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Mathematical modelling of drying of bay leaves

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Abstract

This paper presents a study on the mathematical modelling of bay (*Laurus nobilis L.*) leaves. Drying experiments were performed in a laboratory scale dryer constructed in the Department of Agricultural Machinery, Faculty of Agriculture, Ege University, Izmir, Turkey. The leaves were 90–100 mm long and 30–40 mm wide, and ones with no blemish were selected and used for the drying tests. The tests were performed with various relative humidities (5%, 15% and 25%) and temperatures (40, 50 and 60 °C) at a constant air velocity of 1.5 m/s. Fifteen different mathematical drying models were compared based on their correlation coefficient, root mean square error, mean bias error, reduced chi-square and *t*-statistic method to estimate the drying curves. It may be concluded that the Page model could sufficiently describe drying of bay leaves.

Keywords: Drying; Bay (Laurel) leaves; Modelling

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Nomenclature

a, b, c, g, h, n	dimensionless drying constant in drying models
k, k_0, k_1	drying velocity constant in drying models (1/h)
L	slice half thickness (mm)
M_t	moisture content (% dry basis) ($g_{water}/g_{dry\ solids}$)
MBE	mean bias error
M_R	moisture ratio
N	total number of observations
n	number of constants
R	correlation coefficient
R^2	coefficient of determination
RH	mean effective relative humidity in drying chamber (decimal)
RMSE	root mean square error
T	temperature (°C)
t	time (h)
t-stat	t-statistic method

Greek symbols

v	degrees of freedom
σ	standard deviation
χ^2	reduced chi-square

Subscripts

0	initial
crit	critical
e	equilibrium
exp	experimental
m	mean
pre	predicted

1. Introduction

In many agricultural countries, large quantities of food products are dried to improve shelf life, reduce packing costs, lower shipping weights, enhance appearance, encapsulate original flavour and maintain nutritional value. In this regard, the goals of drying process research in the food industry may be classified in three groups as follows: (a) economic considerations, (b) environmental concerns and (c) product quality aspects. Though the primary objective of food drying is preservation, depending on the drying mechanisms, the raw material may end up a completely different material with significant variation in product quality [1].

Drying is an energy intensive operation of some industrial significance. In most industrialized countries, the energy used in drying accounts for 7–15% of the nation's industrial energy, often with relatively low thermal efficiencies ranging from 25% to 50% [2,3]. The most important aspect of drying technology is the mathematical modelling of the drying processes and equipment. Its purpose is to allow design engineers to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet desired operating conditions. The principle of modelling is based on having a set of mathematical equations that can adequately characterize the system. In particular, the solution of these equations must allow prediction of the process parameters as a function of time at any point in the dryer based only on the initial conditions [4,5].

In recent years, the drying behaviour of different products has been studied by many investigators [6–12]. Some products studied are as follows: Sultana grape [6], banana [7], apricot [8], seedless grape, fig, green pea, tomato and onion [9], pistachio [10], potato slice [11], pumpkin slice [12] and eggplant [13]. There are, however, few works on the drying process of bay leaves in the literature [14].

The main objective of the present study is to develop a mathematical model for drying of bay leaves.

2. Material and method

2.1. Dryer

Drying experiments were performed in a laboratory scale dryer constructed in the Department of Agricultural Machinery, Faculty of Agriculture, Ege University, Izmir, Turkey. A schematic diagram of the laboratory dryer is illustrated in Fig. 1, while the drying system has been described in detail elsewhere [15]. The dryer consists mainly of three subsystems, namely (a) air supply unit, (b) drying unit with heater and humidifier and (c) data acquisition and electronic control unit.

Temperature control, data acquisition and storage as well as the general supervision of the unit: start-up and shut down of electric heaters, injecting hot water into the air stream and circulating cold water through the cooling tower, are done by the GENIE data acquisition software.

