Journal of the Saudi Society of Agricultural Sciences (2013) **12**, 121–127

King Saud University

Journal of the Saudi Society of Agricultural Sciences

www.ksu.edu.sa
www.sciencedirect.com

FULL LENGTH ARTICLE

Drying characteristics of sardine fish dried with microwave heating

Hosain Darvishi [a,*], Mohsen Azadbakht [b], Abbas Rezaeiasl [b], Asie Farhang [c]

[a] *Department of Engineering, Shahr-e Ray Branch, Islamic Azad University, Tehran, Iran*
[b] *Department of Agricultural Machinery Mechanics, Agricultural Sciences & Natural Resources University of Gorgan, Gorgan, Iran*
[c] *Department of Veterinary Medicine, Tehran University, Tehran, Iran*

Received 11 April 2012; accepted 16 September 2012
Available online 26 September 2012

KEYWORDS

Sardine fish;
Microwave;
Drying kinetic;
Modelling;
Energy consumption

Abstract Fresh fish contains up to 80% of water. It is a highly perishable material and having a short storage life. Therefore, the study of the drying kinetics of fish is necessary. In this study, the effect of microwave drying on drying rate, effective diffusivity, and energy consumption of sardine fish was examined at four different microwave powers (200, 300, 400 and 500 W). It was found that the moisture content was reduced from 2.76 to 0.01 (dry basis) and drying time of the samples was significantly reduced from 9.5 to 4.25 min as the power input increased. Five thin layer drying models were fitted to drying data. The Midilli model was selected as the best according to R^2, χ^2 and RMSE. The drying of fish samples took place in the falling rate period and was governed by moisture diffusion. The effective diffusivity varied from 7.158×10^{-8} to 3.408×10^{-7} m^2/s over the microwave power range. No significant differences were observed between the specific energy consumption of microwave-dried sardine fish ($\alpha = 0.05$). However, minimum specific energy consumption (3.78 MJ/kg water) was obtained at 500 W microwave levels.

1. Introduction

Fish is an important source of high-quality protein required in human diet (Jain, 2006; Ayyappan and Diwan, 2003). Fish is a highly perishable food product and has a very short span of shelf life. Cooling is a widely used and important preservation technique to maintain quality and prevent the spoilage and the simplest method of cooling of fish is icing (Jain et al., 2005; Jain, 2006). When, the fresh fish is not utilised by consumers and converted into finished product then it remains surplus and goes waste.

Drying of fish is important, because it preserves fish by inactivating enzymes and removing the moisture necessary for bacterial and mould growth (Bellagha et al., 2002; Bala and Mondol, 2001; Duan et al., 2004). Dried fish is one of the most important exported marine products in many countries such as Turkey, Iran, India, Thailand, Russia, China, Malaysia and United States. Drying of fish is mainly carried out traditionally under open sun. In 2006, a modern fish drying technique was tested on a solar tunnel dryer (Innotech, 2009). Heilporn et al. (2010) studied the fish kinetics of typical mobile

* Corresponding author. Tel.: +98 (21) 44194911–4; fax: +98 (21) 44196524.
E-mail address: Hosaindarvishi@gmail.com (H. Darvishi).
Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

1658-077X © 2012 King Saud University. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jssas.2012.09.002

drying at different temperatures, air velocities, drying time and mass of fish in dryer, reporting that at 0.3 m/s, 6 h and 15 min and 50 kg a good quality product is achieved, providing that the average solar flux is about 700 W/m^2 and the ambient temperature outside the dryer about 40 °C. Jain (2006) evaluated the convective heat and mass transfer coefficient for chelwa fish under solar drying and developed a mathematical model for predicting the drying parameters.

Experimental investigation on solar drying of fish using solar tunnel dryer was carried out by Bala and Mondol (2001). Jain and Pathare (2007) studied the drying characteristics of prawn and chelwa fish in an open sun dryer from 32.5 to 42.5 °C temperature and relative humidity that varies between 15% and 32%. They found that the logarithmic model could adequately describe the drying of fish; and reporting that the effective moisture diffusivity was 8.708×10^{-11} m^2/s for chelwa fish. Chiralt et al. (2001) reported 0.139×10^{-10} and 4.15×10^{-10} m^2/s as effective salt diffusivity for beef and salmon with or without vacuum, while Boudhrioua et al. (2009) reported values of 3.0×10^{-9} and 3.80×10^{-9} m^2/s for sardine fillets.

Chukwu and Shaba (2009), and Chukwu (2009) studied the influence of two different drying methods (smoking kiln and electric oven) on proximate compositions of catfish and tilapia Fish. They found that the electric oven drying is recommended for healthy eating and for longer shelf-life of dried fish.

