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ORIGINAL

Drying kinetics of apricot halves in a microwave-hot air hybrid oven

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Abstract Drying behavior and kinetics of apricot halves were investigated in a microwave-hot air domestic hybrid oven at 120, 150 and 180 W microwave power and 50, 60 and 70 °C air temperature. Drying operation was finished when the moisture content reached to 25% (wet basis) from 77% (w.b). Increase in microwave power and air temperature increased drying rates and reduced drying time. Only falling rate period was observed in drying of apricot halves in hybrid oven. Eleven mathematical models were used for describing the drying kinetics of apricots. Modified logistic model gave the best fitting to the experimental data. The model has never been used to explain drying behavior of any kind of food materials up to now. Fick's second law was used for determination of both effective moisture diffusivity and thermal diffusivity values. Activation energy values of dried apricots were calculated from Arrhenius equation. Those that obtained from effective moisture diffusivity, thermal diffusivity and drying rate constant values ranged from 31.10 to 39.4 kJ/mol, 29.56 to 35.19 kJ/mol, and 26.02 to 32.36 kJ/mol, respectively.

List of symbols

a, *b*, *c*, *g*, *h*, *l*, *n*	Equation constants
α	Thermal diffusivity (m^2/s)
α_0	Pre-exponential constant of Arrhenius equation (m^2/s)
AOAC	Association of official analytical chemists
DR	Drying rate (g water/g dry matter.min)
D_{eff}	Effective moisture diffusivity (m^2/s)
D_0	Pre-exponential constant of Arrhenius equation (m^2/s)
E_a	Activation energy (kJ/mol)
FAO	Food and Agriculture Organization of the United Nations
k	Drying rate constant (1/min)
k_0	Pre-exponential constant of Arrhenius equation (1/min)
L	Half thickness of sample (m)
M_0	Initial moisture content (g water/g dry matter)
M_e	Final moisture content (g water/g dry matter)
M_t	Moisture content at any time (g water/g dry matter)
MR	Moisture ratio
$MR_{exp,i}$	Experimental moisture ratio
$MR_{pre,i}$	Predicted moisture ratio
N	Number of experimental data
R	Universal gas constant (kJ/mol K)
R	Function
R^2	Correlation coefficient
RMSE	Root mean square error
t	Drying time (min)
T	Temperature of slab at any time (°C)
T_0	Initial temperature of slab (°C)
T_s	Temperature of drying chamber (°C)
TR	Dimensionless temperature ratio
x	Independent variable
χ^2	Reduced Chi square
W_R, w	Uncertainty
w.b	Wet basis
z	Number of parameters in the model

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1 Introduction

Turkey is the biggest apricot producer in the world. According to the FAO statistical database [1] about 8.11 × 10^5 tons of fresh apricots were produced in Turkey in 2013. This value is about 20% of the total production in the world. Also, the world's total annual production of dried apricot is about 2.1 × 10^5 tons of which 77% from Turkey.

Apricots contain several health-developing components for example carotenoids, polyphenols, vitamins, and natural salicylic acids, which importantly promote their taste, color, nutritional and functional values. Presently there is a substantial concern with these bioactive parts because of their antioxidant capacity and power to relieve chronic diseases [2]. Apricots are seasonal and perishable food therefore; some preservation techniques must be applied in order to make them shelf stable for further evaluation [3].

Drying is well known and popular food preservation process, which improves the consumption period of biological materials, i.e., fruits and vegetables. The main aim of drying is the decrease of moisture content up to the desired level. Also, it provides reduction in size and transportation costs. Hot air drying is the most prevalent technique for drying of fruits and vegetables, however, this process also has a negative impact on product quality such as color, rehydration capacity, texture, and other properties due to long drying time and less efficiency of heat transfer [4–6]. Microwave drying is a relatively new technology in which has been proposed as a rapid and efficient drying alternative to hot air drying. Although microwave drying has become popular as an alternative drying method, it has some major drawbacks when it applies alone. These are non-uniform heating due to materials' shape cause overheating and charring, also the conversion of microwave energy to the heat is reduced at lower moisture content cause again overheating and charring, possible textural damage and limited penetration of the microwaves through the product. Certain combined method can be successfully applied to avoid these effects. One of the most common techniques is microwave-hot air combined (hybrid) drying. In literature, there are several studies about application of microwave-hot air drying technique. Askari et al. [6] dried apple, strawberry, tomatoes and button mushrooms at 300 W microwave power and 50, 40, 55 and 50 °C, respectively. Andrés et al. [7] dried apple cylinders under 0, 3, 5, 7, and 10 W/g microwave power and 25, 30, 40, and 50 °C hot air. Karaaslan and Tunçer [8] dried spinach at 180 and 540 W microwave power and 100, 180 and 230 °C air temperature. Chard leaves were dried at 350, 500, and 650 W microwave power and 50, 75 and 100 °C hot air and pumpkin slices were dried at 160 and 350 W power and 50 and 75 °C hot air, respectively [9, 10]. In the aforementioned studies only Karaslan and Tunçer [8] and Alibas [9, 10] used a hybrid oven which had both microwave and convectional systems for drying applications.

Modeling of drying studies is one of the most substantial viewpoints of drying technology. Semi theoretical and empirical models are applied for determination not only describing drying kinetics of fruits and vegetables but also design and optimization of dryers. The estimation of drying rates for thin layer drying and effective moisture diffusion factors of fruits and vegetables are important issues for drying simulation by models and are fundamental for a moisture transfer analysis [11, 12].