2.2. Experiments

Experiments were performed to determine the effect of the drying air temperature and relative humidity. Three temperature points of 40, 50 and 60 °C at a relative humidity of 15% were selected to determine the effect of the temperature of the drying air on the drying coefficient. The tests were also performed to determine the effect of relative humidity of the air flow on the drying with relative humidity of 5–25% at temperatures of 50 and 60 °C. All experiments were conducted at an air velocity of 1.5 m/s in three replications. Before starting the experiments, the system was run for at least one hour to obtain steady state conditions. The leaves were 90–100 mm long and 30–40 mm wide, and ones with no blemish were selected and used for the drying tests. The leaves were hung in a vertical drying channel, as the surface of the leaves was held parallel to the direction of air flow. The initial moisture content of the bay leaves was determined by leaving the samples in an air-circulated oven for 5 h at 105 °C.

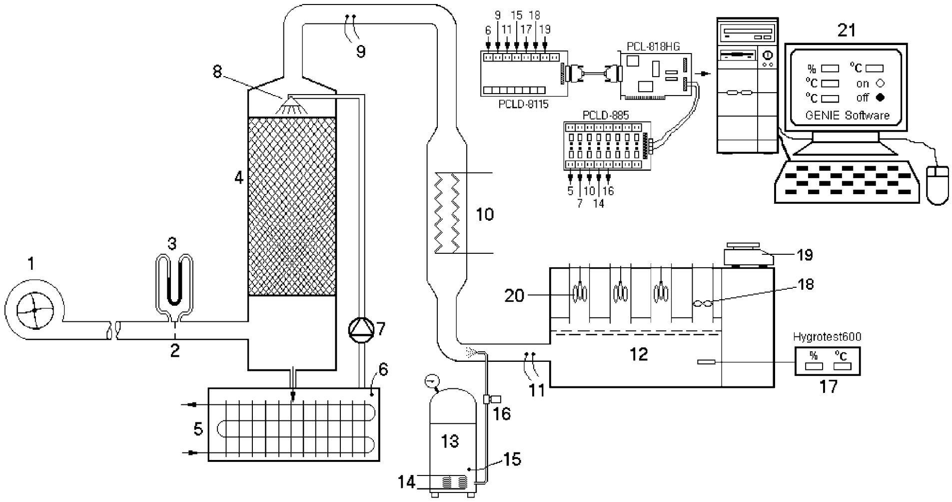

Fig. 1. Schematic diagram of the laboratory dryer (1—centrifugal fan; 2—orifice plate; 3—differential manometer; 4—cooling and saturating tower; 5—cold water tank and evaporator; 6,9,11,15—thermocouples (T type); 7—cold water circulation pump; 8—cold water shower; 10—electric heaters; 12—mixing chamber and drying air channels; 13—steam tank; 14—electric water heater; 16—injector and solenoid valve; 17—relative humidity and temperature sensor; 18—anemometer; 19—balance; 20—bay leaves; 21—computer with data acquisition and control cards).

2.3. Mathematical modelling of drying curves

The drying curves obtained were processed to find the most convenient one among 15 different expressions defining drying rates, as given in Table 1, by several investigators [16–34]. 630 experiments of bay leaves were performed with various relative humidities (5%, 15% and 25%) and temperatures (40, 50 and 60 °C) at a constant air velocity of 1.5 m/s. The initial moisture content of the

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

Model no.	Model name	Model equation	References
1	Lewis	$M_R = \exp(-kt)$	[16,17]
2	Page	$M_R = \exp(-kt^n)$	[18,19]
3	Modified Page	$M_R = \exp[-(kt)^n]$	[20,21]
4	Henderson and pabis	$M_R = a\exp(-kt)$	[22,23]
5	Yagcioglu et al.	$M_R = a\exp(-kt) + c$	[14]
6	Two-term	$M_R = a\exp(-k_0t) + b\exp(-k_1t)$	[24,25]
7	Two-term exponential	$M_R = a\exp(-kt) + (1-a)\exp(-kat)$	[26]
8	Wang and Singh	$M_R = 1 + at + bt^2$	[27]
9	Thomson	$t = a.\ln(M_R) + b[\ln(M_R)]^2$	[28,29]
10	Diffusion approach	$M_R = a\exp(-kt) + (1-a)\exp(-kbt)$	[30]
11	Verma et al.	$M_R = a\exp(-kt) + (1-a)\exp(-gt)$	[31]
12	Modified Henderson and pabis	$M_R = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	[32]
13	Simplified Fick's diffusion (SFFD) equation	$M_R = a\exp[-c(t/L^2)]$	[33]
14	Modified Page equation-II	$M_R = \exp[-k(t/L^2)^n]$	[34]
15	Midilli and Kucuk	$M_R = a\exp(-kt^n) + bt$	[35]