Duan et al. (2010) used combined microwave – hot air drying for tilapia fish fillets at microwave power from 200 to 600 W and air temperature from 40 to 50 °C with constant air velocity of 1.5 m/s. They found that hot air-microwave drying technology can be used for dehydration of fresh tilapia fillets due to decrease in drying time and to improve quality (rehydration ratio). Hot air drying followed by microwave drying can decrease remarkably the drying time for drying fresh tilapia fillets compared with hot air drying.

The salted fishes were dried in an industrial drier at a relative humidity close to 60%, at a temperature of 19–20 °C and an air velocity of 2–2.6 m/s (Bras and Costa, 2010). Rozainee and Ng (2010) investigated the effects of microwave power and hot air temperature on drying time, dehydration behaviour, energy consumption and colour of dried catfish at microwave – hot air dryer, reporting that microwave assisted dehydration saving energy about 80–90% compared to convective hot air drying. Wu and Mao (2008) studied the influences of hot air drying and microwave drying on nutritional and odorous properties of grass carp fillets. They found that the microwave drying as an efficient drying process for fish fillets.

Bellagha et al. (2007) studied the drying of salted fish (sardine) at 40 °C, 15% RH and 1.5 m/s. They observed that the drying rate showed two falling drying periods. Drying rate during the first falling period was affected by salting method.

One of the most important aspects of drying technology is the modelling of the drying process. Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously. 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.

Most of the above studies examined on convective, solar, superheated steam and heat-pump drying kinetics of fish. But, limited studies concerning microwave drying kinetics and consumption energy of fish have been performed up to now. In addition, improving drying processes by reducing energy consumption and providing high quality with minimal increase in economic input has become the goal of modern drying (Raghavan et al., 2005; Sanga et al., 2000). Therefore, the aim of this study was to study the effects of microwave power on drying kinetics, specific energy consumption and modelling of drying of sardine fish.

2. Materials and methods

2.1. Materials

The fresh sardine fish samples (Sardine laurite) used in this study were obtained from Fish Bazar, Guilan, Iran during the summer season of 2010. The selected samples were cleaned with tap water to make samples free from foreign materials. Surface water was removed by blotting with absorbent paper. In order to preserve its original quality, they were stored in a refrigerator at −2 °C until drying experiments. The average initial moisture contents of the sardine fish samples were found to be 2.755 on dry basis, as determined by using convective oven at 103 ± 1 °C (Jain, 2006).

2.2. Experimental set-up

The schematic of the experimental microwave drying set-up is given in Fig. 1. The microwave oven was operated by a control terminal which could control both microwave power level and emission time. The dimensions of the microwave cavity (M945, LG Samsung) were 327 × 370 × 207 mm. In order to weigh the samples without taking them out of the oven, a weighing system was integrated to the oven. A digital balance (GF-600, A & D, Japan) which has a sensitivity of 0.01 g and a plastic disc was mounted to the bottom of the microwave oven. The disc was rotated at 5 rpm on a ball bearing shaft driven by an electrical motor. The presence of the rotating disc was necessary to obtain homogeneous drying and to decrease the level of the reflected microwaves onto the magnetrons. The oven has ventilation holes on the top as well as on the bottom. Air

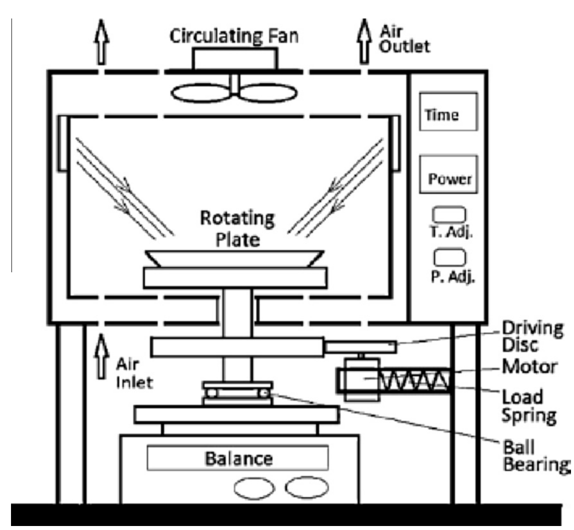

Figure 1 Schematic illustration of the microwave drying set-up.

velocity was kept at a constant value of 1 m/s with an accuracy of ± 0.1 m/s measured with a Vane Probe anemometer AM-4202 Lutron flowed perpendicular to the bed. Drying experiments were carried out with 200, 300, 400 and 500 W microwave power levels to investigate the effects of microwave power on drying of fish. Samples (45 ± 1 g) were placed in a single layer on a rotating glass plate in the oven. Moisture loss of the samples was recorded by means of the balance at 15 s intervals until no discernible weight change was observed. Rotating was stopped by pulling back the driving disc when recording the weight data.

