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Full Length Research Paper

Drying characteristics of bay laurel (*Laurus nobilis* L.) fruits in a convective hot-air dryer

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In this study, drying characteristics of bay laurel (*Laurus nobilis* L.) fruits were investigated in a laboratory scale hot-air dryer at air temperature in a range of 70 to 100°C. Moisture transfer from the test samples was described by applying the Fick's diffusion model and the effective diffusivity was calculated. Temperature dependence of the effective diffusivity was described by the Arrhenius-type relationship. The experimental drying data of bay laurel fruits were used to fit page, logarithmic, Two-term and approximation of diffusion, and Midilli et al. (2002) models and the statistical validity of models tested were determined by non-linear regression analysis. The Two-term model showed a better fit to experimental drying data obtained when compared with other models.

Key words: Bay laurel fruits, convective air drying, moisture ratio, effective diffusivity, activation energy.

INTRODUCTION

The Lauraceae has 32 genera and about 2000 to 2500 species. *Laurus nobilis* (Lauraceae) L. is an evergreen tree up to 10 m in height. It is widely distributed to the Mediterranean region, which is cultivated in many countries with moderate and subtropical climate (Baytop, 1991). Bay laurel is grown commercially for its aromatic leaves and oils in Turkey, Algeria, Morocco, Portugal, Spain, Italy, France and Mexico. *L. nobilis* L. is commonly named in English "Sweet Bay", "True Laurel", "Bay Laurel", "Laurel", in French "Laurier", in German "Lorbeer", in Arabic "Ghar", in Italian "Allora", in Greek "Daphane" and Turkish "Defne", "Gar" and "Tehnel".

Several uses of bay laurel plant oil are known for cosmetic industry, food and medicinal purposes. The fruits contain much more oil than leaves (Engel, 1967; Wren, 1975). The fruits of bay laurel plants contain 24 to 30% of fixed oil. *L. nobilis* seeds and leaves are rich in volatile oils such as 1.8 cineol and terpinene (Bown, 2002). The volatile oils of the leaves and fruits are used widely in the perfume and soap industry (Duke, 1989). Afifi et al. (1997) reported antiulcerogenic activities of the extracts of the *L. nobilis* seeds and the crude extract and the volatile oil fraction of the *L. nobilis* seeds have some gastroprotective effect.

In Turkey, the seed oil of bay laurel is obtained from fruits of the plant traditionally by pressing or boiling in water and is used locally and also exported (Baser, 1997). The poor quality fixed oil obtained from fruits by traditional method can cause lost of market value. But in Europe, the fixed oil of bay laurel is obtained by pressing technique from dried and powdered fruits. In spite of this easy method for getting oil, it remains 5 to 10% oil in oil cake. In recent years, in Europe, approximately 99% of the fixed oil of fruits or seeds in plant is obtained by extraction techniques. Physical properties, moisture content of raw material and required temperature are

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Abbreviations: ***a, b, c,*** Coefficients in models; D_{eff}, effective diffusivity, m^2/s; D_0, pre-exponential factor, m^2/s; E_a, activation energy, kJ/mol; ***k,*** k_0, drying rate constants in models, 1/h; ***m,*** exponent in drying model; ***M,*** moisture content at any time, % d.b.; M_e, equilibrium moisture content, % d.b.; M_0, initial moisture content, % d.b.; M_R, dimensionless moisture ratio; $M_{R,ex}$, experimental dimensionless moisture ratio; $M_{R,pre}$, predicted dimensionless moisture ratio; ***n,*** positive integer; ***N,*** number of observations; ***P,*** mean relative percent deviation, %; ***R,*** universal gas constant, kJ/mol.K; R_e, equivalent radius, m; ***RMSE,*** root mean square error; R^2, coefficient of determination; ***t,*** drying time, h; T_a, absolute air temperature, K; ***z,*** number of constants; χ^2, reduced chi-square.

Figure 1. Bay laurel fruits.

important factors that affect the yield in this technique (Beis, 1994).

Drying characteristics of the bay laurel fruits are important factor for obtaining oils from dried fruits by pressing technique. Knowledge of the drying characteristics of biological materials is essential to the design, optimization and control of the drying processes. Data on the drying characteristics of the bay laurel fruits, however, are not available for engineering design of drying systems. This study was undertaken to investigate the drying characteristics of the bay laurel fruits in a convective hot-air dryer, to calculate the effective diffusivity and activation energy of samples and to fit the experimental drying data obtained by the drying models widely used to describe drying of agricultural products.