Modified Logistic models (sigmoidal) have been developed for describing the whole microbial growth curve, biovolume, and biomass productions [13]. This model has been applied to the experimental data to explain whole sorption process (kinetic and equilibrium) [14]. Typical drying behavior is also sigmoidal which has heating up, constant rate period and falling rate periods. If this model is well fitted to drying kinetics, it can be used for describing whole drying behavior. Therefore, the model was applied on the drying study, which has never been used in food drying areas up to now to the best of our knowledge.

Although the most commonly used technique for apricot drying is sun drying, the method is slow therefore drying needs too much time and products expose uncontrolled weather and unhygienic conditions. These situations lead to decrease product quality and safety [2]. There is hardly any data on alternative and hybrid drying methods of apricot halves. Therefore, in this research, a hybrid (microwave-hot air) domestic oven was used to (1) dry apricot halves as single layer under controlled conditions (2) determine drying kinetic, effective moisture diffusivity, thermal diffusivity and activation energy.

2 Materials and methods

Apricots (*Prunus armenica* L., Hacıhaliloğlu variety) were supplied from Malatya/Turkey. The apricots were examined to eliminate overripe, unripe and bruised fruits. After separation process, fruits were stored at 4 °C and processed within 4–5 days. Apricots were halved by a sharp knife and arranged as single layer on the drying tray. The initial moisture content of apricots was determined according to AOAC method no. 934.06. A vacuum oven was used at 70 °C until constant weight of sample obtained [15].

2.1 Drying equipment and drying procedure

A programmable air-circulating hybrid domestic microwave oven (Arçelik, KMF 833 I, Turkey) was used for drying of apricot halves (Fig. 1). The dimensions of the hybrid oven are 455 × 594 × 567 mm in height, width and depth,

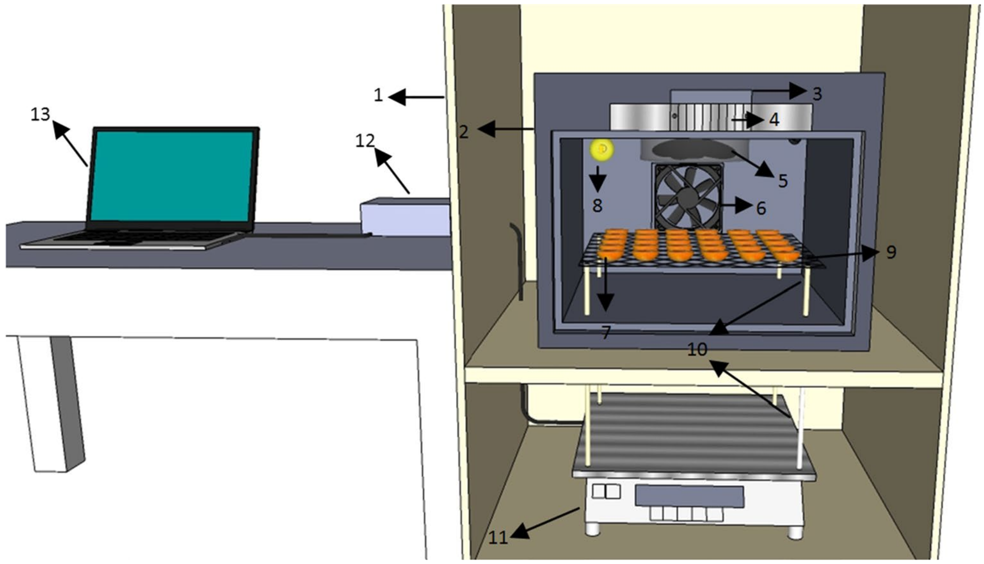

Fig. 1 Schematic representation of microwave-convective hybrid oven: *1* drying cabinet; *2* hybrid oven; *3* display; *4* control buttons; *5* microwave emitter; *6* fan; *7* apricot halves; *8* light; *9* polyamide tray; *10* polyamide legs; *11* analytical balance; *12* data logger; *13* PC

Table 1 Design of drying experiments

Drying run	Microwave power (W)	Hot air temperature (°C)
1	120	50
2	120	60
3	120	70
4	150	50
5[a]	150	60
6	150	70
7	180	50
8	180	60
9	180	70

[a] Run 5 was repeated 5 times

respectively. Microwave and conventional energies are utilized at the same time in the oven. The oven has a maximum output of 900 W at 2465 MHz frequency. Microwave power can be adjusted to desired levels. Conventional heating system can supply hot air from 40 to 280 °C. Microwave is emitted from top of the oven. The oven contains a fan for circulating air and perforated polyamide platforms and trays holding the samples. Four holes were opened from bottom of the oven for connecting the platforms to digital balance placed at the bottom of drying cabinet. A 0.02 g precision analytical balance (Radwag, PS3500/C/1, Radom, Poland) with capacity 3.5 kg was positioned at the bottom of drying cabinet. Weight loss was recorded automatically by the digital balance connected to a computer.

Drying operations were performed at three microwave power and temperature levels. These were 120, 150, 180 W and 50, 60, 70 °C, respectively. A 3-level factorial experimental design was created by use of Design Expert (Version 6, Minneapolis, USA) and represented in Table 1. According to the experimental design, there are five center points whose results were expressed in average. 810 ± 1.0 g of apricot halves were put into the drying tray for every run. The moisture losses (weight of samples) and center temperature of apricots and dryer medium were recorded at every second during drying operation by the analytical balance and thermocouples (ReFlex™, Neoptix, Canada), respectively. Recorded data were transferred to the computer by data logger (Elimko, E-680, Turkey).

Drying operations were carried out until moisture content of samples reduced 25 ± 1% (wet basis, w.b) from 77 ± 0.5% (w.b). This final moisture content of dried apricots was selected that is available in the markets.

