



Microwave and Infrared Drying Characteristics of Mango Slices

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Abstract

In this study, mango slices were dried with using both microwave and infrared methods. The microwave and infrared power levels are determined between 90 – 800W and 75 – 104 W, respectively. The results of this study show that microwave and infrared power levels have an effect on drying kinetics. Five thin-layer drying models that were widely used in the literature were applied to the experimental data and the effective moisture diffusivity, activation energy and energy consumptions are also calculated. Midilli & Kucuk model was the best fits of experimental data for both microwave and infrared drying. The effective moisture diffusivity values were determined to be between 2.28×10^{-9} and 4.66×10^{-8} m²/s, and 5.07×10^{-10} - 1.27×10^{-9} m²/s for microwave and infrared drying, respectively. The values of activation energy for microwave and infrared drying were found as 39.135 and 4.482 kW/kg, respectively.

Keywords — Drying, Effective Moisture Diffusivity, Infrared, Mango, Microwave.

1 Introduction

Mango is a type of a cultivated fruit, which belong to the *genus Mangifera*, consisting of numerous tropical fruiting trees. The main family of the mango is *Anacardiaceae* and the native of this fruit is belongs to South Asia [1]. World production of mangoes in 2013 was 42.66 million tons. Five largest producers in the World were India, China, Thailand, Indonesia and Mexico with the productions of 18.00, 4.45, 3.14, 2.06 and 1.90 million tons, respectively [2]. The energy value per 100 g mango is 250 kJ (60 kCal), and contains significant amounts of the daily values of vitamin C and folate. Also mango contains vitamin A, thiamine (B1), riboflavin (B2), niacin (B3), pantothenic acid (B5), vitamin B6, folate (B9), vitamin E, vitamin K, calcium, iron, magnesium, manganese, phosphorus, and potassium [3]. In spite of its excellence, the perishable nature of this fruit and its short harvest season severely limit its utilization. Drying may be an interesting method in order to prevent fresh fruit deterioration [4].

Moisture content in the food products lead to decay and spoil due to its microbiological activity. For long term preservation, several drying processes are used in the literature. With some disadvantages such as lower energy efficiency and long drying times the simplest method is the hot-air drying method [5-7]. A new efficient method,

which is microwave drying method, has been in interest among the researchers for the last two decades. This new method is used due to rapid absorption of heat by water inside the food product that causes rapid removal of water molecules, which leads to the decrease in the drying time and energy. In literature with the method of microwave, several vegetables and fruits are studied by the researchers. Carrot [7], garlic [8], green pea [9], mushroom [10], potato [11], apple [12], blueberry [13], cranberry [14], mango [15], eggplant [16] and mussel [17] are some examples that were studied in the literature by using microwave methods.

Infrared drying has gained popularity as other an alternative drying method for a variety of agricultural products. When infrared radiation is used to warm up or dry moist materials, it penetrates the material where the energy of radiation converts into heat. The infrared radiation technology for drying foods could reduce the drying time, maintain a uniform temperature in the product and provide a better quality for the finished products [18]. This drying method is particularly suitable for thin layers of material with large surface exposed to radiation. By using the infrared method; green beans [6], apples [18], strawberry [19], potato [20], sweet potato [21], and red pepper [22] were studied.



Drying is a complicated process involving simultaneous, coupled mass and heat transfer, particularly under transient conditions [23]. From an engineering point of view, it is important to develop a better understanding of the controlling parameters of this complex process. Mathematical models of the drying processes are used for designing new or improving existing drying systems or even for the control of the drying process. Many mathematical models have proposed to describe the drying process, of them thin-layer drying models have been widely in use. These models can be categorized as theoretical, semi-theoretical, and empirical. The drying characteristics and kinetics of mango slices have been studied by some investigators [4,15,24].

From the studies in the literature it is seen that the microwave and infrared drying kinetics of mango slices were not studied in detail. So in this study, the thin-layer drying behaviour of mango slices is investigated by using five thin-layer drying models then the values of effective moisture diffusivity and activation energies are calculated.

2 Material And Methods

2.1 Samples

Mangos are purchased from a local market in Istanbul. Mango slices were cut into layers of 0.5 cm thickness. Initial moisture content of mango slices was determined using the AOAC-Method 934.06 [25] in an Ecocell LSIS-B2V/EC55 (MMM Medcenter Einrichtungen GmbH, Planegg, Germany) model oven at 105°C for 24 h.

