's semi-empirical equation for the purpose of simulation and scaling up of the process.

II. Materials and Methods

Banana 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 prepared as cubic shape with dimension of 30×30×30 mm. The initial moisture content of the samples found about 77.9±1% (w.b.) and was determined by drying in an air convection oven at 103±1 °C till the weight did not change any more [22]. A domestic microwave oven (M 945, Samsung Electronics Ins) with maximum output of 1000 W at 2450 MHz 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 1% (w.b.) [23]. All measurements were carried out in triplicate. The moisture ratio (MR) was calculated using the following equation:

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

where, MR is the moisture ratio (dimensionless); M_t, Me and M_0 are the moisture content at any time, the equilibrium moisture content, the initial moisture content (kg [H_2O]/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 Me 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 [24]:

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

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 statistical parameters were calculated using equations [25]:

$$\mathrm{R^2} = 1 - \frac{\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \overline{\mathrm{MR}}_{\mathrm{exp,i}}\right)^2} \qquad (3)$$

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

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\mathrm{N}}\right)^{\frac{1}{2}} \qquad (5)$$

where MR_{exp} is the experimental dimensionless moisture ratio, MR_{pre} is the predicted dimensionless moisture ratio by Page 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 [26].

Drying rate was defined as:

$$\mathrm{DR} = \frac{\mathrm{M_{t+\Delta t}} - \mathrm{M_t}}{\Delta \mathrm{t}} \qquad (6)$$

where $M_{t+\Delta t}$ is moisture content at time t+Δt (kg [H_2O]/kg dry mater), t is the time (min) and DR is the drying rate (kg [H_2O]/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:

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2} \quad (7)$$

By using appropriate initial and boundary conditions, Crank [27] gave the analytical solutions for various geometries and the solution for slab object with constant diffusivity is given as:

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

where D_{eff} is the effective diffusivity (m^2/s), and 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:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2} D_{eff}\, t\right) \quad (9)$$

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 $\pi^2 D_{eff}/4L^2$ [28].

Inasmuch as temperature is not precisely measurable inside the microwave drier, the activation energy is found as modified from the revised Arehnious 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 (10) can be effectively used as follows [29]:

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

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 utilised for evaporating water from the sample to the heat supplied by the dryer [30].

$$\eta = \frac{m_w \times \lambda_w}{P \times t} \quad (11)$$

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 vaporisation of water (2257 kJ/kg).

III. Results and Discussion

The moisture content versus drying time curves for microwave drying of banana samples as affected by various microwave powers are shown in Fig. 1. The time required to dry banana samples from initial moisture content of 77.9±1% (w.b.) to the final moisture content of 4±1% (w.b.) was 29.5, 13, 8.5 and 6 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.

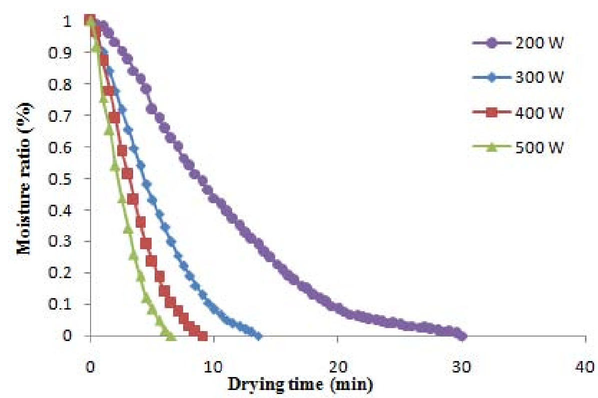

Figure 1 : The variation of the moisture content with drying time at various microwave powers

Fig. 2 shows how the drying rate of banana 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 0.243, 0.441, 0.739 and 1.134 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.

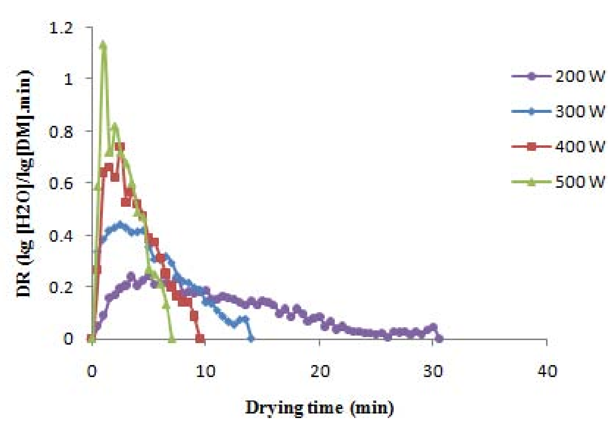

Figure 2 : Variation of drying rate with drying time for banana samples

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 0.9991 to 0.9999, 1.6618×10^{-5} to 9.9983×10^{-5} and 0.0043 to 0.0102, respectively. 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:

$$k = 0.032\exp(0.003P) \qquad R^2 = 0.944$$

$$n = 0.992 + 0.001P - 2\times10^{-6}P^2 \qquad R^2 = 0.988$$

$$a = 0.973 + 7\times10^{-5}P - 1\times10^{-8}P^2 \qquad R^2 = 0.862$$

$$b = -0.011 + 6\times10^{-5}P - 1\times10^{-7}P^2 \qquad R^2 = 0.972$$

Table 1 : Results of statistical analysis on the modeling (Midilli's model) of moisture content and drying time for banana samples