2.3. Modelling of drying process

The moisture content of drying sample at time t can be transformed to be moisture ratio (MR):

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_t, M_0 and M_e are moisture content at any time of drying (kg water/kg dry matter), initial moisture content (kg water/kg dry matter) and equilibrium moisture content (kg water/kg dry matter), respectively.

The moisture ratio was simplified to M_t/M_0 instead of Eq. (1) by some investigators (Al-Harahsheh et al., 2009; Doymaz, 2005) due to the continuous fluctuation of the relative humidity of the drying air during microwave drying process.

The drying rate of samples was calculated using the following equations:

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

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

The drying data obtained were fitted to five thin-layer drying models detailed in Table 1 using the nonlinear least squares regression analysis. Statistical analyses of the experimental data were performed by using the software SPSS 17.0. The coefficient of determination (R^2) is one of the primary criteria for selecting the best model to define the drying curves. In addition to R^2, reduced chi-square (χ^2) and root mean square error (RMSE) are used to determine the quality of the fit. These parameters can be calculated as follows:

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp,i}} - \mathrm{MR}_{\mathrm{pre,i}})^2\right]^{1/2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp,i}} - MR_{\mathrm{pre,i}})^2}{N - Z} \tag{4}$$

where $\mathrm{MR}_{\mathrm{exp,i}}$ is experimental moisture ratio; $\mathrm{MR}_{\mathrm{pre,i}}$ is predicted moisture ratio; N is number of observations; z is number of constants. The best model describing the drying characteristics of samples was chosen as the one with the highest coefficient of determination, the least reduced chi square, root mean square error and mean relative percent error (Sarimeseli, 2011; Caglar et al., 2009).

2.4. Energy of drying

Specific energy consumption (E_s) of the drying process was expressed in MJ/kg water evaporated. Therefore, the E_s could be determined as follows (Varith et al., 2007; Soysal, 2004):

$$E_s = \frac{3.6 \times E_{\mathrm{microwave}}}{(M_t - M_0) \times m_s} \tag{5}$$

The energy consumption of microwave could be calculated as follows:

$$E_{\mathrm{microwave}} = P \times t \tag{6}$$

where $E_{\mathrm{microwave}}$ is the electrical power consumption from microwave oven (kW h); P is the microwave power input (kW); and m_s is the mass of dry solid (kg).

2.5. Moisture diffusivity

In most studies carried out on drying, diffusion is generally accepted to be the main mechanism during the transport of moisture to the surface to be evaporated. The effective moisture diffusivity can be determined from the slope of the normalised plot of the unaccomplished moisture ratio, ln(MR) vs time, using the following equation (Sarimeseli, 2011; Al-Harahsheh et al., 2009):

$$\ln(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{\mathrm{eff}}}{4L^2}\right)t \tag{7}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), and L is the half-thickness of thin layer sample (m).

3. Results and discussion

3.1. Drying curves and modelling drying data

The changes in moisture ratio with drying time of sardine fish in microwave drying are presented in Fig. 2 It was found that the moisture content is effected by the microwave power input and drying time of the sardine fish was significantly reduced from 9.5 to 4.25 min, as the power input increased as can be seen in Fig. 2 It is also clear from the same figure that, increasing the power output resulted in shortened drying times up to 51%. Duan et al. (2010) dried tilapia fish in hot air – micro-

Table 1 Mathematical models given by various authors for drying curves.

Model name	Model	References
Page	$\mathrm{MR} = \exp(-kt^n)$	Sarimeseli (2011)
Wang and Singh	$\mathrm{MR} = 1 + bt + at^2$	Arslan and Ozcan (2010)
Parabolic	$\mathrm{MR} = c + bt + at^2$	Sharma and Prasad (2001)
Logarithmic	$\mathrm{MR} = a\exp(-kt) + b$	Akpinar (2008)
Midilli	$\mathrm{MR} = a\exp(-kt^n) + bt$	Midilli et al. (2002)

where, k is the drying constant and a, b, n are equation constants.

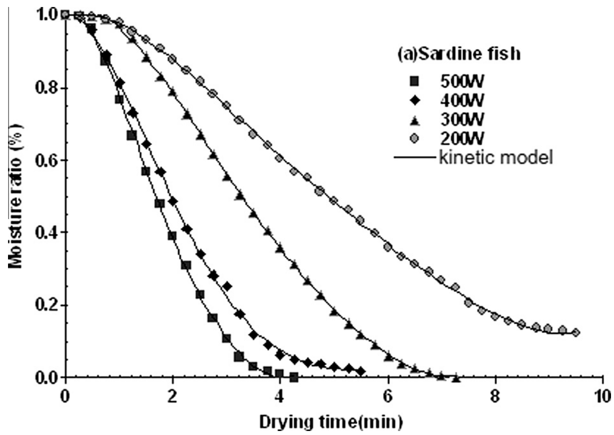

Figure 2 Variation of moisture ratio of sardine fish during the microwave drying process.