2.2 Drying Procedure

Microwave drying experiments were carried out in a Bosch HMT72G420 (Robert Bosch Hausgerate GmbH, Munich, Germany) domestic microwave oven (Maximum output: 800 W, 2450 MHz). Drying experiments was made using the microwave power levels between 90 and 800 W. The weights of mango slices are used in the range of 7.6 and 9.7 g in these experiments.

Infrared drying experiments were carried out in a Snijders Moisture Balance, which has a 250 W halogen lamp (Snijders b.v., Tilburg, Holland). The drying experiments were performed at infrared power level varying from 75 to 104 W. The weight of the used mango slices used in the experiments is 25 ± 0.5 g.

At the end of the determined time, the samples were removed of each dryer and their weights were recorded using an Ohaus PA214C digital balance, which has an accuracy of 0.001 g (Ohaus Corporation, NY, USA). When the moisture contents decreased to 0.5–0.6 kg water/kg dry matter in microwave drying and 0.15 kg water/kg dry matter in infrared drying process experiments

were stopped. Final moisture content of microwave is higher than the infrared moisture content due to the fast burning of samples below 0.5 kg water/kg dry matter.

Dried mango slices were cooled in a desiccator and packed in low density polyethylene bags. Drying experiments were repeated three times and average moisture contents were used in the drying curve plots.

2.3 Mathematical modelling

The moisture content is calculated using Equation (2.1)

$$M = \frac{m_w}{m_d} \quad (2.1)$$

where M is the moisture content (kg water/kg dry matter), m_w is the water content (g) and m_d is the dry matter content (g).

Drying rate is calculated using (2.2):

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2.2)$$

where DR is the drying rate (kg water/kg dry matter \times min), M_{t+dt} is the moisture content at $t+dt$ (kg water/kg dry matter) and t is the drying time (min).

Moisture ratio was calculated using (2.3):

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (2.3)$$

where MR is the moisture ratio (dimensionless), M_t , M_e and M_i are the moisture content at selected time, at equilibrium and the initial value in kg water/kg dry matter. The experimental data of MR obtained at different microwave and infrared power levels were fitted to five thin-layer drying models, where the models used are given in Table 1.

Table 1. Models used for fitting the experimental data

Model Name	Equation	Reference
Aghbashlo et al.	$MR = \exp\left(-\frac{k_1 \times t}{1 + k_2 \times t}\right)$	[26]
Henderson & Pabis	$MR = a \times \exp(-k \times t)$	[27]
Logaritmic	$MR = a \times \exp(-k \times t) + c$	[17]
Midilli & Kucuk	$MR = a \times \exp(-k \times t^n) + b \times t$	[28]
Parabolic	$MR = a + b \times t + c \times t^2$	[29]

2.4 Statistical Analysis

Based on the Lavenberg-Marquardt algorithm, model parameters were estimated using a non-linear regression

procedure by the help of Statistica 8.0 computer programme (StatSoft Inc., Tulsa, USA). The predicted data obtained were evaluated by the coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE). Since, higher R^2 values and lower χ^2 and RMSE values were accepted as better results [15,17]. The equations of R^2 , χ^2 and RMSE are given in (2.4), (2.5) and (2.6), respectively:

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^N \left(MR_{exp,i} - \left(\frac{1}{N} \sum_{i=1}^N MR_{exp,i} \right) \right)^2} \quad (2.4)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (2.5)$$

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right)^{1/2} \quad (2.6)$$

where MR_{exp} and MR_{pre} represent experimental and predicted values of moisture ratio, respectively. N is the total number of data obtained, and z is the number of constants in the model.

Calculation of effective moisture diffusivity

In the drying of agricultural products, Fick's second law of diffusion equation, which symbolized as a mass-diffusion equation in the falling rate period, is shown in (2.7):

$$\frac{\partial M}{\partial t} = \square [D_{eff}(\square M)] \quad (2.7)$$

The analytical solution of Fick's second law (2.7) unsteady state diffusion with the assumptions of moisture migration due to diffusion, negligible shrinkage, constant diffusion coefficients and temperature during the drying process is given in (2.8):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (2.8)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), t is the drying time (s), L is the half-thickness of samples (m) and n is the positive integer. In Equation (2.8) the first term is significant and the equation can be simplified and written into logarithmic form as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (2.9)$$

So the values of D_{eff} can be determined by the slope of the curve obtained by plotting experimental drying data in terms of $\ln(MR)$ versus drying time.

$$D_{eff} = -\frac{slope \times 4L^2}{\pi^2} \quad (2.10)$$

Determination of activation energy

Temperature is not directly measurable quantity in the microwave and infrared drying processes. Given by Kipcak [17], the activation energy can be calculated by the modified form of Arrhenius equation, where the equation shows the relationship between the effective moisture diffusivity and the microwave power to sample weight instead of temperature:

$$D_{eff} = D_0 \exp\left(-\frac{E_a \times m}{P}\right) \quad (2.11)$$

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

3. Results and Discussion

3.1 Drying curves

Drying curve of moisture content with respect to time for mango slices is given in Figures 1 and 2.

