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Mathematical Modelling and the Determination of Some Quality Parameters of Air-dried Bay Leaves

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Bay leaves (*Laurus nobilis L.*) were dried at 40, 50 and 60°C air temperatures and 5, 10, 15% relative humidities and also under sun and shade in outdoor areas to see whether any significant difference of quality occurs in drying with hot air. During the drying tests with hot air, air flow velocity was held stable at $1{\cdot}5\,\mathrm{m\,s^{-1}}$ and the samples were hung in the drying channels as the surface of the leaves were held parallel to the direction of air flow. To find out the moisture content changes of the samples, weight loss from the leaves were recorded at fixed intervals. Then, the data obtained from the drying tests were applied to various well-known semi-empirical mathematical models of drying. As part of this effort, five well-known models with drying rate constant as a function of air temperature and both temperature and relative humidity were tested for goodness of fit. Furthermore, to determine the effects of the drying conditions on the colour and the amount of essential oil of the bay leaves, fresh leaves and the leaves dried under different conditions were compared. Among all the drying models, the Page model was found to satisfactorily describe the kinetics of convection drying of bay leaves. It was concluded that no significant loss of quality occurs when drying bay leaves at 60°C air temperature.

1. Introduction

Bay leaves are widely used and known as a flavouring and medicinal herb since ancient Greek and Roman times. They are pruned from an evergreen small tree or shrub formed plant that is botanically known as *Laurus nobilis L.* The approved name of this leaf is 'bay leaf', but the name 'laurel' is frequently used. Bay leaves are smooth, leathery and glossy green above and paler beneath. Alternately affixed to branches, they are short-petioled, oblong lancelote or oblong in shape.

Laurus nobilis L. is native to the Mediterranean region and Asia Minor. Currently, the plant is cultivated in many Mediterranean countries. Commercial production centres include areas such as Turkey, Algeria, France, Greece, Morocco, Portugal, Spain, Belgium, The Canary Islands, Mexico, Central America, and the Southern United States.

Turkey is one of the main producers and suppliers of bay leaves. The average amount of exported dried bay leaves from Turkey was 4 million kg per year during the 1999–2001 (Artukoğlu & Uzmay, 2003).

Bay leaves are strongly aromatic, but also quite bitter. However, by an appropriate drying procedure, the bitterness can be significantly reduced, and the flavour can be improved. Being one of the best-known flavouring leaves in all countries, they are commonly used in soups, stews, sauce, pickles, sausages, and also an essential ingredient of the herb mixes. As a medicinal plant, bay leaves have been used as a cure for rheumatism, skin rashes and earaches. In addition, it has been used as a stomatic, astringent, carminative, diaphoretic, stimulatory, emetic, emmenagogic, abortifacient agent, and as an insect repellent. In addition, essential oil is used by the cosmetic industry. The oil content of bay leaves ranges from 1 to 3% on fresh-weight basis. There appears to be a seasonal periodicity in oil synthesis and accumulation with significant oil increase in early summer and it becomes maximum in mid-summer. The main constituent of the essential oil includes 1·8 cineol (45–50%), α and β pinene, sabinene, linalool, eugenol, eugenol acetate, methyleugenol, ternineol acetate, phellandrene, plus other esters and terponoids (Deraz & Bayram, 1996). The high concentrations of oil catechins in bay leaves are maintained by drying.

Drying is the main step in the preparation of bay leaves for marketing. In Turkey, they are generally dried under ambient conditions by sun drying. Branches of leaves are pruned from bay trees and gathered together as bunches allowing natural circulation of air. These branches are then spread out on the ground under the sun or shade.

Drying takes nearly ten days in good sunny conditions, but longer under adverse weather conditions in late autumn, which usually leads to contamination and quality losses. During this kind of drying process in outdoor conditions, leaves usually get polluted by birds, insects, dust, *etc.*, and lose their quality. This problem could be eliminated if bay leaves are dried under controlled conditions using special dryers. In order to accomplish effective drying using special dryers, the suitable drying conditions of the bay leaves to achieve the best possible quality from the point of the shape, colour and the essential oil properties of the dried leaves and the drying characteristics of bay leaves under these conditions must be known. Hence, a study was initiated with the following objectives:

(1) to develop a mathematical model for predicting the kinetics of convection drying of bay leaves in different air temperature and relative humidity conditions; and
(2) to determine the optimum convection drying conditions of bay leaves regarding shape, colour, essential oil and drying time.

2. Literature review

There is limited information and study on the drying characteristics of bay leaves in the literature.

Skrubis (1982) conducted a study to determine the optimum air temperature and layer thickness of bay leaves for drying. He used three different layer thickness of 50, 75 and 100 mm and four temperatures of 40, 50, 60 and 70°C. Based on his findings on the time of drying and the analysis of essential oil contents of dried bay leaves he concluded that bay leaves could be dried at 60°C without any loss in quality.