wave dryer and found their drying time as 10 min. Heilporn et al. (2010) investigated the drying of fish using a typical mobile drying and recorded drying times up to 6 h. Jain and Pathare (2007) dried prawn and chelwa fish in open sun dryer and found their drying time as 14- and 21 h, respectively. The drying times obtained in this present study was extremely low comparing the results obtained in the previous studies given in literature (Duan et al., 2010; Wu and Mao, 2008; Kituu et al., 2010; Jain and Pathare, 2007; Sobukola and Olatunde, 2010). Therefore, convective drying is long and causes many undesirable changes in the fish. The results indicate 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 vapour pressure difference between the centre and the surface of the product due to characteristic microwave volumetric heating.

As seen in Figs. 3 and 4, all curves have two stages. The drying rate rapidly increases and then slowly decreases as drying progresses. In general, it is observed that drying rate reduces with time or with the reduction of moisture content. As mentioned earlier, the product's moisture content reduces over time. The drying process took place in the falling rate period. Similar trend was also observed by Jain and Pathare (2007) for open sun drying of prawn and chelwa fish. Lahsasni

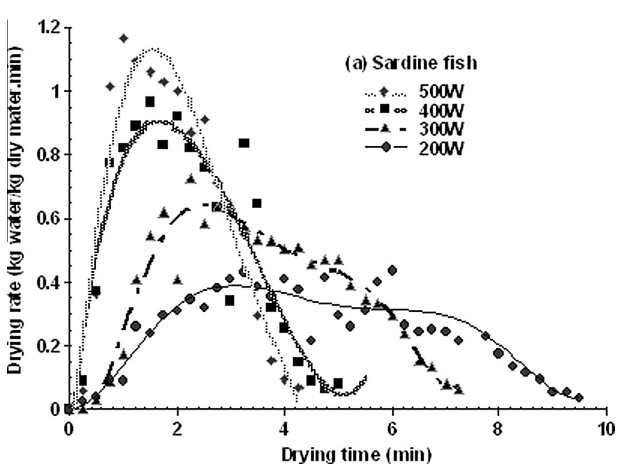

Figure 3 Variation of drying rate with the drying time of sardine fish.

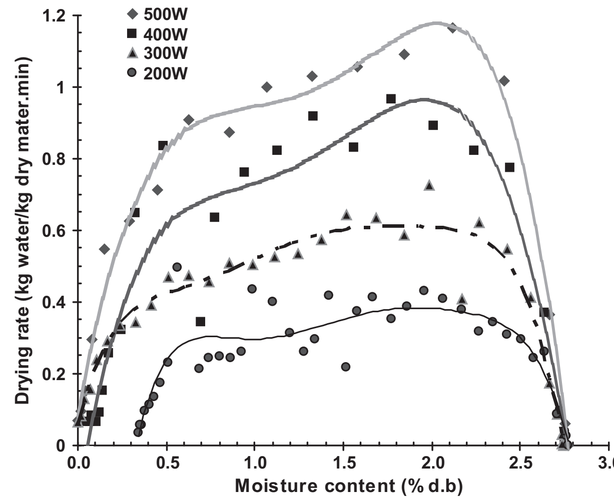

Figure 4 Variation of drying rate with the moisture content of sardine fish.

et al. (2004) reported that the drying during the falling rate period is so governed by water diffusion in the solid.

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. Higher drying rates were obtained at higher microwave output powers. Thus, the microwave output power had a crucial effect on the drying rate. Similar findings were reported in previous studies (Wang et al., 2007; Soysal et al., 2006; Therdthai and Zhou, 2009).

The drying rate by the microwave method can be described by Eq. (8):

$$\mathrm{DR} = At^u + \frac{ht}{1+\exp(\frac{t}{d})} \tag{8}$$

Parameters *a*, *b*, *c* and *d* are given in Table 2. In order to take into account the effect of microwave power on the constants and coefficients of Eq. (8), namely, A, u, h and d, the regression analysis was used to set up the relations between these parameters and the microwave power. Thus, the regression equations of these parameters against microwave power and the drying rate model are as follows:

$h = 4\times10^{-6}P^{2.2729}\quad R^2 = 0.9948$

$u = 4\times10^{-6}P^2 - 0.0044P + 1.0787\quad R^2 = 0.9983$

$d = -2.5381\mathrm{Ln}(P) + 16.76\quad R^2 = 0.9626$

$A = -9\times10^{-8}P^3 + 9\times10^{-5}P^2 - 0.031P + 3.091\quad R^2 = 0.9999$

Table 2 Parameters A, u, h and d of the functions describing the drying rate of sardine fish.