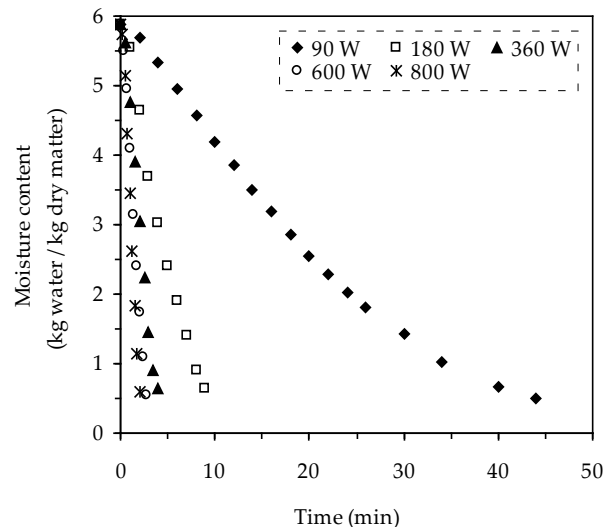


Figure 1. Microwave drying curves of moisture content with respect to time for mango slices

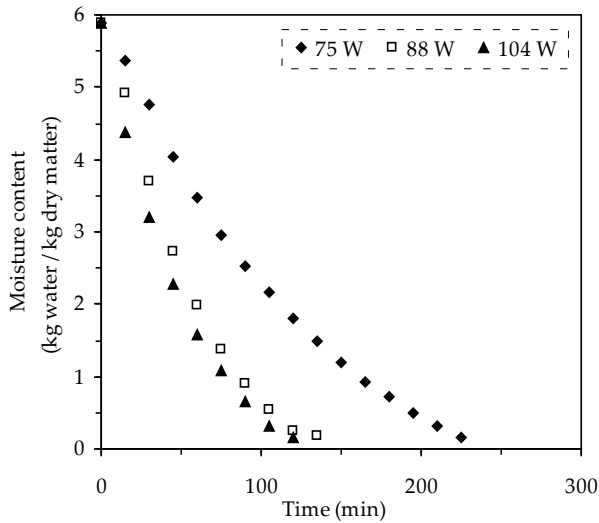


Figure 2. Infrared drying curves of moisture content with respect to time for mango slices

As the microwave and infrared power level increased the moisture contents were decreased faster. The drying time required reaching the final moisture content of samples were found as 44, 10, 4.5, 2.67 and 2 min for the microwave power levels of 90, 180, 360, 600, and 800 W, respectively. On the other hand, for infrared drying the drying times were increased to 225, 135 and 120 min for the infrared power levels of 75, 88 and 104 W, respectively. As expected at higher microwave and infrared power levels, higher heat absorption caused higher product temperature, higher mass transfer driving force, faster drying rate and lesser drying time. This observation is in mutual agreement with the results reported in the literature for microwave and infrared drying of different products such as green bean [6], mussel [17], red pepper [22], onion [30], and spinach leaves [31].

Drying rate

Drying rate curves obtained from the experimental data for microwave and infrared drying processes are given in Figures 3 and 4. All three rate periods namely increasing-rate, constant-rate and falling-rate were obtained in the microwave drying process. On the other hand, increasing-rate and falling-rate periods were seen in the process of infrared drying. Here, the increasing-rate periods is explained as adaptation period and generally it can be negligible. It is observed that the drying rates are increased with increasing microwave and infrared power levels. The decrease in drying time with an increase in the microwave and infrared power level has been reported for other food materials, including and green bean [6], onion [32], and pomegranate aril [33]