bay leaves ranged from 0.86 to 1.15 kg water per kg dry matter and was reduced to the final moisture content of 0.04747–0.07032 kg water per kg dry matter. The moisture ratio was calculated using $M_R = (M_t - M_e)/(M_0 - M_e)$, which was simplified to M_t/M_0 by some investigators [6,8,10] because of the continuous fluctuation of the relative humidity of the drying air during their drying processes.

In the literature, there are several statistical test methods used to evaluate statistically the performance of the drying models. Among these, the correlation coefficient (R^2), the mean bias error (MBE), the root mean square error (RMSE) and the reduced chi-square (χ^2) are the most widely used ones [8–17,35–37], as given below.

2.3.1. Correlation coefficient (R)

The correlation coefficient, R can be used to test the linear relation between measured and estimated values, which can be calculated from the equation

$$R^2 = \frac{\sum_{i=1}^{N}(M_{R_i} - M_{R_{\mathrm{pre,i}}}) * (M_{R_i} - M_{R_{\mathrm{exp},i}})}{\sqrt{\left[\sum_{i=1}^{N}(M_{R_i} - M_{R_{\mathrm{pre,i}}})^2\right] * \left[\sum_{i=1}^{N}(M_{R_i} - M_{R_{\mathrm{exp},i}})^2\right]}} \tag{1}$$

where R^2 is called the coefficient of determination, $M_{R\mathrm{exp},i}$ stands for the experimental moisture ratio found in any measurement, $M_{R\mathrm{pre},i}$ is the predicted moisture ratio for this measurement and N is the total number of observations.

2.3.2. Mean bias error (MBE)

The mean bias error is given as:

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}(M_{R_{\mathrm{pre,i}}} - M_{R_{\mathrm{exp},i}}) \tag{2}$$

The MBE provides information on the long term performance of the correlations by allowing a comparison of the actual deviation between predicted and measured values term by term. The ideal value of MBE is 'zero'.

2.3.3. Root mean square error (RMSE)

The root mean square error may be computed from the following equation

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

which provides information on the short term performance. The value of RMSE is always positive, represented as 'zero' in the ideal case.

2.3.4. Reduced chi-square (χ^2)

The reduced χ-square may be calculated as:

$$\chi^2 = \frac{\sum_{i=1}^{N}(M_{R_{\mathrm{exp},i}} - M_{R_{\mathrm{pre,i}}})^2}{N - n} \tag{4}$$

where n is the number of constants. The lower are the values of the reduced χ-square, the better is the goodness of fit [10].

2.3.5. t-Statistic method (t-stat)

In this study, the t-statistic method was also considered, differing from the previous studies on drying modelling. To determine whether or not the equation estimates are statistically significant, i.e. not significantly different from their actual counterparts, at a particular confidence level, Stone [38] proposed the t-statistic as [39]:

$$t\text{-stat} = \sqrt{\left[\frac{(n-1)\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}\right]} \tag{5a}$$

Using published data in the literature, Stone [38] demonstrated that the MBE and RMSE separately do not represent a reliable assessment of the model's performance and can lead to false selection of the best model from a set of candidate ones. In order for that equation estimates to be significant, the t-value produced by Eq. (5a) must be smaller than the value for that confidence level given in standard statistical tables.