P (W)	Drying kinetic parameters				
	A	u	h	d	R^2
500	−0.439	0.010	5.116	1.156	0.955
400	−0.229	0.054	3.290	1.272	0.900
300	−0.302	0.161	1.475	2.382	0.920
200	−0.127	0.385	0.664	3.326	0.909

The statistical results from models are summarised in Tables 3. The best model describing the thin-layer drying characteristics of sardine fish was chosen as the one with the highest R^2 values and the lowest χ^2 and RMSE values. The statistical parameter estimations showed that R^2, χ^2 and RMSE values ranged from 0.9694 to 0.9999, 0.00009 to 0.10073, and 0.00875 to 0.19779, respectively. Of all the models tested, the Midilli model gives the highest value of R^2 and the lowest values of χ^2 and RMSE. Fig. 5 compares experimental data with those predicted with the Midilli model for sardine fish samples at 200, 300, 400 and 500 W. The prediction using the model showed MR values banded along the straight line, which showed the suitability of these models in describing drying characteristics of sardine fish.

It was determined that the value of k increased with the increase in the microwave power. This data indicate that with an increase in microwave power drying the curve becomes steeper indicating faster drying of the product. A similar trend was observed by Ozkan et al. (2007) for spinach; Sharma and Prasad (2001) for garlic cloves.

In this study, as the temperature is not a measurable variable in the standard microwave oven used for drying process, the Arrhenius equation was used in a modified form to illustrate the relationship between the kinetic rate constant and the ratio of the microwave output power to sample amount instead of the temperature for calculation of the activation energy. After evaluation of the data, the dependence of the kinetic rate constant on the ratio of microwave output power to sample amount was represented with an exponential Eq. (9) derived by Ozbek and Dadali (2007):

$$k = k_0 \exp\left(-\frac{E_a.m}{P}\right) \tag{9}$$

where k is the drying rate constant obtained by using Midilli model (1/min), k_0 is the pre-exponential constant (1/min), E_a is the activation energy (W/g), P is the microwave output power (W) and m is the mass of raw sample (g). The values of k versus m/P shown in Fig. 6, accurately fit to Eq. (9) with coefficient of determination (R^2) of 0.8596. Then, k_0 and E_a values were estimated as 0.8169 (1/min) and 14.138 W/g.

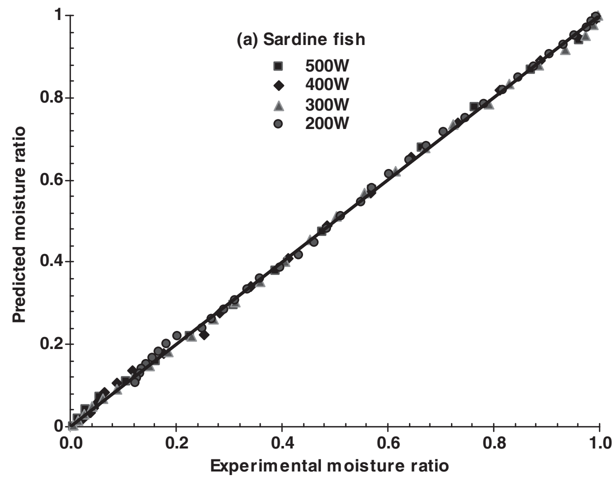

Figure 5 Experimental versus predicted moisture ratio (MR) values for sardine fish drying.

3.2. Effective moisture diffusivity

The values of effective moisture diffusivity ranged from 7.158×10^{-8} m^2/s at 200 W to 3.408×10^{-7} m^2/s at 500 W. In Table 4, it was noted that D_{eff} increased with the increase of microwave power. The D_{eff} values reported herein are within the general range of 10^{-11}–10^{-9} m^2/s for food materials (Doymaz, 2005). This might be explained by the increased heating

Table 3 Results of statistical analysis on the modelling of moisture content and drying time for the microwave dried sardine fish.