MATERIALS AND METHODS

Fresh bay laurel fruits procured from Black Sea Region of Turkey were used in this study in November 2009. Hand harvested bay laurel fruits were cleaned from leafs and foreign materials and stored in a refrigerator at 4°C until drying experiments. The bay laurel fruits are shown in Figure 1. The average values for the major axis, medium axis, minor axis, equivalent mean diameter, sphericity and surface area of the bay laurel fruits were 16.95, 11.73 and 10.68 mm, 12.85, 0.76 and 518 mm^2, respectively. Moisture content was determined by drying in an oven at 105°C for 24 h (Gupta and Das, 1997). Initial moisture content of the bay laurel fruits was found to be 28.01% w.b. (wet basis).

Experimental equipment

The laboratory scale convective air dryer used in the drying experiments has a height of 57 cm, a width of 68 cm and a depth of 57 cm (Figure 2). The dryer consists of a fan to airflow supply, an electrical heater and a weighing system. The samples were dried in a drying basket of 576 cm^2 by 12 cm high. During the drying process, moisture loss in the drying basket was measured by means of load cell and continuously recorded by specially developed software connected to a PC.

Experimental procedure

In each experiment, about 100 g of the bay laurel fruits samples were used. After the system was run for at least half an hour to reach steady conditions for the operation temperatures, the samples were uniformly put into the sample basket as a single layer and dried there. The drying experiments were conducted at 70, 80, 90 and 100°C air temperatures and constant air velocity of 0.5 m/s. Moisture losses of samples were recorded at (1 min intervals throughout runs) 30 min intervals for first five hours and 1 h subsequently thereafter for determination of drying curves. The drying experiments were continued until no further changes in their mass were observed (about 4% d.b.). The dried samples were allowed to cool down at an ambient temperature for 10 min and then packed in low-density polyethylene. All drying experiments were performed in triplicate.

Evaluation of drying data

The experimental drying data obtained were fitted to the five well-known drying models given in Table 1. The moisture ratio is given as follows:

$$M_R = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

Where, M_R is the dimensionless moisture ratio; M, M_e and M_0 are the moisture content at any time, the equilibrium moisture content and the initial moisture content in % d.b., respectively.

However, M_R is simplified to M/M_0 instead of Equation (1) due to the continuous fluctuation of the relative humidity of the drying air during their drying processes (Diamente and Munro, 1993). The drying rate constants and coefficients of models were estimated using a non-linear regression procedure. The statistical validity of models was evaluated and compared by means of the coefficient of determination (R^2), mean relative percent deviation (P), root mean square error ($RMSE$) and reduced chi-square (χ^2). These comparison criteria methods can be calculated as follows:

$$P = \frac{100}{N} \sum_{i=1}^{N} \frac{\left| M_{R,ex,i} - M_{R,pre,i} \right|}{M_{R,\exp,i}} \tag{2}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(M_{R,ex,i} - M_{R,pre,i} \right)^2 \right]^{1/2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (M_{R,ex,i} - M_{R,pre,i})^2}{N - z} \tag{4}$$

Where, $M_{R,ex,i}$ is the ith experimental dimensionless moisture ratio; $M_{R,pre,i}$ is the ith predicted dimensionless moisture ratio; N is the