2.2 Modeling of thin-layer drying

In order to determine the drying model of apricot halves, 10 known thin-layer mathematical drying models and modified Logistic model were used (Table 2). The moisture ratio was calculated by use of Eq. 1.

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where MR is the moisture ratio, M_t, M_e and M_0 are moisture content at any time during drying, final moisture content and initial moisture content in g water/g dry matter, respectively.

Drying rate (DR) of apricots, in g water/(g dry matter. min), was calculated from Eq. 2 given below.

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

where $M_{t+\Delta t}$ is the moisture content at any time in g water/g dry matter and t is drying time in min.

Table 2 Thin-layer mathematical drying models by various authors

Model name	Model	References
Newton	$MR = \exp(-kt)$	[16]
Page	$MR = \exp(-kt^n)$	[17]
Henderson & Pabis (Hend.&Pab.)	$MR = a\exp(-kt)$	[18]
Logaritmic	$MR = a\exp(-kt) + c$	[19]
Two-term (TT)	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	[11]
Two-term exponential (TTE)	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	[20]
Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	[21]
Wang & Singh	$MR = 1 + at + bt^2$	[12]
Diffusion approach (Dif.Appr.)	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[22]
Mod. Henderson & Pabis (mod.Hend.&Pab.)	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	[23]
Modified Logistic (mod.Logistic)	$MR = a/[1 + exp(-4\,k(l-t)/a + 2]$	[13]

k is the drying rate constant and a, b, c, g, h, l, and n are equation constants

Mathematical drying models were fitted to the drying data by use of the Sigma Plot software (Version 11, Erkrath, Germany). The term used to evaluate goodness of fit of the tested models to the experimental data were the correlation coefficient (R^2), reduced Chi square (χ^2), and root mean square error (*RMSE*). The highest R^2 and the lowest χ^2, and *RMSE* values indicate best model [17, 24].

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

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

where $MR_{exp,i}$ is the experimental moisture ratio found in any measurement, $MR_{pre,i}$ is the predicted moisture ratio, N is the number of experimental data and z is the number of parameters in the model.

2.3 Effective moisture and thermal diffusivities

Fick's second law of diffusion was performed to calculate the effective moisture and thermal diffusivities. By using proper initial and boundary conditions, Crank [25] explained the analytical solution for several geometries and the solution for slab object (single layer) with constant diffusivity is given as:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-(2n+1)\pi^2\frac{D_{eff}\,t}{4L^2}\right) \quad (5)$$

$$TR = \left(\frac{T - T_s}{T_0 - T_s}\right) = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-(2n+1)\pi^2\frac{\alpha t}{4L^2}\right) \quad (6)$$

where D_{eff} and α are the effective moisture and thermal diffusivity, respectively (m^2/s), and L is the half thickness of samples (m), *TR* is the dimensionless temperature ratio, T is temperature of slab at any time (°C), T_s is temperature of drying chamber (°C), T_0 is initial temperature of apricot slab (°C). For long drying times n = 1 and the equation could be simplified to straight-line equations (Eqs. 7, 8).

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

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

The effective moisture diffusivity and thermal diffusivity were typically determined by plotting experimental drying data in terms of ln (*MR*) and ln (*TR*) versus drying time (t) separately. A linear regression analysis was performed to calculate the diffusion coefficients from the slopes of the straight lines of Eqs. 7 and 8. The plots give straight lines with slopes given in Eqs. 9 and 10.

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

$$Slope = \frac{\pi^2\alpha}{4L^2} \quad (10)$$

2.4 Activation energy

In the current study, we interested in the falling rate period so as to determine activation energy for diffusions. This was calculated by plotting ln (D_{eff}), ln (α) and ln (k) versus the reciprocal of the absolute temperature as presented in Eqs. 11, 12 and 13. The slope of the straight line is $-E_a/R$ assuming that Arrhenius equation (Eqs. 11, 12, 13) applies.

Table 3 Uncertainties of the experimental measurements and total uncertainties for predicted values

Parameter	Unit	Comment
Experimental measurement		
Temperature measurement	°C	0.806
Mass loss measurement	g	0.022
Time measurement	min	0.0166
Predicted values		
Moisture ratio (MR)	Dimensionless	±0.96%[a]
Temperature ratio (TR)	Dimensionless	±3.40%[b]
Drying rate	g water/(g dry solid.min)	±1.60%[c]
Effective moisture diffusivity	m^2/s	±4.54%[d]
Thermal diffusivity	m^2/s	±7.36%[e]
Activation energy	kJ/mol	±7.76%[f]

[a] Nominal value was taken as 0.9350

[b] Nominal value was taken as 0.2000

[c] Nominal value was taken as 0.0036 g water/(g dry solid.min)

[d] Nominal value was taken as 2×35^{-10} m^2/s

[e] Nominal value was taken as 3.29×10^{-9} m^2/s

[f] Nominal value was taken as 33.21 kJ/mol

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{11}$$

$$\alpha = \alpha_0 \exp\left(-\frac{E_a}{RT}\right) \tag{12}$$

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \tag{13}$$

where D_0 and α_0 are the pre-exponential constants of the Arrhenius equation (m^2/s), k is the drying rate constant obtained from the best fitted model (1/min), k_0 is the pre-exponential constant of the Arrhenius equation (1/min), E_a is the activation energy in kJ/mol, R is the ideal gas constant (8.314 kJ/mol K), T is the temperature in (K).

2.5 Data analysis

The study was carried out by using three level factorial design. Sigma Plot (SigmaPlot for Windows version 11.0) package program was used for graphical, statistical and non-linear regression analysis. Regression results include correlation coefficient (R^2), reduced Chi square (χ^2) and root mean square error (*RMSE*).