Model	P (W)	Model constants	R^2	$\chi2$	RMSE
Page	500	k = 0.244, n = 2.012	0.999	0.00020	0.01334
	400	k = 0.203, n = 1.821	0.999	0.00012	0.01025
	300	k = 0.051, n = 2.197	0.999	0.00020	0.01363
	200	k = 0.040, n = 1.808	0.999	0.00018	0.01316
Wang and Singh	500	a = 0.0185, b = −0.3335	0.9713	0.00427	0.06163
	400	a = 0.0214, b = −0.3068	0.9744	0.00342	0.05592
	300	a = −0.0013, b = −0.1431	0.9694	0.00427	0.06312
	200	a = −0.0008, b = −0.0940	0.9794	0.00204	0.04399
Parabolic	500	a = 0.0385, b = −0.4384, c = 1.1150	0.9850	0.00237	0.04447
	400	a = 0.0334, b = −0.3874, c = 1.1134	0.9883	0.00101	0.02960
	300	a = 0.0062, b = −0.2097, c = 1.1229	0.9841	0.10073	0.20109
	200	a = 0.0024, b = −0.1307, c = 1.0883	0.9896	0.04238	0.19779
Logarithmic	500	k = 0.241, a = 1.851, b = −0.742	0.982	0.00293	0.04939
	400	k = 0.284, a = 1.473, b = −0.359	0.981	0.00199	0.04160
	300	k = 0.112, a = 2.148, b = −1.00	0.981	0.00194	0.04179
	200	k = 0.070, a = 2.109, b = −1.00	0.988	0.00095	0.02964
Midilli	500	k = 0.253, a = 1.011, b = −0.007	0.999	0.00012	0.00982
	400	k = 0.207, a = 1.005, b = 0.0011	0.999	0.00012	0.01012
	300	k = 0.059, a = 1.016, b = −0.006	0.999	0.00009	0.00881
	200	k = 0.041, a = 1.006, b = 0.002, n = 1.817	0.999	0.00009	0.00875

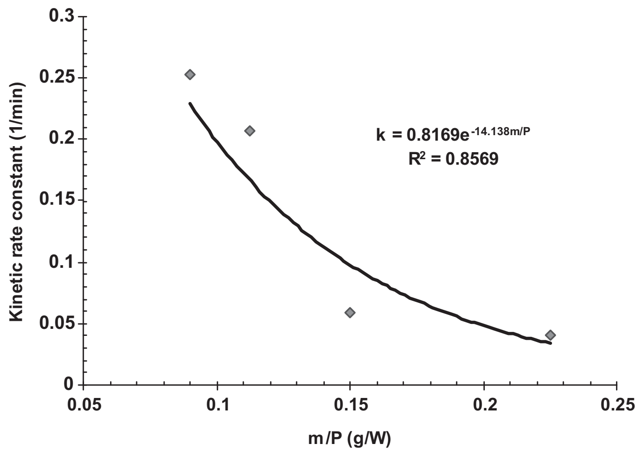

Figure 6 The relationship between the values of drying rate constant versus sample amount/power.

Table 4 Effective diffusivity coefficient values for sardine fish at different microwave powers.

P (W)	Effective diffusivity (m^2/s)
500	3.048×10^{-7}
400	2.302×10^{-7}
300	1.758×10^{-7}
200	7.158×10^{-8}

energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power density. The relationship between effective moisture diffusivity and microwave power can be represented as:

$$D_{\text{eff}} = (0.086P - 9.713) \times 10^{-8} \quad R^2 = 0.9842 \tag{10}$$

In the literature, although effective moisture diffusion for fish under sun and hot air drying was studied by Boudhrioua et al. (2009), Chiralt et al. (2001) and Jain and Pathare (2007) no documentary was found about investigation of the effective moisture diffusivity for fish undergoing microwave treatment. As a result, although the similar trends were observed, the range of effective moisture diffusivity of fish undergoing microwave drying, in this present study, were higher than the values obtained by these researchers, because of the lower drying times required under microwave treatment.

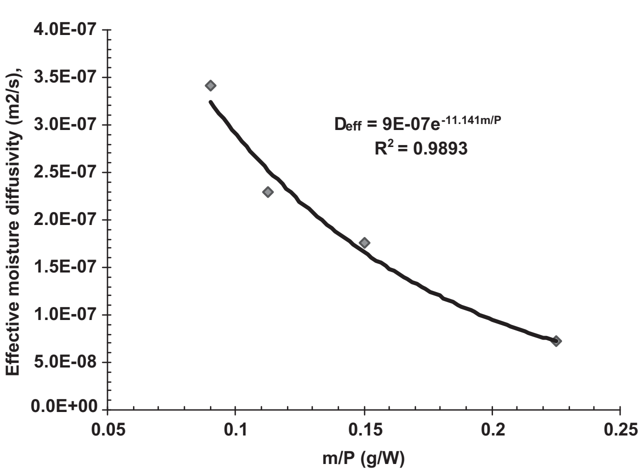

Figure 7 The relationship between the values of effective moisture diffusivity versus sample amount/power.

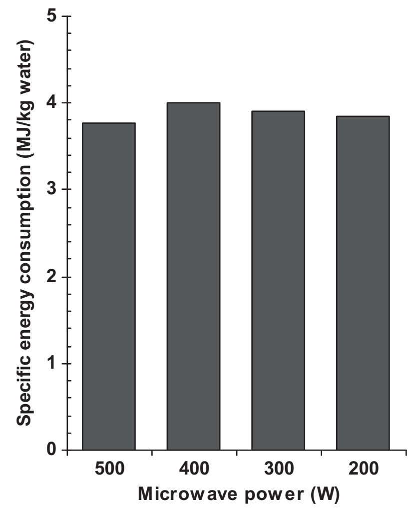

Figure 8 Specific energy consumption for microwave drying of sardine fish.