Table 1- Results of statistical analysis on the modeling (Midilli's model) of moisture content and drying time for banana samples

P (W)	Model Constants		R^2	$\chi^2\times10^{-5}$	RMSE
200	a= 0.9893	b= -0.00294	0.9991	9.9983	0.0101
	k= 0.0764	n= 1.282			
300	a= 0.9909	b= -0.00377	0.9998	2.0442	0.0047
	k= 0.0890	n= 1.36			
400	a= 1.005	b= -0.00488	0.9999	1.6618	0.0043
	k= 0.1349	n= 1.435			
500	a= 1.006	b= -0.01082	0.9993	8.5333	0.0102
	k= 0.2361	n= 1.443			

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

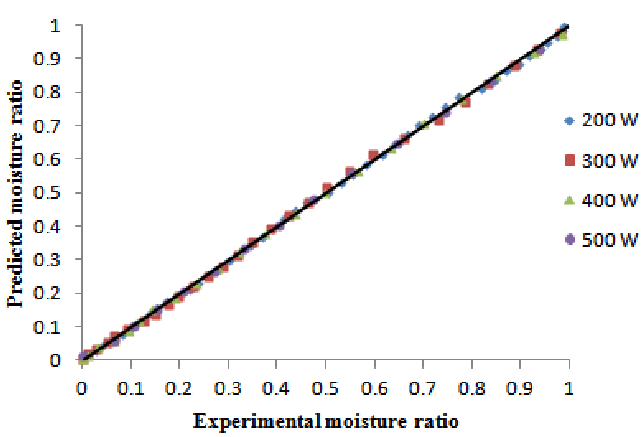

Figure 3: Comparison of experimental and calculated dimensionless moisture content values by the Midilli's model

The determined values of Deff 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 Deff 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 potato

P(W)	Effective diffusivity (m^2/min)
200	1.4×10^{-5}
300	2.86×10^{-5}
400	4.18×10^{-5}
500	5.52×10^{-5}

The activation energy was calculated by plotting the natural logarithm of Deff versus sample amount/power (m/P) as presented in Fig. 4. The plot was found to be a straight line in the range of microwave power studied, indicating Arrhenius dependence as Fig. 5. Then, the dependence of the effective diffusivity of banana samples on the microwave power can be represented by the following equation:

$$D_{eff} = 13.2\times10^{-5}\exp\left(-11.2\frac{m}{P}\right) \qquad (12)$$

The activation energy for banana samples was found to be 11.2 W/g.

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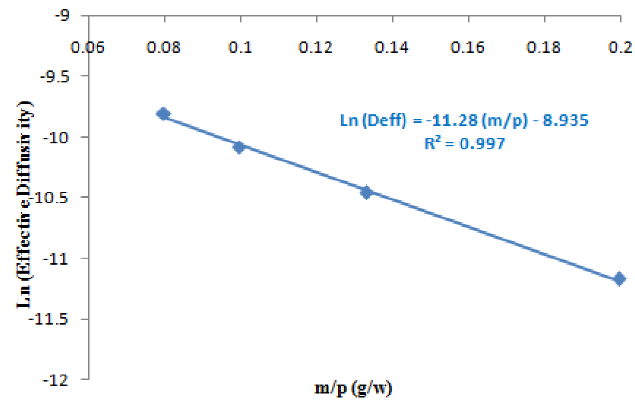

Figure 4 : Arrhenius-type relationship the values of $Ln(D_{eff})$ versus sample amount/power

Fig. 6 shows the variation of energy efficiency whit drying time for microwave drying of banana 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 banana samples ranged from 8.8 to 39% for the output microwave power.

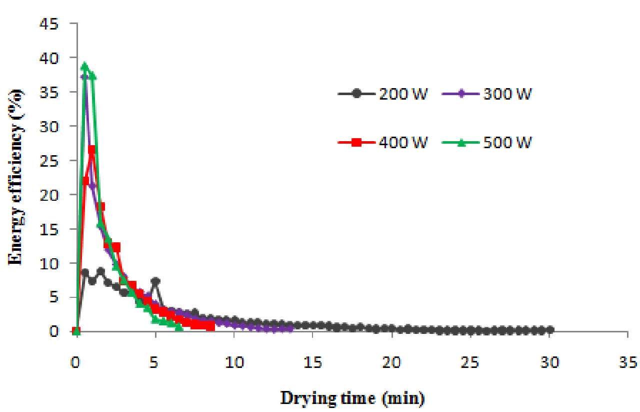

Figure 5 : Energy efficiency versus drying time for microwave drying of potato samples

IV. Conclusion

Characteristics of the microwave drying of banana samples (with dimension of 30×30×30 mm) were determined. Microwave drying period of samples lasted between 29.5 and 6 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 banana samples with respect to drying time and energy efficiency. The values of effective diffusivity for microwave drying of banana samples ranged from 1.4×10^{-5} to 5.52×10^{-5} m^2/min and activation energy was found 11.2 W/g. Energy efficiency increases with the increase of microwave drying power and moisture content.

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