The t-statistic may also be calculated from [40]

$$t\text{-stat} = \frac{MR_{\mathrm{m,exp}} - MR_{\mathrm{m,pre}}}{\left[\dfrac{\sigma^2_{\mathrm{exp}}}{n_{\mathrm{exp}}} + \dfrac{\sigma^2_{\mathrm{pre}}}{n_{\mathrm{pre}}}\right]} \tag{5b}$$

where the subscript m is the mean of the data and σ is the standard deviation of the data. The degrees of freedom for the experimental and predicted values are approximated by

$$v = \frac{\left[\dfrac{\sigma^2_{\mathrm{exp}}}{n_{\mathrm{exp}}} + \dfrac{\sigma_{\mathrm{pre}^2}}{n_{\mathrm{pre}}}\right]^2}{\dfrac{\left(\frac{\sigma^2_{\mathrm{exp}}}{n_{\mathrm{exp}}}\right)^2}{n_{\mathrm{exp}} - 1} + \dfrac{\left(\frac{\sigma^2_{\mathrm{pre}}}{n_{\mathrm{pre}}}\right)^2}{n_{\mathrm{pre}} - 1}} \tag{5c}$$

where v is rounded down to an integer. The confidence level is taken as 0.05.

In this study, the constants and coefficients of the best fitting model involving the drying variables such as temperature and relative humidity of the drying air were determined. The effects of these variables on the constants and coefficients of the drying air expression were also investigated by multiple linear regression analyses.

2.4. Uncertainty analysis

Errors and uncertainties in experiments can arise from instrument selection, instrument condition, instrument calibration, environment, observation and reading and test planning [41].

Table 2
Uncertainties in measurement of parameters during drying of bay leaves

Instrument		Range	Estimated uncertainty
Electronic balance		0–610 g	± 0.01 g (based on manufacturer's specification)
Hygrometer	Humidity	0–100% R_H	± 3% R_H (based on calibration data)
	Temperature	−20 to +120 °C	± 0.5 °C (−20 to +50 °C); ± 1.5% (>50 °C) (based on calibration data)
Thermocouples (type T; copper + constantan)		0–400 °C	± 0.5 °C (based on manufacturer's specification)
Anemometer		0–20 m/s	± 0.1 m/s (based on manufacturer's specification)

Uncertainty analysis is needed to prove the accuracy of the experiments. An uncertainty analysis was performed using the method described by Holman [40]. This calculation method concerning uncertainty analysis was also used in many studies [42–44]. In the present study, the air temperatures, velocities, weights and humidities were measured with appropriate instruments as explained previously. The total uncertainties of these parameters are presented in Table 2. Using a similar calculation procedure explained in detail elsewhere [38,44], the uncertainties in calculating the moisture content and ratio were obtained to be ± 4.24% and 5.99%, respectively.

3. Results and discussion

Figs. 2–4 illustrate the changes in the moisture ratio of the bay leaves with drying time, and drying rates versus drying time. It is clear from these figures that the drying rate decreases

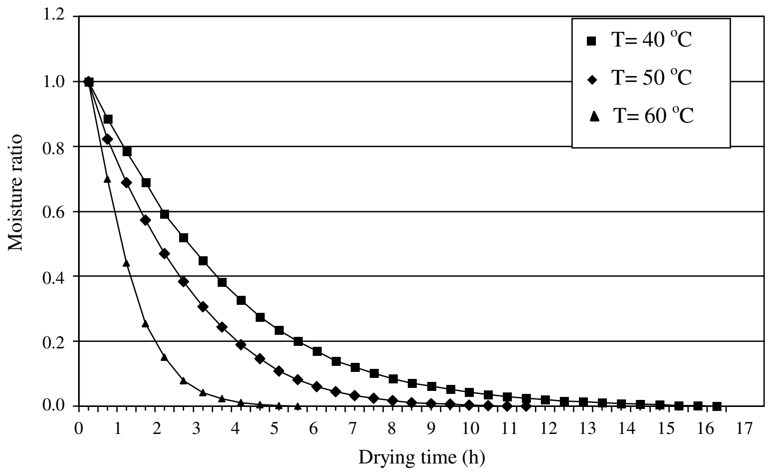

Fig. 2. Relationship between the moisture ratio and drying time at different air temperatures at 15% relative humidity.