Uncertainty analysis is required to demonstrate the precision of the experiments. Instrument selection, calibration, observation and reading and test planning may cause to increase errors and uncertainties [26]. The uncertainty analysis was carried out by use of the method described by Holman [27]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{14}$$

3 Results and discussion

A detailed uncertainty analysis was carried out for the experimental evaluation of the parameters and total uncertainties of predicted values. Results of the uncertainty analysis are listed in Table 3. In literature, Erbay and Icier [28] found that the uncertainty values for moisture ratio, effective moisture diffusivity and activation energy for diffusion of convective dried olive leaves were 1.77, 0.98 and 0.16%, respectively. Gunhan et al. [29] reported that the uncertainty value for moisture ratio of convective dried bay leaves was 5.99%. Midilli [30] found that experimental uncertainty of sun dried pistachio was 16.25%. According to these results, uncertainty values for effective moisture diffusivity, thermal diffusivity and activation energy of hybrid dried apricots were higher than that of results obtained by Erbay and Icier [28]. This could be due to standard deviation of half thickness of apricot andtotal error of temperature measurement.

3.1 Drying characteristics of apricots

The changes in the moisture ratio with time during drying of the apricots were given Fig. 2. The common trend of the curves was similar like a typical drying curve. The time required for drying of apricots from initial moisture content to the final moisture content changed from 409 to 1560 min according to microwave powers and hot air temperatures. Microwave power and air temperature had a significant effect ($p < 0.05$) on drying time. Drying time decreased with increase in microwave power and drying temperature. Similar results were observed by Igual et al. [2], Alibas [9] and Varith et al. [31]. While drying at 50 and 60 °C air temperature, increase in microwave power from 120 to 180 W caused a reduction in drying time by 50 and 49.5%, respectively. However, the reduction in drying time was found as 42.5 at 70 °C. On the other hand, at 120 and 150 W microwave power levels, the increase in drying temperature from 50 to 70 °C caused a reduction in drying time by 54.4 and 57.8%, respectively, whereas the reduction in drying time was 47.5% at 180 W. From these results, it can be concluded that air temperature had a slightly more effect on drying time than microwave power especially at low microwave power. In the final stage of drying, product absorbs less microwave energy due to its low dielectric property. Therefore, air drying became more dominant on drying rate during the final stage of drying [5]. According to the drying curves, drying time decreased with increasing microwave power and air temperature. The results pointed

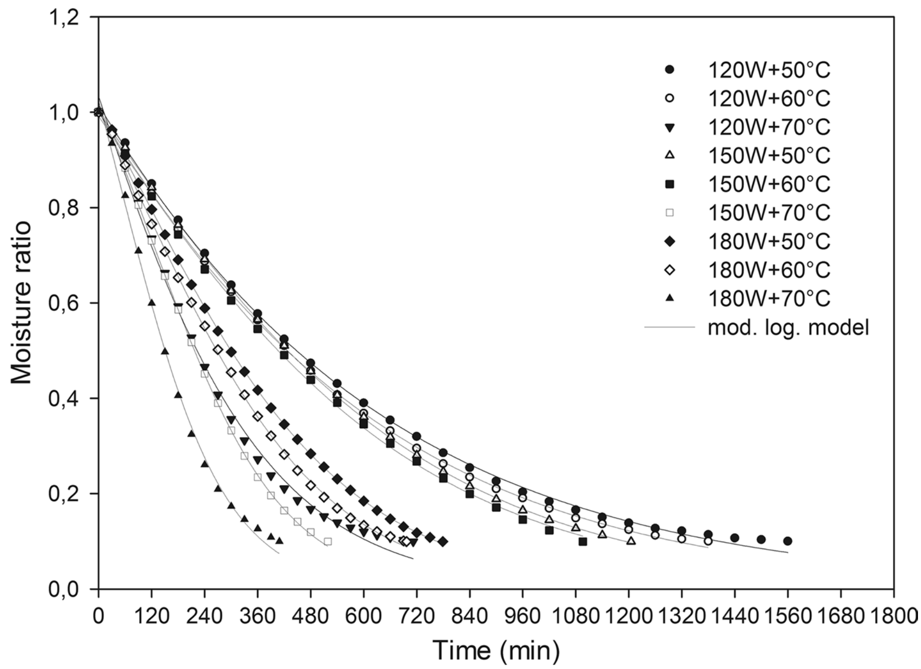

Fig. 2 Drying curves of apricot halves with those predicted from modified logistic model