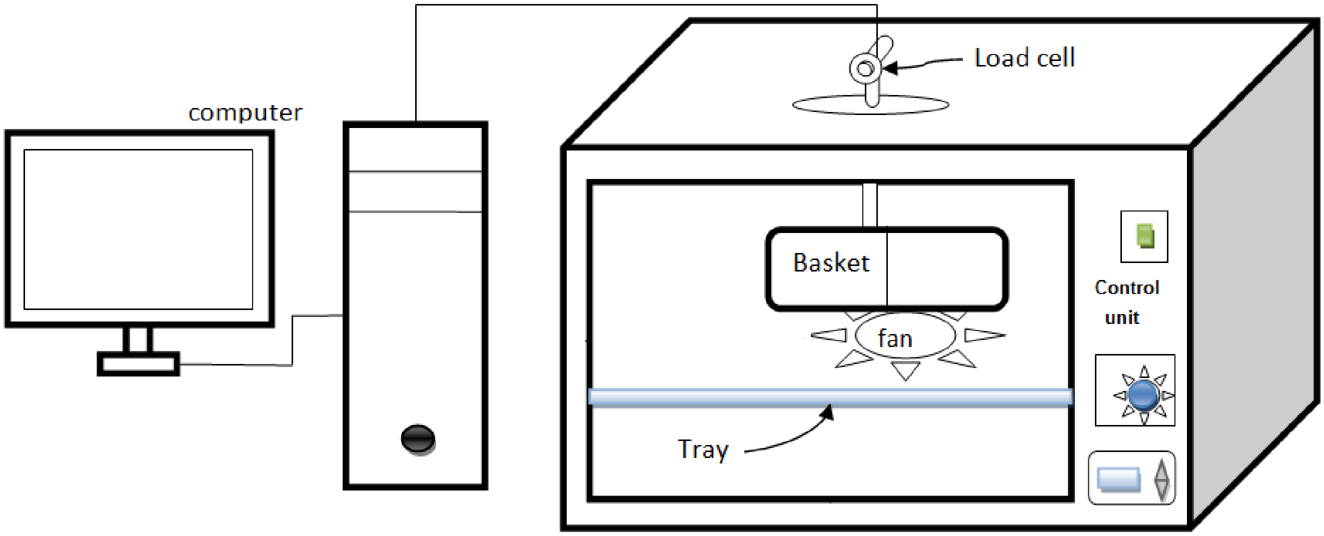

Figure 2. The schematic diagram of drying system used in experiments.

Table 1. Thin-layer drying models used for drying curves.

Model name	Model	Reference
Page	$M_R = \exp(-kt^m)$	Agrawal and Singh (1977)
Logarithmic	$M_R = a\exp(-kt) + c$	Yagcioglu et al. (1999)
Two-term	$M_R = a\exp(-kt) + b\exp(-k_0t)$	Henderson (1974)
Approximation of diffusion	$M_R = a\exp(-kt) + (1 - a)\exp(-kbt)$	Yaldiz and Ertekin (2001)
Midilli et al.	$M_R = a\exp(-kt^m) + bt$	Midilli et al. (2002)

number of observations; and z is the number of constants.

R^2 was used as the primary comparison criteria for selecting the best model to fit the five models to the experimental data. Also, the lower values of the mean relative percent deviation P, the root mean square error *RMSE* and the reduced chi-square were chosen as the comparison criteria for the goodness of fit of the experimental data obtained.

Calculation of effective diffusivity and activation energy

Drying process during the falling rate period is governed by water diffusion in the solid. This is a complex mechanism involving water in both liquid and vapour states. The experimental drying data for the determination of effective diffusivity were interpreted by using Fick's diffusion model. General series solution of Fick's second law in spherical, coordinates with the assumptions of moisture migration being by diffusion, negligible shrinkage, constant diffusion coefficients and temperature is given as follows (Crank, 1975):

$$M_R = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 D_{eff}\,t}{R_e^{\,2}}\right) \tag{5}$$

For long drying periods, Equation (5) can be further simplified to only the first term of the series and the moisture ratio M_R was reduced to M/M_0 because M_e was relatively small when compared with M and M_0. Then, Equation (5) can be written in logarithmic form:

$$\ln\frac{M}{M_0} = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\,t}{R_e^{\,2}}\right) \tag{6}$$

Where, R_e is the equivalent radius of the bay laurel fruits being dried in m; n is a positive integer and D_{eff} is the effective diffusivity in m^2/s.

The dependence of the effective diffusivity on the temperature is generally described by the Arrhenius equation (Equation 7):

$$D_{eff} = D_0\exp\left(-\frac{E_a}{RT_a}\right) \tag{7}$$

Where, D_0 is the pre-exponential factor of the Arrhenius equation in m^2/s; E_a is the activation energy in kJ/mol; R is the universal gas constant in kJ/mol.K and T_a is the absolute air temperature in K.