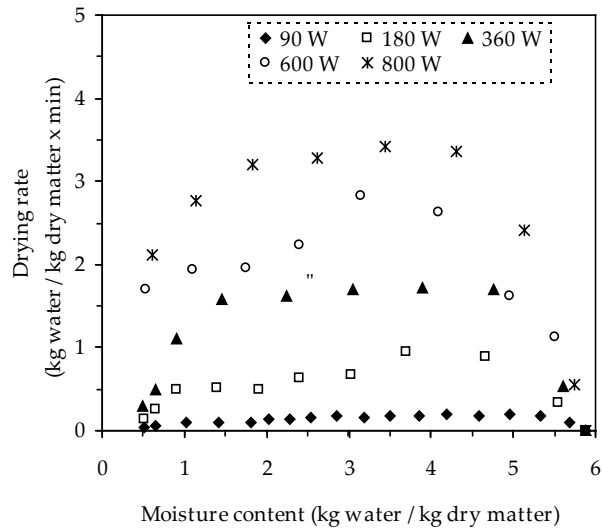


Figure 3. Microwave drying rate curves of mango slices

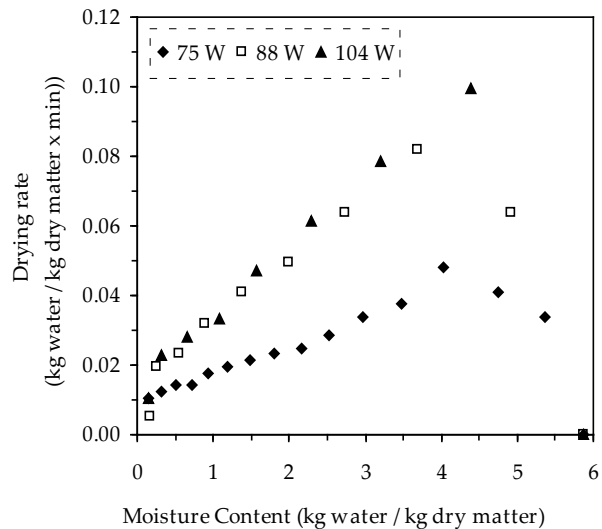


Figure 4. Infrared drying rate curves of mango slices

Evaluation of the drying models

Estimated model coefficients and statistical data obtained from different drying models are shown in Tables 2 and 3. According to the data obtained, the best model is selected as Midilli & Kucuk based on the highest R^2 and the lowest χ^2 , and RMSE values. In microwave drying process, the highest R^2 , lowest χ^2 , and RMSE values are found between 0.998004- 0.999883, 0.000011–0.000205, and 0.003084–0.012199, respectively. On the other hand, in infrared drying process, the highest R^2 , lowest χ^2 , and RMSE values are found between 0.999618-0.999888, 0.000494– 0.001305, and 0.019606–0.034984, respectively. To compare the selected model, the plots of experimental MR and predicted MR by Midilli & Kucuk are



given in Figures 5 and 6. These curves were very close to the bisector showing a good agreement between experimental and predicted moisture ratio.

Table 2. Estimated coefficients and statistical data obtained from different drying models microwave drying of mango slices

Model No	Coefficients	Power (W)				
		90	180	360	600	800
Aghbashlo et al.	k_1	0.030973	0.122574	0.219221	0.279011	0.315482
	k_2	-0.011547	-0.056808	-0.159697	-0.266334	-0.379875
	R^2	0.998626	0.996722	0.994540	0.997178	0.995189
	χ^2	0.000251	0.000794	0.001499	0.000712	0.001250
	RMSE	0.014946	0.025485	0.034628	0.023537	0.031185
Henderson & Pabis	a	1.079075	1.094781	1.119263	1.109552	1.131214
	k	0.046393	0.205167	0.441612	0.608009	0.774025
	R^2	0.992227	0.986376	0.973645	0.966794	0.957782
	χ^2	0.001418	0.003283	0.007159	0.008254	0.010767
	RMSE	0.035497	0.051824	0.075679	0.080124	0.091511
Logarithmic	a	1.369321	1.513256	2.049904	11.85390	16.45200
	k	0.028673	0.107152	0.155684	0.031900	0.030600
	c	-0.328163	-0.464412	-0.988260	-10.80910	-15.37760
	R^2	0.998409	0.996244	0.992279	0.996405	0.993882
	χ^2	0.000310	0.001023	0.002419	0.001058	0.001854
	RMSE	0.016082	0.027278	0.041154	0.026560	0.035156
Midilli & Kucuk	a	1.002849	1.010841	0.999765	1.000326	1.007682
	k	0.016256	0.090974	0.201278	0.323615	0.490283
	n	1.306941	1.430547	1.794384	1.708550	1.911859
	b	-0.000459	-0.000484	0.005756	-0.030062	-0.027193
	R^2	0.999883	0.998004	0.999166	0.999448	0.999681
	χ^2	0.000011	0.000205	0.000131	0.000097	0.000048
	RMSE	0.003084	0.012199	0.009578	0.008025	0.005676
Parabolic	a	1.035524	1.048227	1.066533	1.037163	1.048582
	b	-0.036376	-0.154731	-0.319957	-0.358509	-0.415534
	c	0.000331	0.005666	0.020435	-0.001691	-0.037384
	R^2	0.999214	0.997153	0.993106	0.996536	0.995228
	χ^2	0.000153	0.000776	0.002161	0.001020	0.001447
	RMSE	0.011306	0.023755	0.038898	0.026073	0.031058