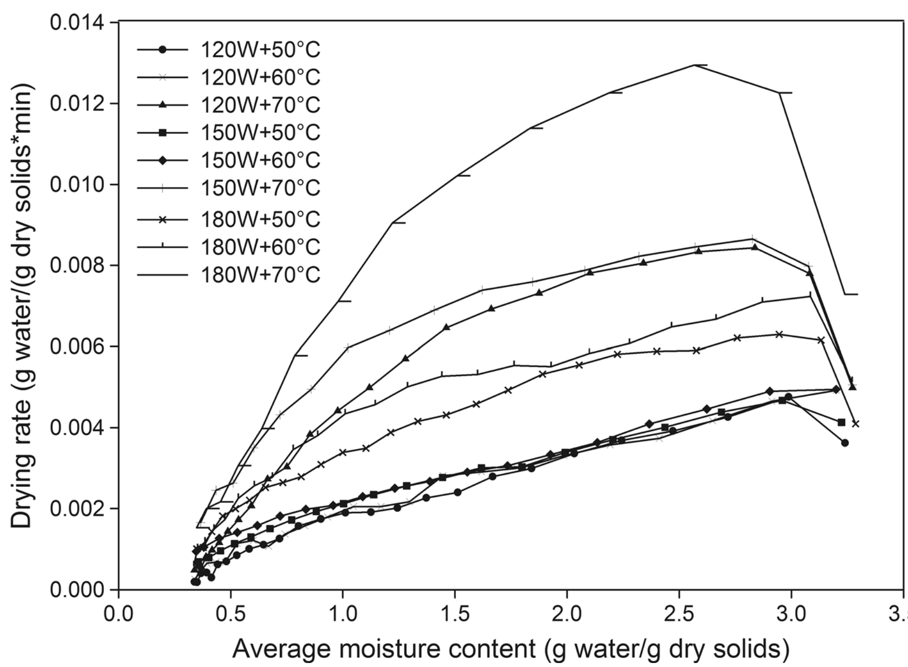

Fig. 3 Drying rate behavior of apricot halves versus average moisture content

out that mass and heat transfer within the samples would be more rapid at higher microwave power and drying temperature. These conditions create a great vapor pressure difference between the center and the surface of the products, resulting in faster water vapor diffusion [32, 33].

Drying rate values of apricot halves were calculated from Eq. 2. The calculated drying rate values at different times were plotted against average moisture content and shown in Fig. 3. It was obviously seen in this figure that drying rates increased at initial drying stage due to adaptation of the food materials to the drying medium and ease of removal of free water from the food material. Drying rates reduced with the reduction of moisture content of apricots. The moisture content of the product was high at the initial stage of the drying operation. High moisture causes higher absorption of microwave energy and the higher moisture diffusion. Because of this reason, high drying rates were observed at high microwave power and drying temperature.

The highest drying rate was observed at 180 W microwave power and 70 °C air temperature. Drying occurred in falling rate period and there was no constant rate period under any of the test conditions. This indicated that diffusion was the dominant mechanism for removing of water from apricot halves. Similar results were also observed by Maskan [34] and Özgen [35].

3.2 Evaluation of drying models

Eleven different mathematical models were used to describe influence of drying conditions on drying kinetics of apricot halves. The statistical analysis was summarized in Table 4. These models had high coefficient of determination (R^2), low Chi square (χ^2) and root mean square (*RMSE*) values ranging between 0.9666 to 0.9999, 0.4×10^{-5} to 3.28×10^{-3} and 0.0018 to 0.0501, respectively, which indicated good fitting. The best model to describe the drying characteristics of apricot halves were selected on the basis of highest R^2 and lowest χ^2 and *RMSE* values. Among those models examined, modified logistic model was the best one for describing all the experimental data. As it was seen in Table 4, the R^2, χ^2 and *RMSE* values for modified Logistic model ranged from 0.9960 to 0.9999, 0.8×10^{-5} to 38×10^{-5} and 0.0027 to 0.0184, respectively. According to the literature, there is no any research has been carried out in the literature for describing the drying data by use of the modified Logistic model. Figure 4 shows a comparison between experimental data with those predicted from the modified model for apricot halves. As it was seen from this figure, there was a good conformity between experimental and predicted moisture ratio values banned along the straight line. This also shows the convenience of the modified Logistic model for describing drying behavior of apricot halves. In literature, Toğrul and Pehlivan [11] concluded that logarithmic model gave the best fit to apricot drying with four levels of hot air temperature and air flow rates. Mirzaee et al. [36] dried apricot halves at 40, 50, 60 and 70 °C hot air and 1 and 2 m/s air velocity and used twelve mathematical models in order to determine the drying behavior of the apricot halves. They found that Logarithmic and Midilli et al. models could satisfactorily describe the drying behavior of the apricot halves. Igual et al. [2] stated that Page's model adequately explained the experimental drying kinetics data of dried apricot in both air drying process and falling rate period of microwave-hot air drying process.

Empirical models procure enough representation of experimental results. These models do not require assumptions of food features, which from a practical point of view is important. For these reason, empirical models provide generally good results for engineering application in food industry [24].

3.3 Effective moisture and thermal diffusivities and activation energy

Effective moisture and thermal diffusivities of dried apricots calculated from Eqs. 7 and 8 by use of the method of slopes. ln (*MR*) versus time and ln (*TR*) versus time were plotted by use of the experimental data. Effective moisture and thermal diffusivity values are given in Table 5 and ranged between 6.75×10^{-10} to 2.56×10^{-9} and 3.64×10^{-10} to 1.34×10^{-9}, respectively. It can be seen from the Table 5 that the values of $D_{eff}$and α increased with increasing microwave power and drying temperature. This trend could be clarified by the increasing in heating energy which would increase water molecule activity to diffuse [18, 37].

Thermal diffusivity is a substantial transport feature which is used for explanation of modeling and computations of transient heat and mass transfer in basic food processes, such as drying, thermal processing and cooling/freezing [38]. However, limited data have been published on the thermal diffusivity properties of dried and semi-dried foods. Çağlar et al. [37] dried seedless grape under infrared drying and reported that thermal diffusivity of the sample increased with increase in drying temperature and decrease in moisture content. Mariani et al. [39] applied convectional drying at different temperatures varied from 17 to 65 °C in order to obtain the thermal diffusivity of banana samples by use of inverse method. They found that the thermal diffusivities ranged from 1.88×10^{-7} to 9.47×10^{-11} m^2/s and diffusivity depends on several parameters, among other the composition of the product, direction of the fibers and in particular of its temperature. Singh and Goswami [40] measured thermal diffusivity of cumin seeds in the temperature range of −50 to 50 °C at 10 °C intervals. They concluded that the thermal diffusivity (ranged from 6.53×10^{-8} to 16.64×10^{-8} m^2/s) increased with increase in temperature at all the moisture contents and followed a second order polynomial relationship. Kostaropoulos and Saravacos [38] found that a nonlinear relationship between thermal diffusivity and moisture content in granular and porous foods in the low moisture region. They also indicated that a considerable influence of physical structure of food products particularly porosity on the thermal diffusivity.