RESULTS AND DISCUSSION

Drying characteristics of bay laurel fruits

The moisture content changes with time during the drying

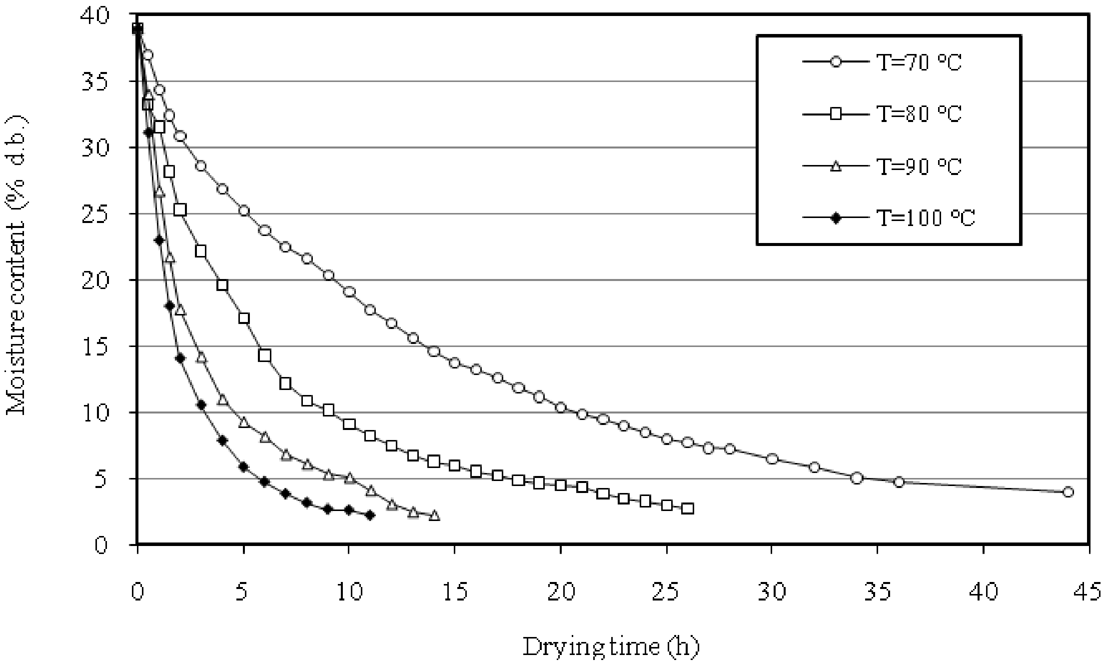

Figure 3. Effect of drying air temperature on moisture content of bay laurel fruit samples.

period for bay laurel fruits at different temperatures are given in Figure 3. There was no constant-rate period in this curve. The initial moisture content of bay laurel fruits was about 39% (d.b.). It is clear that as expected for thin samples, moisture content decreases continuously with drying-time. The air temperature had a significant effect on the moisture content of samples. The drying time required to reduce the moisture from the initial moisture content to a desired moisture content for bay laurel fruits was 44, 26, 14 and 10 h at air temperatures of 70, 80, 90 and 100°C, respectively. The decrease in the drying time with an increase in the air temperature have been observed by Doymaz et al. (2004) for olive cake, Ozdemir and Devres (1999) for hazelnut and Sacilik et al. (2010) for einkorn wheat.

The effect of air temperature on the drying rate of bay laurel fruits at 70, 80, 90 and 100°C air temperatures is indicated in Figure 4. It can be seen that the drying rate decreased continuously with a decrease in the moisture content or with an increase in the drying time at a given air temperature.

Determination of effective diffusivity and activation energy

During the falling rate drying period, the internal resistance governs the mass transfer. In this case, Fick's second law can be used to estimate the effective diffusivity. The effective diffusivity is typically calculated by plotting experimental drying data in terms of ln(M_R) versus drying time. From Equation (6), a plot of ln (M_R) versus the drying time gives a straight line with a slope:

$$\text{Slope} = \frac{\pi^2 D_{eff}}{R_e^{\ 2}} \tag{8}$$

The values of D_{eff} for the bay laurel fruits at air temperatures of 70, 80, 90 and 100°C are given in Table 2. The effective diffusivity was greatly influenced by the air temperatures. The values of D_{eff} increased with an increase in the air temperature due to rapid movement of water at high temperatures. The values of D_{eff} obtained from this study are within the general range 10^{-9} to 10^{-11} m^2/s for drying of food materials and comparable with the reported values of 2.02×10^{-10} to 4.24×10^{-10} m^2/s for garlic slices in a temperature range of 50 to 90°C (Madamba et al., 1996), 2.32×10^{-10} to 2.76×10^{-9} m^2/s for hot air drying of mulberry at 60 to 80°C (Maskan and Gogus, 1998), 20.28×10^{-10} m^2/s for hot air drying of paprika at 60°C (Ramesh et al., 2001), 2.17×10^{-10} to 2.40×10^{-10} m^2/s for hot air drying of plums at 60°C and air velocity of 1.2 m/s (Doymaz, 2004). These values are consistent with the present estimated D_{eff} values for the bay laurel fruits.

The activation energy was calculated by plotting the natural logarithm of D_{eff} versus reciprocal of the absolute temperature as presented in Figure 5. The slope of the line is ($-E_a/R$) and the intercept equals ln(D_0). The results show a linear relationship due to Arrhenius-type dependence. Equation (9) shows the effect of temperature on

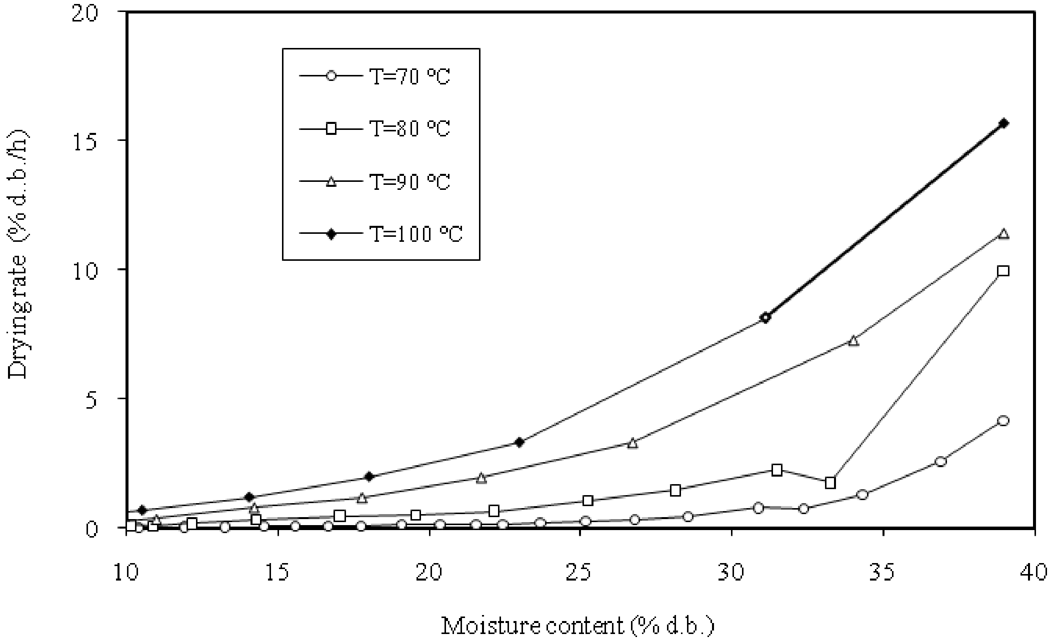

Figure 4. Drying rate curves of bay laurel fruits at indicated air temperatures.

Table 2. Values of effective diffusivity at various air temperatures.

Air temperature (°C)	Effective diffusivity (m^2/s)
70	1.95×10^{-10}
80	2.95×10^{-10}
90	3.54×10^{-10}
100	4.46×10^{-10}