Table 3. Estimated coefficients and statistical data obtained from different drying models for infrared drying of mango slices.

Model No	Coefficients	75 W	88 W	104 W
Aghbashlo et al.	k_1	0.007385	0.013577	0.018271
	k_2	-0.002141	-0.003944	-0.002924
	R^2	0.999417	0.999396	0.999824

	RMSE	0.010402	0.011293	0.005928
Henderson & Pabis	a	1.067332	1.058279	1.024586
	k	0.010745	0.019761	0.022749
	R ²	0.992665	0.992267	0.996771
	χ ²	0.001357	0.001807	0.000725
	RMSE	0.036841	0.040333	0.025384
Logarithmic	a	1.273322	1.209528	1.116053
	k	0.006848	0.013816	0.017756
	c	-0.250958	-0.183032	-0.113311
	R ²	0.999531	0.998435	0.999923
	χ ²	0.000093	0.000413	0.000020
	RMSE	0.009332	0.018169	0.003922
Midilli & Kucuk	a	5.918746	5.889616	5.874951
	k	0.004707	0.006160	0.016321
	n	1.130777	1.257914	1.050788
	b	-0.002302	-0.001287	-0.002994
	R ²	0.999618	0.999698	0.999888
	χ ²	0.01305	0.001374	0.000494
	RMSE	0.034984	0.033157	0.019606
Parabolic	a	1.007549	1.012988	0.980024
	b	-0.007623	-0.014276	-0.015923
	c	0.000015	0.000052	0.000067
	R ²	0.999461	0.999483	0.998979
	χ ²	0.000107	0.000136	0.000262
	RMSE	0.010003	0.010441	0.014284

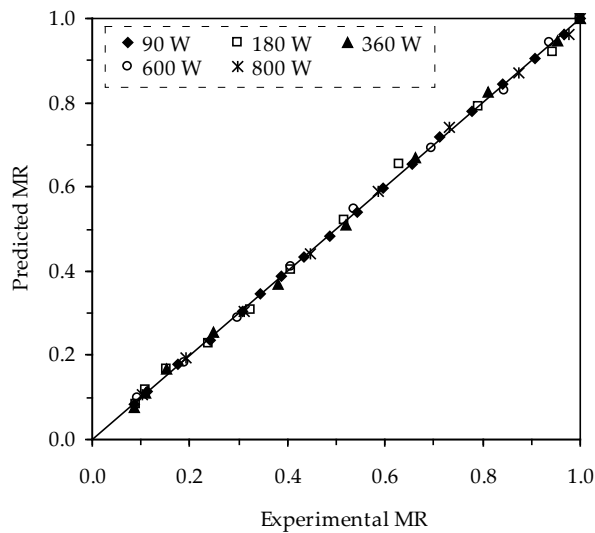


Figure 5. The plot of experimental MR and predicted MR obtained from Midilli & Kucuk for microwave drying

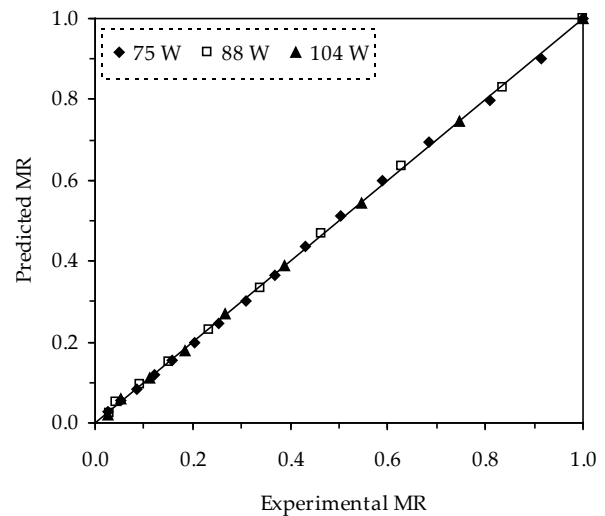


Figure 6. The plot of experimental MR and predicted MR obtained from Midilli & Kucuk for infrared drying



Effective moisture diffusivity

From the plot of $\ln(MR)$ versus drying time for mango slices, the linear equations obtained are given in the Tables 4 and 5 for microwave and for infrared drying, respectively.