D_{eff} values obtained from this study lie within the general range of 10^{-11}–10^{-6} m^2/s for food materials [41]. In literature, several authors reported results of their studies about effective moisture diffusivity in various food materials. Zarein et al. [18] found D_{eff} values of 5 mm thick apple slices dried by microwave at 200, 400 and 600 W power levels to change from 3.93×10^{-7} to 2.27×10^{-6} m^2/s. Demiray and Tulek [42] reported that the effective moisture diffusivity of tomato slices (cv. Rio Grande) when drying at

Table 4 Results of statistical analysis on the modeling of moisture ratio and drying time of dried apricot halves

Drying conditions		Model name										
		Newton	Page	Hend. & Pab.	Logarithmic	TT	TTE	Verma	Wang&Singh	Diffusion approach	mod. Hend.&Pab.	mod. Logistic
120 W + 50 °C	R^2	0.9978	**0.9990**	0.9987	0.9987	0.9987	0.9978	0.9983	0.9981	0.9983	0.9988	**0.9990**
	RMSE	0.0128	0.0097	0.0096	0.0096	0.0096	0.0128	0.0114	0.0118	0.0114	0.0094	**0.0087**
	χ^2	17×10^{-5}	$\mathbf{8.17 \times 10^{-5}}$	9.97×10^{-5}	10×10^{-5}	11×10^{-5}	17×10^{-5}	15×10^{-5}	15×10^{-5}	15×10^{-5}	13×10^{-5}	8.4×10^{-5}
	k	1.58×10^{-3}	1.08×10^{-3}	1.63×10^{-3}	1.62×10^{-3}	1.63×10^{-3}	4.62×10^{3}	1.21×10^{-3}	–	1.21×10^{-3}	1.63×10^{-3}	1.40×10^{-3}
120 W + 60 °C	R^2	0.9984	0.9997	0.9990	0.9994	0.9989	0.9984	0.9994	0.9983	0.9995	0.9989	**0.9998**
	RMSE	0.0108	0.0043	0.0087	0.0064	0.0087	0.0108	0.0062	0.0110	0.0061	0.0058	**0.0039**
	χ^2	12×10^{-5}	1.98×10^{-5}	8.29×10^{-5}	4.7×10^{-5}	9.12×10^{-5}	120×10^{-5}	4.37×10^{-5}	132×10^{-5}	4.37×10^{-5}	4.43×10^{-5}	$\mathbf{1.82 \times 10^{-5}}$
	k	1.68×10^{-3}	1.12×10^{-3}	1.71×10^{-3}	1.59×10^{-3}	1.71×10^{-3}	4.89×10^{3}	1.17×10^{-3}	–	1.17×10^{-3}	1.71×10^{-3}	1.47×10^{-3}
120 W + 70 °C	R^2	0.9853	**0.9963**	0.9924	0.9931	0.9924	0.9853	0.9898	**0.9963**	0.9898	0.9924	0.9960
	RMSE	0.0353	0.0178	0.0254	0.0242	0.0254	0.0353	0.0295	**0.0176**	0.0245	0.0232	0.0184
	χ^2	130×10^{-5}	$\mathbf{34 \times 10^{-5}}$	70×10^{-5}	66×10^{-5}	77×10^{-5}	135×10^{-5}	99×10^{-5}	$\mathbf{34 \times 10^{-5}}$	99×10^{-5}	71×10^{-5}	38×10^{-5}
	k	3.34×10^{-3}	1.04×10^{-3}	3.59×10^{-3}	3.32×10^{-3}	3.59×10^{-3}	1.51×10^{4}	1.96×10^{-3}	–	1.96×10^{-3}	3.59×10^{-3}	2.45×10^{-3}
150 W + 50 °C	R^2	0.9932	0.9997	0.9958	0.9937	0.9959	0.9932	0.9993	0.9998	0.9993	0.9958	**0.9999**
	RMSE	0.0229	0.0046	0.0178	0.0070	0.0178	0.0229	0.0075	0.0036	0.0075	0.0061	**0.0027**
	χ^2	55×10^{-5}	2.34×10^{-5}	35×10^{-5}	5.64×10^{-5}	39×10^{-5}	58×10^{-5}	6.55×10^{-5}	1.39×10^{-5}	6.4×10^{-5}	5.14×10^{-5}	$\mathbf{0.88 \times 10^{-5}}$
	k	1.72×10^{-3}	6.70×10^{-4}	1.80×10^{-3}	1.43×10^{-3}	1.80×10^{-3}	2.67×10^{3}	8.94×10^{-4}	–	8.94×10^{-4}	1.80×10^{-3}	1.42×10^{-3}
150 W + 60 °C	R^2	0.9938	0.9988	0.9954	0.999945	0.9954	0.9938	**0.99995**	0.9991	**0.99995**	0.9954	0.9994
	RMSE	0.0214	0.0095	0.0184	0.0021	0.0184	0.0217	**0.0018**	0.0081	**0.0018**	0.0184	0.0066
	χ^2	48×10^{-5}	9.98×10^{-5}	38×10^{-5}	0.45×10^{-5}	43×10^{-5}	51×10^{-5}	$\mathbf{0.4 \times 10^{-5}}$	7.33×10^{-5}	$\mathbf{0.4 \times 10^{-5}}$	49×10^{-5}	5.17×10^{-5}
	k	1.80×10^{-3}	8.09×10^{-4}	1.87×10^{-3}	1.39×10^{-3}	1.87×10^{-3}	1.56×10^{3}	8.61×10^{-4}	–	8.61×10^{-4}	1.87×10^{-3}	1.47×10^{-3}
150 W + 70 °C	R^2	0.9666	**0.9997**	0.9801	0.9957	0.9801	0.9666	0.9935	0.9949	0.9935	0.9801	**0.9997**
	RMSE	0.0540	0.005	0.0416	0.0194	0.0416	0.0501	0.0234	0.021	0.0238	0.0187	**0.0047**
	χ^2	309×10^{-5}	2.8×10^{-5}	195×10^{-5}	45×10^{-5}	223×10^{-5}	328×10^{-5}	68×10^{-5}	50×10^{-5}	68×10^{-5}	53×10^{-5}	$\mathbf{2.69 \times 10^{-5}}$
	k	3.55×10^{-3}	3.92×10^{-4}	3.92×10^{-3}	2.18×10^{-3}	3.92×10^{-3}	8.24×10^{3}	9.77×10^{-4}	–	9.77×10^{-4}	3.92×10^{-3}	2.51×10^{-3}
180 W + 50 °C	R^2	0.9826	**0.9999**	0.9908	0.9983	0.9909	0.9826	0.9972	0.9987	0.9972	0.9909	**0.9999**
	RMSE	0.0374	**0.0027**	0.0270	0,0116	0.0270	0.0374	0.0151	0.0102	0.0151	0.0107	0.0031
	χ^2	145×10^{-5}	$\mathbf{0.78 \times 10^{-5}}$	79×10^{-5}	15×10^{-5}	86×10^{-5}	151×10^{-5}	26×10^{-5}	11×10^{-5}	26×10^{-5}	15×10^{-5}	1.07×10^{-5}
	k	2.52×10^{-3}	5.45×10^{-4}	2.72×10^{-3}	1.89×10^{-3}	2.72×10^{-3}	5.51×10^{3}	9.97×10^{-4}	–	9.97×10^{-4}	2.72×10^{-3}	1.86×10^{-3}
180 W + 60 °C	R^2	0.9805	0.9993	0.9884	0.9971	0.9885	0.9805	0.9963	0.9984	0.9963	0.9884	**0.9996**
	RMSE	0.0403	0.0077	0.0310	0,0154	0.0310	0.0403	0.0176	0.0115	0.0176	0.0144	**0.0055**
	χ^2	169×10^{-5}	6.42×10^{-5}	104×10^{-5}	27×10^{-5}	114×10^{-5}	176×10^{-5}	35×10^{-5}	14×10^{-5}	35×10^{-5}	27×10^{-5}	$\mathbf{3.5 \times 10^{-5}}$
	k	2.86×10^{-3}	5.73×10^{-4}	3.09×10^{-3}	2.11×10^{-3}	3.09×10^{-3}	1.63×10^{4}	1.13×10^{-3}	–	1.13×10^{-3}	3.09×10^{-3}	2.14×10^{-3}