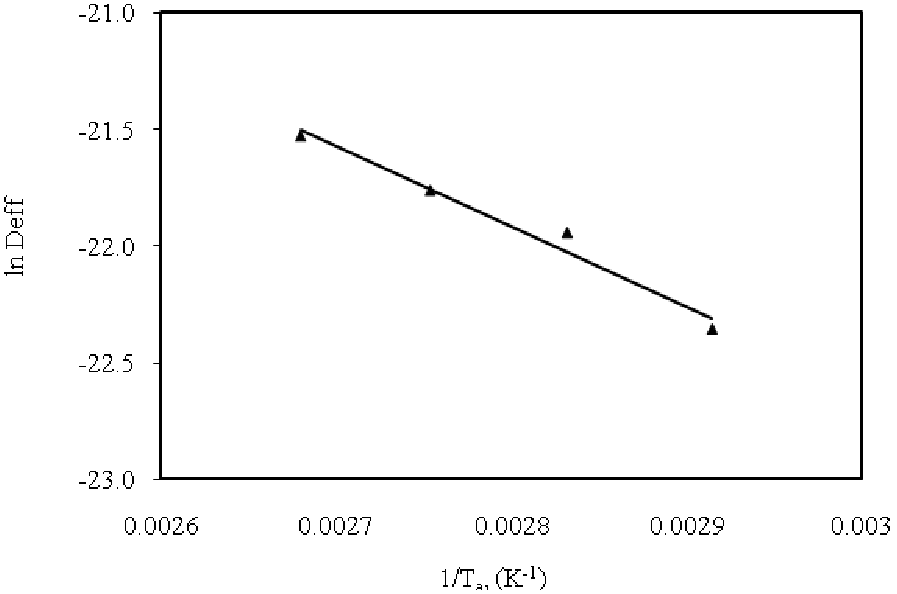

Figure 5. Arrhenius-type relationship between the effective diffusivity and absolute temperature.

Table 3. Parameter estimation and comparison criteria of the five drying models of the bay laurel fruits.

T (°C)	Model name	Estimated value	R^2	P (%)	RMSE	χ^2
70	Page	k=0.1199; m=0.7953	0.9986	1.77	0.009344	0.000092
	Logarithmic	a=0.8610; k=0.0786; c=0.0859	0.9957	2.61	0.016945	0.000306
	Two-term	**a=0.1576; k=0.6937; b=0.8478; k_0=0.0563**	**0.9993**	**1.88**	**0.006991**	**0.000052**
	Approximation of diffusion	a=0.1533; k=0.6581; b=0.0855	0.9992	1.86	0.006996	0.000051
	Midilli et al.	a=0.9997; k=0.1250; m=0.7627; b=-0.0008	0.9989	1.74	0.008620	0.000079
80	Page	k=0.2923; m=0.7089	0.9903	12.32	0.026631	0.000766
	Logarithmic	a=0.8666; k=0.2288; c=0.1020	0.9954	8.62	0.018629	0.000376
	Two-term	**a=0.2775;k=0.0467; b=0.7158; k_0=0.3120**	**0.9987**	**1.91**	**0.010012**	**0.000109**
	Approximation of diffusion	a=0.7147; k=0.3194; b=0.1502	0.9987	1.99	0.009961	0.000107
	Midilli et al.	a=1.0138; k=0.2778; m=0.7931; b=0.0025	0.9966	6.05	0.016210	0.000285
90	Page	k=0.3841; m=0.7471	0.9926	8.64	0.025707	0.000762
	Logarithmic	a=0.8894; k=0.3465; c=0.0896	0.9915	13.32	0.028503	0.000947
	Two-term	**a=0.4375; k=0.1223; b=0.5765; k_0=0.6245**	**0.9973**	**3.46**	**0.016466**	**0.000320**
	Approximation of diffusion	a=-0.2455; k=0.2686; b=1.0011	0.9645	30.19	0.058572	0.004002
	Midilli et al.	a=1.0184; k=0.3911; m=0.7878; b=0.0025	0.9949	6.52	0.022902	0.000619
100	Page	k=0.5054; m=0.7628	0.9950	7.50	0.021899	0.000575
	Logarithmic	a=0.9068; k=0.4866; c=0.0728	0.9933	10.95	0.026590	0.000864
	Two-term	**a=0.4684; k=0.3632; b=0.4684; k_0=0.3632**	**0.9975**	**5.86**	**0.016188**	**0.000320**
	Approximation of diffusion	a=0.4661; k=0.2004; b=4.3520	0.9786	27.11	0.050028	0.003128
	Midilli et al.	a=1.0090; k=0.5103; m=0.8106; b=0.0030	0.9964	3.56	0.020338	0.000517

D_{eff} of samples with the following coefficients:

$$D_{eff} = 4.33\times10^{-6}\exp\left(-\frac{3416.46}{T}\right) \qquad (9)$$

with values for R^2 of 0.9739.