The dependence of the effective moisture diffusivity on the ratio of microwave output power to sample amount was evaluated using the Arrhenius type equation as given below (Ozbek and Dadali, 2007):

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a.m}{P}\right) \tag{11}$$

where D_0 is the pre-exponential factor (m^2/s) and E_a is the activation energy (W/g). The fitness of data with the model is illustrated in Fig. 7. The values of D_0 and E_a were estimated as 9×10^{-7} m^2/s and 11.14 W/g. As a conclusion, the value of E_a found from this study was quite similar to the value (14.138 W/g) obtained from the previous section by using Eq. (9).

3.3. Energy efficiency of microwave drying

Fig. 8 shows the microwave specific energy consumption values at different amounts of microwave powers for the drying of sardine fish. Statistical analyses showed that microwave power in the range of 200–500 W was not significant on the specific energy consumption values of sardine fish ($\alpha = 0.05$). However, it was noted that the lowest specific energy consumption occurred in 500 W. Drying energy consumption at 500 W was 3.78 MJ/kg water. Rozainee and Ng (2010) reported that the energy consumption of convective hot air drying of 70 °C was 164.3 MJ/kg water, whereas microwave-hot dehydration with low (91 W), medium low (217 W) and medium (373 W) mode of microwave power coupled with hot air temperature of 70 °C required only 15.7, 33.0 and 27.7 MJ/kg water, respectively.

4. Conclusions

The drying kinetics of sardine fish was investigated in a microwave dryer as a single layer at the drying microwave powers of

200, 300, 400 and 500 W. Based on non-linear regression analysis, the Midilli model was considered adequate to describe the thin-layer drying behaviour of sardine fish samples. The microwave drying of sardine fish took place in the falling drying rate period. The calculated effective diffusivities ranged from 7.158×10^{-8} to 3.408×10^{-7} m^2/s, increasing with increased microwave power. Energy activation values estimated from diffusivity data were close to energy activation values from drying kinetics data. Minimum specific consumption and maximum drying efficiency values are obtained to be 68.65% and 91.79% at 500 W.

References

Akpinar, E.K., 2008. Mathematical modeling and experimental investigation on sun and solar drying of white mulberry. Ministry Sci.Technol. 22, 1544–1553.

Al-Harahsheh, M., Al-Muhtaseb, A.H., Magee, T.R.A., 2009. Microwave drying kinetics of tomato pomace: effect of osmotic dehydration. Chem. Eng. Process. 48, 524–531.

Arslan, D., Ozcan, M.M., 2010. Study the effect of sun, oven and microwave drying on quality of onion slices. LWT – Food Sci. Technol. 43, 1121–1127.

Ayyappan, S., Diwan, A.D., 2003. Fish for food security—an opportunity. Indian Farming 53 (7), 47–51.

Bala, B.K., Mondol, M.R.A., 2001. Experimental investigation on solar drying of fish using solar tunnel dryer. Drying Technol. 19 (2), 427–436.

Bellagha, S., Amami, E., Farhat, A., Kechaou, N., 2002. Drying kinetics and characteristic drying curve of lightly salted Sardine (*Sardinella aurita*). Drying Technol. 20 (7), 1527–1538.

Bellagha, S., Sahli, A., Farhat, A., Kechaou, N., Glenza, A., 2007. Studies on salting and drying of sardine (*Sardinella aurita*): experimental kinetics and modeling. J. Food Eng. 78, 947–952.

Boudhrioua, N., Djendoubi, N., Bellagha, S., Kechaou, N., 2009. Study of moisture and salt transfers during salting of sardine fillets. J. Food Eng. 94, 83–89.

Bras, A., Costa, R., 2010. Influence of brine salting prior to pickle salting in the manufacturing of various salted-dried fish species. J. Food Eng. 100, 490–495.

Caglar, A., Togrul, I.T., Togrul, H., 2009. Moisture and thermal diffusivity of seedless grape under infrared drying. Food Bioprod. Process. 87, 292–300.

Chiralt, A., Fito, P., Barat, J.M., Andres, A., Gonzalez-Martinez, C., Escriche, I., Camacho, M.M., 2001. Use of vacuum impregnation in food salting process. J. Food Eng. 49, 141–151.

Chukwu, O., Shaba, I.M., 2009. Effects of drying methods on proximate compositions of catfish (*Clarias gariepinus*). World J. Agri. Sci. 5 (1), 114–116.

Chukwu, O., 2009. Influences of drying methods on nutritional properties of tilapia fish (*Oreochromis nilotieus*). World J. Agri. Sci. 5 (2), 256–258.