Table 4. The equations of $\ln(MR)$ versus drying time and the D_{eff} values for microwave drying of mango slices

Power (W)	Equation	R ²	D _{eff} (m ² /s)
90	$\ln(MR) = -0.0009 t + 0.1962$	0.9809	2.28×10^{-9}
180	$\ln(MR) = -0.0043 t + 0.2506$	0.9522	1.09×10^{-8}
360	$\ln(MR) = -0.010 t + 0.3224$	0.9354	2.56×10^{-8}
600	$\ln(MR) = -0.0134 t + 0.2944$	0.9521	3.39×10^{-8}
800	$\ln(MR) = -0.0184 t + 0.3354$	0.9088	4.66×10^{-8}

Table 5. The equations of $\ln(MR)$ versus drying time and the D_{eff} values for infrared drying of mango slices

Power (W)	Equation	R ²	D _{eff} (m ² /s)
74	$\ln(MR) = -0.0002 t + 0.3240$	0.9379	5.07×10^{-10}
88	$\ln(MR) = -0.0004 t + 0.3060$	0.9709	1.01×10^{-9}
104	$\ln(MR) = -0.0005 t + 0.2448$	0.9691	1.27×10^{-9}

By using the equations in the Tables 4 and 5, the effective moisture diffusivity values are calculated. As it is seen from the results of D_{eff} values increased slightly with increasing both microwave and infrared power level, due to the fact that the increase in the power level caused the rapid increase in temperature of the mango slices, which raises the vapour pressure. Calculated D_{eff} values are within the range of 10^{-12} to 10^{-8} m²/s for drying of agricultural products [34]. These diffusivities were also close to range from 2.61×10^{-10} to 1.09×10^{-9} m²/s obtained by Dissa et al. [24] and from 4.97×10^{-10} to 1.08×10^{-9} m²/s obtained by Akoy [4] during convective drying of mango slices. The effect of microwave and infrared power on the D_{eff} values can be calculated by the equations of (3.9) and (3.10), respectively.

$$D_{eff} = 6 \times 10^{-11} P - 3 \times 10^{-10} \quad (R^2 = 0.9757) \quad (3.9)$$

$$D_{eff} = 3 \times 10^{-11} P - 1 \times 10^{-9} \quad (R^2 = 0.9389) \quad (3.10)$$

Activation energy calculation

By using equation (2.11), the plot of $\ln(D_{eff})$ versus m/P is drawn for both microwave and infrared drying and the equations of (3.11) and (3.12) are obtained, respectively.

$$\ln(D_{eff}) = 39135 \times \frac{m}{P} - 16.483 \quad (R^2 = 0.9868) \quad (3.11)$$

$$\ln(D_{eff}) = 4482 \times \frac{m}{P} - 20.14 \quad (R^2 = 0.9905) \quad (3.12)$$

From the slope and intercept of the lines, D_0 and E_a values are calculated as 6.94×10^{-8} m²/s and 39.13 kW/kg for microwave drying and 1.79×10^{-9} m²/s and 4.48 kW/kg for infrared drying.

4. Conclusions

In this study, the drying characteristics of mango slices were investigated by using microwave and infrared energy. All three rate periods of increase-rate, constant-rate and falling-rate were seen on the microwave drying, where in the infrared drying the drying process took place in the increase and falling-rate periods. The drying time decreased with the increase in both microwave and infrared power level. From the mathematical modelling results Midilli & Kucuk model gave the best results for both microwave and infrared drying. The effective moisture diffusivity values were found range from 2.28×10^{-9} to 4.66×10^{-8} m²/s and 5.07×10^{-10} to 1.27×10^{-9} m²/s, for microwave and infrared drying, respectively. The activation energy values were calculated as 39.13 kW/kg and 4.48 kW/kg for microwave drying and infrared drying, respectively. In conclusion the method of microwave drying is rapid and effective then the infrared drying method. In the next study, the effect on the quality parameters of the products dried by these two drying methods will be investigated.

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