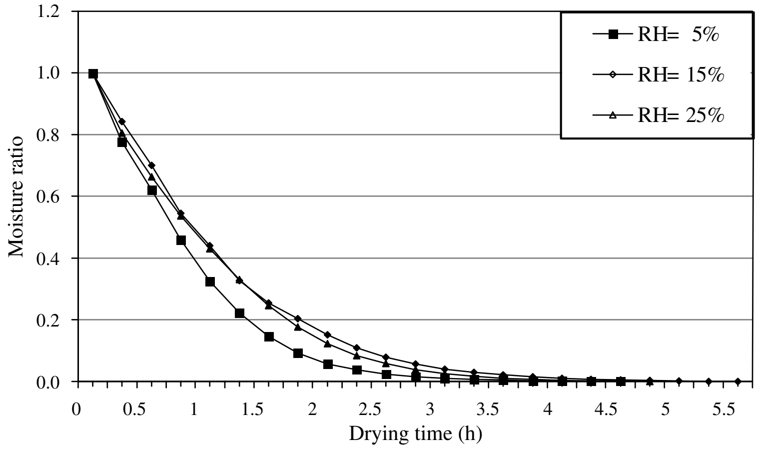

Fig. 3. Relationship between the moisture ratio and drying time at different relative humidity at 60 °C air temperatures.

continuously with the moisture content or drying time. There is not any constant rate drying period in these curves, and all the drying operations are seen to occur in the falling rate period. Final drying duration takes 5–18 h in the dryer, while it takes about 8 and 25–30 days in the months of September and October in open air sun drying, respectively. As can be seen from Figs. 2–4, one of the main factors influencing the drying kinetics of bay leaves is the drying air temperature during the falling rate drying period. An increase in drying air temperature resulted in a decrease in the drying time.

The moisture content data obtained for different drying air temperatures and relative humidities were converted to the moisture ratio expression and then curve fitting computations with the drying time were performed on the 15 drying models given by previous investigators. These models and the results of the statistical analyses are shown in Tables 2 and 3. As can be seen from the statistical analysis results, generally high correlation coefficients are found for the drying models. Nevertheless, the results have shown that the highest values of R and the lowest values of χ^2, MBE, RMSE and t-stat could be obtained with the Page, Modified Page, Modified Page equation II and Midilli and Kucuk expressions. In this study, the Page model was preferred due to its simplicity. Thus, the Page model may be assumed to represent the drying behaviour of bay leaves (see Table 4).

Further regressions were made to take into account the effect of the drying variables on the Page model constant k (h^{-1}). The effects of temperature, T (°C) and relative humidity, RH (%) of the drying air on k were also included in the model by multiple regression analyses. The multiple combinations of the variables that gave the highest R were finally covered in the final model. Based on the multiple regression analyses, the accepted model constants and coefficients were as follows:

$$M_R = \exp(-kt^n) \tag{6}$$

where

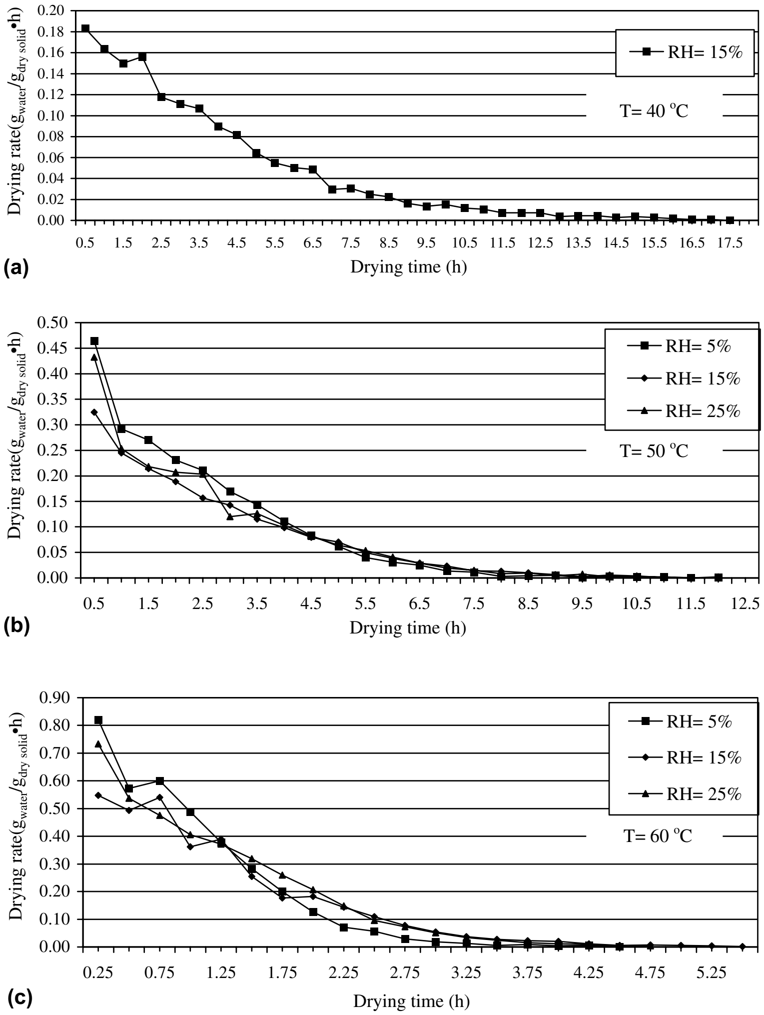

Fig. 4. Drying rate of bay leaves versus drying time.

$$
\begin{aligned}
k &= \exp(-4.4647 + 0.07455T - 0.00714\mathrm{RH}) \quad R = 0.964 \\
n &= 1.14325
\end{aligned} \tag{7}
$$

Using Eq. (6), the moisture contents of bay leaves at any time during the drying process could be easily estimated. Validation of the established model was made by comparing the computed moisture contents with the measured moisture contents in any particular drying run under certain conditions. The performance of the model at an air temperature of 60 °C and a relative humidity of 15% is shown in Fig. 5. It is obvious from this figure that the predicted data generally banded around the straight line, which indicated the suitability of the model proposed in describing the drying behaviour of bay leaves.

Table 3
Results of statistical analyses on the modelling of bay leaves drying at 15% RH with 40 °C

Model no.	Model constant	R	MBE	RMSE	χ^2	t-value
1	$k = 0.284924$	0.9973	0.0037943	0.020257039	0.000414	1.972438
2	$k = 0.237818$; $n = 1.122381$	0.9989	0.00105562	0.012859195	0.000168	0.852028
3	$k = 0.278136$; $n = 1.122381$	0.9989	0.00105562	0.012859195	0.000168	0.852026
4	$a = 1.036579$; $k = 0.294803$	0.9979	0.00488335	0.017987510	0.000330	2.917855
5	$a = 1.043381$; $k = 0.279231$; $c = -0.01679$	0.9984	−2.771E−09	0.015605286	0.000250	1.84E−06
6	$a = 0.518289$; $k_0 = 0.294803$; $b = 0.518289$ $k_1 = 0.294803$	0.9979	0.00488335	0.017987511	0.000336	2.917855
7	$a = 0.132493$; $k = 1.876398$	0.9911	0.00568685	0.036694611	0.001372	1.622709
8	$a = -0.170961$; $b = 0.006911$	0.9691	0.01543932	0.067851837	0.004691	2.417147
9	$a = 3.806987$; $b = 0.200703$	0.9962	0.00364	0.01420	0.00020	2.747
10	$a = -1.788212$; $k = 0.485588$; $b = 0.806496$	0.9989	0.00058452	0.012668979	0.000165	0.477761
11	$a = -1.301731$; $k = 0.176634$; $g = 0.215758$	0.9985	−0.0017876	0.015178881	0.000237	1.226736
12	$a = 0.345526$; $k = 0.294803$; $b = 0.345526$; $g = 0.29480264$; $c = 0.345526$; $h = 0.294803$	0.9979	0.00488335	0.017987511	0.000343	2.917855
13	$a = 1.036609$; $c = 0.006634$	0.9979	0.00487605	0.017987510	0.000330	2.913146
14	$k = 0.003365$; $n = 1.122308$	0.9989	0.00108415	0.012859242	0.000169	0.875219
15	$a = 0.995057$; $k = 0.235415$; $n = 1.122828$; $b = -0.000185$	0.9989	5.8563E−06	0.012719529	0.000168	0.004763