Doymaz, I., 2005. Sun drying of figs: an experimental study. J. Food Eng. 71, 403–407.

Duan, Z.H., Jiang, L.N., Wang, J.L., Yu, X.Y., Wang, T., 2010. Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. Food Bioprod. Process.. http://dx.doi.org/10.1016/j.fbp. 2010.11.005.

Duan, Z.H., Zhang, M., Tang, J., 2004. Thin layer hot-air drying of bighead carp. Fish. Sci. 23 (3), 29–32.

Heilporn, C., Haut, B., Debaste, F., Pol, F.V.D., Boey, C., Nonclercq, A., 2010. Implementation of a rational drying process for fish conservation. Food Security 2, 71–80.

Innotech, 2009. Solar tunnel dryer ‘‘Hohenheim’’. <http://www.innotech-ing.de/Innotech/english/TT-Dryer.html> (accessed 29.09.09).

Jain, D., 2006. Determination of convective heat and mass transfer coefficients for solar drying of fish. Biosyst. Eng. 94 (3), 429–435.

Jain, D., Pathare, P.B., 2007. Study the drying kinetics of open sun drying of fish, study the drying kinetics of open sun drying of fish. J. Food Eng. 78, 1315–1319.

Jain, D., Ilyas, S.M., Pathare, P., Prasad, S., Singh, H., 2005. Development of mathematical model for cooling the fish with ice. J. Food Eng. 71 (3), 324–329.

Kituu, G.M., Shitanda, D., Kanali, C.L., Mailutha, J.T., Njoroge, C.K., Wainaina, J.K., Silayo, V.K., 2010. Thin layer drying model for simulating the drying of Tilapia fish (*Oreochromis niloticus*) in a solar tunnel dryer. J. Food Eng. 98, 325–331.

Lahsasni, S., Kouhila, M., Mahrouz, M., Jaouhari, J.T., 2004. Drying kinetics of prickly pear fruit (*Opuntia ficus indica*). J. Food Eng. 61, 173–179.

Midilli, A., Kucuk, H., Yapar, Z., 2002. A new model for single layer drying. Drying Technol. 20 (7), 1503–1513.

Ozbek, B., Dadali, G., 2007. Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. J. Food Eng. 83, 541–549.

Ozkan, I.A., Akbudak, B., Akbudak, N., 2007. Microwave drying characteristics of spinach. J. Food Eng. 78, 577–583.

Raghavan, G.S.V., Rennie, T.J., Sunjka, P.S., Orsat, V., Phaphuangwittayakul, W., Terdtoon, P., 2005. Overview of new techniques for drying biological materials with emphasis on energy aspects. Braz. J. Chem. Eng. 22 (2).

Rozainee, T.M., Ng, P.S. 2010. Microwave assisted hot air convective dehydration of fish slice: drying characteristics, energy aspect and colour. World Engineering Congress 2010, August 2–5, 2010. Kuching, Sarawak, Malaysia Conference on Advanced Processes and Materials.

Sanga, E., Mujumdar, A.S., Raghavan, G.S.V., 2000. Principles and application of microwave drying. In: Mujumdar, A.S. (Ed.), Drying Technology in Agriculture and Food Sciences. Science Publishers, Inc., Enfield, NH.

Sarimeseli, A., 2011. Microwave drying characteristics of coriander (*Coriandrum sativum* L.) leaves. Energy Convers. Manage. 52, 1449–1453.

Sharma, G.P., Prasad, S., 2001. Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination. J. Food Eng. 50, 99–105.

Sobukola, O.P., Olatunde, S.O., 2010. Effect of salting techniques on salt uptake and drying kinetics of African catfish (*Clarias gariepinus*). Food Bioprod. Process.. http://dx.doi.org/10.1016/j.fbp.2010.06.002.

Soysal, A., Oztekin, S., Eren, O., 2006. Microwave drying of parsley: modelling, kinetics, and energy aspects. Biosyst. Eng. 93 (4), 403–413.

Soysal, Y., 2004. Microwave drying characteristics of parsley. Biosyst. Eng. 89, 167–173.

Therdthai, N., Zhou, W., 2009. Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia Opizex Fresen*). J. Food Eng. 91, 482–489.

Varith, J., Dijkanarukkul, P., Achariyaviriya, A., Achariyaviriya, S., 2007. Combined microwave-hot air drying of peeled longan. J. Food Eng. 81, 459–468.

Wang, Z., Sun, J., Chen, F., Liao, X., Hu, X., 2007. Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying. J. Food Eng. 80, 536–544.

Wu, T., Mao, L., 2008. Influences of hot air drying and microwave drying on nutritional and odorous properties of grass carp (*Ctenopharyngodon idellus*) fillets. Food Chem. 110, 647–653.