The value of activation energy was found to be 28.41 kJ/mol, according to Equation (9). The value obtained in this study is in agreement with range of 12.7 to 110 kJ/mol for various foods reported by Zogzas et al. (1996).

Evaluation of the models

The drying data obtained from the experiments were fitted by five drying models mentioned in Table 1. Non-linear regression analysis was used to estimate the parameters of those models. The statistical results from models are summarised in Table 3. The best model describing the thin-layer drying characteristics of bay laurel fruits was chosen as the one with the highest R^2 values and the lowest *P*, *RMSE* and χ^2 values. The R^2 values of all models were all above 0.9645, indicating a good fit. The values of R^2, *P*, *RMSE* and χ^2 changed between 0.9645 to 0.9993, 1.74 to 30.19, 0.006991 to 0.058572 and 0.0000517 to 0.004002, respectively. Of all the models tested, the Two-term model gave the highest value of R^2 and the lowest values of *P*, *RMSE* and χ^2. Comparisons between the experimental and predicted moisture ratios with the Two-term model versus the drying time at 70, 80, 90 and 100°C are also shown in Figure 6. It can be seen from this that there was a good conformity between experimental and predicted moisture ratios. Accordingly, this indicates the suitability of the Two-term model in describing the drying characteristics of the bay laurel fruits.

Conclusions

The results from this study show that drying curves were greatly affected by the air temperatures. Drying rate increased with the increase in the drying air temperature, hence, reducing the drying time. The drying time required to reduce the moisture from the initial moisture content to a desired moisture content for the bay laurel fruits was 44, 26, 14 and 10 h at air temperatures of 70, 80, 90 and 100°C, respectively. The effective diffusivity increased from 1.95×10^{-10} to 4.46×10^{-10} m^2/s as temperature increased from 70 to 100°C. Temperature dependence of the effective diffusivity was described by Arrhenius-type relationship. The activation energy for moisture diffusion was found as 28.41 kJ/mol, which was in agreement with

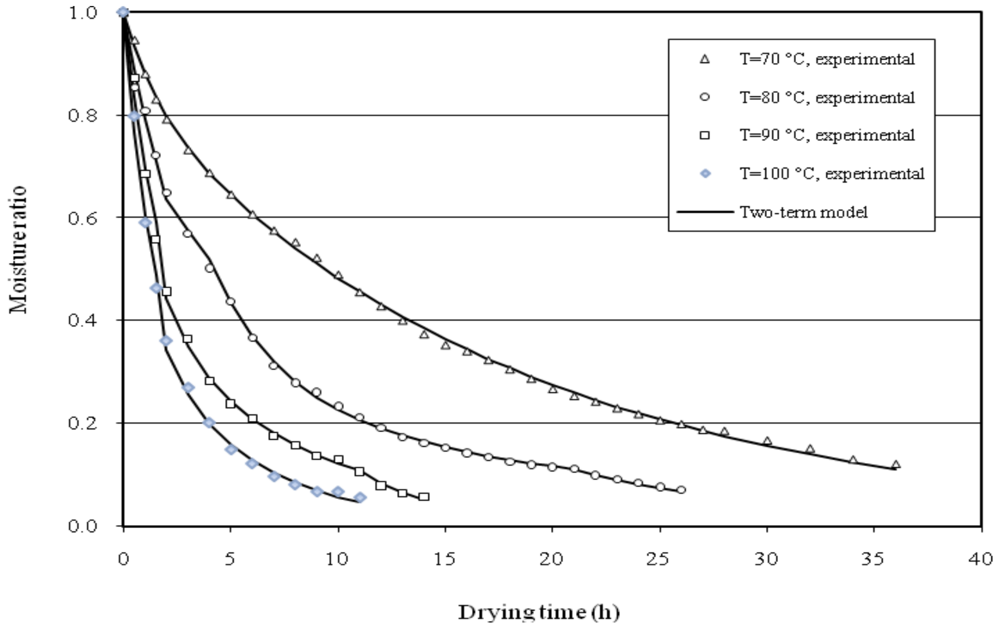

Figure 6. Variation of the experimental and predicted moisture ratios by the Two-term model for drying characteristics of the bay laurel fruits.

data in the literature. Of all the five models tested, the Two-term model gave an excellent fit to the experimental data obtained with a value for R^2 of greater than 0.9645 within the experimental range of study.

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