Table 4
Results of statistical analyses on the modelling of bay leaves drying at 5% RH with 60 °C

Model no.	Model constant	R	MBE	RMSE	χ^2	t-value
1	$k = 1.169940$	0.9954	0.00645539	0.028139597	0.0008060	1.763755
2	$k = 1.151324$; $n = 1.226905$	0.9993	0.00212662	0.011030505	0.0001261	1.470327
3	$k = 1.121707$; $n = 1.226905$	0.9993	0.00212662	0.011030505	0.0001261	1.470327
4	$a = 1.040074$; $k = 1.211591$	0.9961	0.00852362	0.025794509	0.0006896	2.619986
5	$a = 1.055218$; $k = 1.124126$; $c = -0.025315$	0.9973	2.0088E−09	0.021350896	0.0004812	7.04E−07
6	$a = 0.520037$; $k_0 = 1.211595$; $b = 0.520037$; $k_1 = 1.211595$	0.9961	0.00852362	0.025794509	0.0007156	2.619986
7	$a = 1.762239$; $k = 1.585509$	0.9992	0.00317603	0.011682648	0.0001414	2.114027
8	$a = -0.682655$; $b = 0.108237$	0.9726	0.01463499	0.068174338	0.0048167	1.644789
9	$a = -0.814722$; $b = 0.006640$	0.9676	−0.00881	0.03024	0.00094	2.281
10	$a = -1.319392$; $k = 0.655407$; $b = 1.2727502$	0.9979	−0.00314869	0.018857884	0.0003754	1.267278
11	$a = -5.883639$; $k = 0.724701$; $g = 0.7746501$	0.9980	−0.00338323	0.018728536	0.0003702	1.374442
12	$a = 0.3466910$; $k = 1.211590$; $b = 0.346691$; $g = 1.2115901$; $c = 0.3466914$; $h = 1.211591$	0.9961	0.008523621	0.025794509	0.0007436	2.619986
13	$a = 1.0400749$; $c = 0.027261$	0.9961	0.00852369	0.025794501	0.0006896	2.620014
14	$k = 0.0109577$; $n = 1.226754$	0.9993	0.00213394	0.011030513	0.0001261	1.475584
15	$a = 0.9880610$; $k = 1.131991$; $n = 1.240885$; $b = -0.000669$	0.9993	0.00030946	0.010503498	0.0001186	0.220575

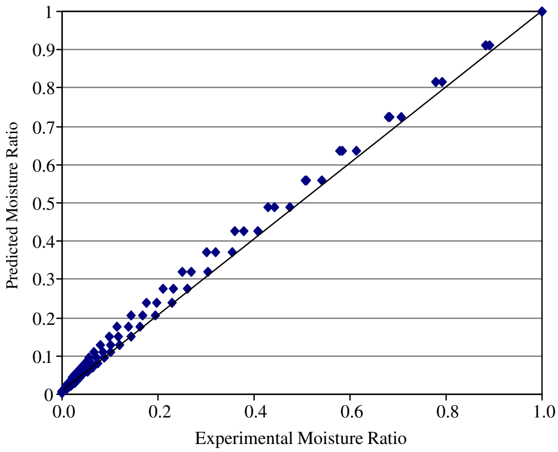

Fig. 5. Experimental and predicted moisture ratio at 60 °C air temperatures and 15% relative humidity.

4. Conclusions

In this study, the drying behaviour of bay leaves was investigated. The drying process occurred in the falling rate period, starting from the initial moisture content to the final moisture content of 0.04747–0.07032 kg water per kg dry matter. In order to describe the drying behaviour of bay leaves, 15 models proposed by previous investigators were applied to the drying process, while a new model was developed. Among these models, the drying model developed by Page [18,19] showed good agreement with the data obtained from the experiments of the present study. It may be concluded that the model developed adequately explained the drying behaviour of the product studied at a temperature range of 40–60 °C with 5–25% relative air humidity.

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