Table 4 continued

Drying conditions		Model name										
		Newton	Page	Hend. & Pab.	Logarithmic	TT	TTE	Verma	Wang&Singh	Diffusion approach	mod. Hend.&Pab.	mod. Logistic
180 W + 70 °C	R^2	0.9760	**0.9982**	0.9961	0.9920	0.9861	0.9760	0.9890	0.9933	0.9890	0.9861	0.9975
	RMSE	0.0470	**0.0129**	0.0359	0.0272	0.0359	0.0471	0.0319	0.0249	0.0319	0.0261	0.0152
	χ^2	237×10^{-5}	$\mathbf{19 \times 10^{-5}}$	149×10^{-5}	93×10^{-5}	175×10^{-5}	256×10^{-5}	127×10^{-5}	72×10^{-5}	127×10^{-5}	113×10^{-5}	29×10^{-5}
	k	5.10×10^{-3}	9.53×10^{-4}	5.54×10^{-3}	4.21×10^{-3}	5.54×10^{-3}	1.23×10^{4}	2.20×10^{-3}	–	2.20×10^{-3}	5.54×10^{-3}	3.77×10^{-3}

Bold values indicate the best values

60, 70, 80, 90 and 100 °C hot air with 0.2 m/s air velocity ranged between 1.015 and 2.650 × 10^{-9} m^2/s. In another study on drying of sulphur dioxide treated apricots, the effective moisture diffusivity values were found to change between 4.86 × 10^{-9} and 8.32 × $10^{-9}$$m^2$/s. The apricots has been dried at 50, 60, 70 and 80 °C from 74% moisture content to 16% final moisture content [11]. The moisture diffusivity values obtained from our study are in agreement with the literature values although some differences exist. These differences may come from type and geometric shape of product, dryer type and pretreatments.

The activation energies were calculated from slope of the ln D_{eff} versus 1/T plot, slope of ln α vs 1/T and ln k versus 1/T. The activation energies were found as 37.12, 39.40, and 31.10 kJ/mol (35.88 kJ/mol in average) from moisture diffusivity values, 35.19, 34.86 and 29.56 kJ/mol (33.21 kJ/mol in average) from thermal diffusivity values and 26.31, 26.02 and 32.36 kJ/mol (28.23 kJ/mol in average) for 120, 150, and 180 W microwave power levels, respectively. According to these findings, the average E_a values found from moisture diffusivity, thermal diffusivity and drying rate constant were similar. This is an important finding and it can be concluded that activation energy of dried fruits can be calculated from thermal diffusivity and drying rate constant values as well. The values of the activation energy vary from 12.7 to 110 kJ/mol for most food materials [41]. Mirzaee et al. [43] calculated the activation energy of convectional dried apricot by use of moisture diffusivity. It varied from 29.35 to 33.78 kJ/mol for dried apricots for different hot air temperatures. Also, Aghbashlo et al. [44] found that the activation energy of hot air dried sour cherry, which was calculated by use of moisture diffusivity, were varying from 64.39 to 66.05 kJ/mol when drying at 60, 70 and 80 °C hot air and 0.3 0.6 and 0.9 m/s air velocity. Özbek and Dadali [45] obtained that activation energies of microwave dried mint leaves by use of both drying kinetic rate constant and moisture diffusivity were 12.28 and 11.05 W/g respectively.

4 Conclusions

In this study, drying behavior of hybrid (microwave-convective) dried apricot halves were firstly investigated during the whole drying process. The drying time of apricot halves decreased and drying rate increased with increasing in microwave power and hot air temperature. Constant rate period was not observed and drying carried on in falling rate period. The ten thin layer drying models and modified Logistic Model were used to describe drying kinetics of the fruit and it was realized that the modified Logistic Model best fitted our experimental data. The model has never been used in food drying areas up to now. However,

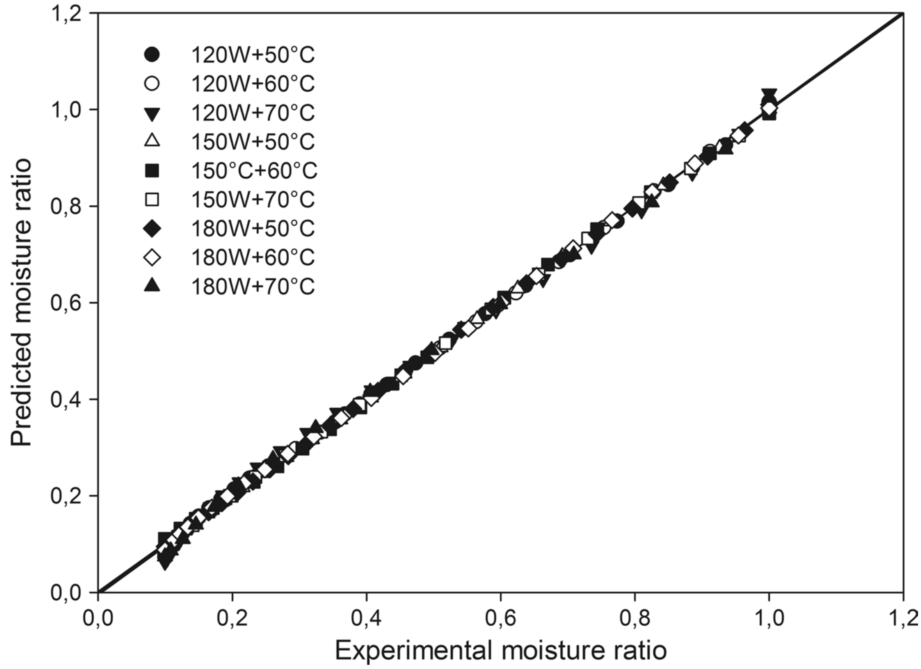

Fig. 4 Comparison of experimental and predicted moisture ratio from modified Logistic model

Table 5 Effective moisture diffusivity and thermal diffusivity values of dried apricot halves

Drying cond.	Effective moisture diffusivity (m^2/s)	Thermal diffusivity (m^2/s)
120 W + 50 °C	6.75×10^{-10}	3.64×10^{-10}
120 W + 60 °C	7.42×10^{-10}	3.95×10^{-10}
120 W + 70 °C	1.52×10^{-9}	7.86×10^{-10}
150 W + 50 °C	8.30×10^{-10}	4.77×10^{-10}
150 W + 60 °C	8.77×10^{-10}	5.10×10^{-10}
150 W + 70 °C	1.97×10^{-9}	1.02×10^{-9}
180 W + 50 °C	1.30×10^{-9}	7.04×10^{-10}
180 W + 60 °C	1.49×10^{-9}	8.31×10^{-10}
180 W + 70 °C	2.56×10^{-9}	1.34×10^{-9}

in the current study it can be concluded that this model can be used for describing of drying kinetics of fruits and vegetables according to the statistical analysis. The effective moisture and thermal diffusivities varied from 6.75×10^{-10} to 2.56×10^{-9} and 3.64×10^{-10} to 1.34×10^{-9} m^2/s, respectively at various drying conditions. The diffusivities increased with increase in microwave power and hot air temperature. The activation energies of dried apricots were found for whole system that 35.88, 33.21 and 28.23 kJ/mol by use of effective moisture diffusivity, thermal diffusivity and drying rate constant values in Arrhenius equation, respectively.

Practically, the application of empirical models and diffusional equations in food drying can be considered a basis for certain parameter estimation such as drying time, moisture diffusivity, thermal diffusivity and activation energy value. The mathematical models used in this study have much more practical utility as far as process design, optimization and selection of industrial equipment of food industry is concerned.

The hybrid (microwave-conventional) drying technique used in this study has some advantages over microwave and convectional techniques applied alone. These are elimination of overheating and long drying time, energy consumption, drying expenditure and improvement of product quality. Therefore, the hybrid drying technique can be accepted as an alternative drying technique and applied in industrial and domestic scale for fruits and vegetables drying. With these results, drying of apricots can be carried out by the food industry more effectively and efficiently.

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