Yagcioglu *et al*. (1999) studied the effects of air velocities and the temperature on drying of bay leaves and worked with 40, 50 and 60°C air temperatures and 1, 1·5 and 2 $m\,s^{-1}$ air velocities without considering the relative humidity for the drying tests and determined the drying characteristics of bay leaves. They indicated that air velocity had insignificant effect on the drying of bay leaves. The results from the study were similar to those obtained by Skrubis (1982).

Ceylan and Ozay (1990) conducted a study to determine the most suitable picking time of bay leaves with respect to the amount of essential oil. They concluded that June, July and August are the most suitable months for picking the leaves and leaves picked from the lower branches of trees have more essential oil than the leaves picked from the upper levels.

Deraz and Bayram (1996) tried to find out the effects of picking time of bay leaves on the amount of essential oil. For this purpose, they collected the leaves in June, July and August at 8:00 a.m., 1:00 and 6:00 p.m. As a result of their study they found that the leaves collected in August at 8:00 a.m. had the highest amount of essential oil. They predicted that less amount of oil from the leaves collected at 1:00 and 6:00 p.m. in August could be due to the evaporation.

3. Materials and methods

3.1. *Materials*

The bay leaves used for the drying tests were collected from the lower branches of the bay trees located on the campus area of Ege University, between 7:30 and 8:00 a.m. in July and August as indicated by Ceylan and Ozay (1990) and Deraz and Bayram (1996). Unblemished leaves measuring approximately 90–100 mm long and 30–40 mm wide were selected and used for the drying tests.

3.2. *Experimental apparatus*

All tests were accomplished using drying apparatus shown in *Fig. 1*. Parts of the apparatus were similar to the apparatus described by Greig (1970) and Woods and Favier (1993) and consist of the following main parts.

3.2.1. *Air supply unit*

Airflow rate was controlled by changing the rotational speed of the electric motor for the fan.

3.2.2. *Cooling and saturating unit*

This unit consists of cooling and saturating tower, cold water tank and circulating pump. The cooling and saturating tower is filled up with plastic pipe pieces (outside diameter of 50 mm, length of 50 mm) to increase contact surface area between cold-water and air. The air stream enters the cooling tower at the bottom and leaves from top. Also cold water enters the

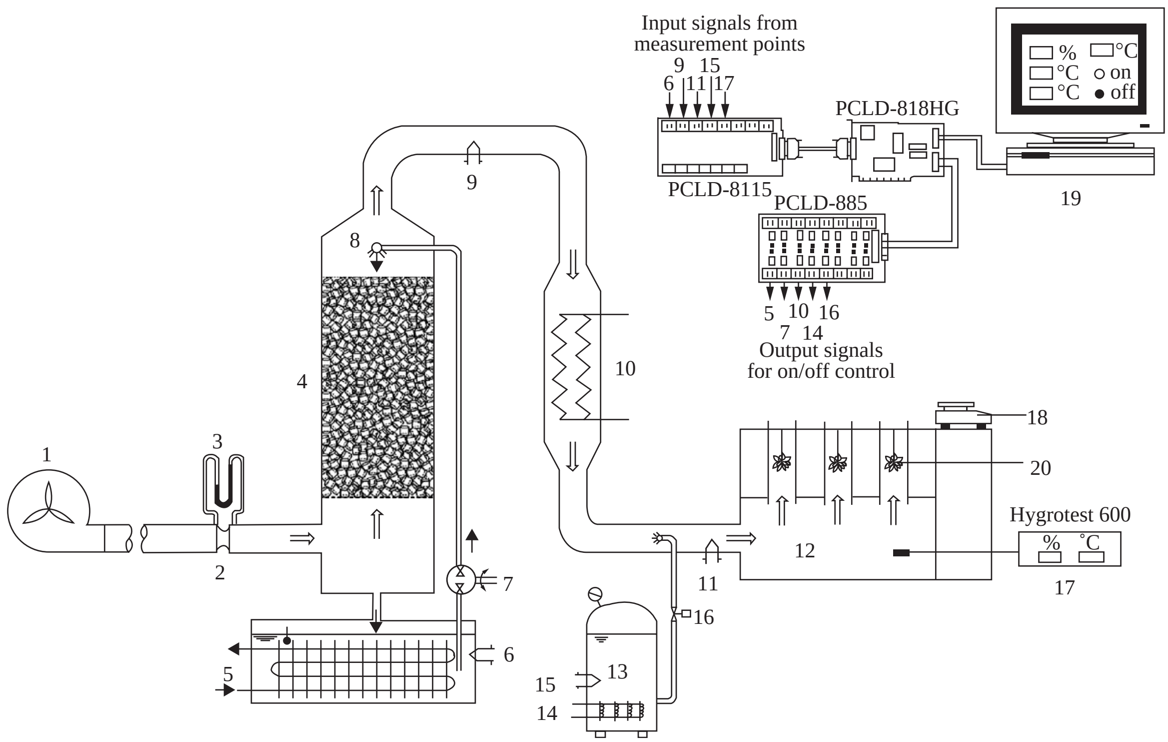

Fig. 1. Schematic representation of the drying apparatus: (1) centrifugal fan; (2) orifice plate; (3) differential manometer; (4) cooling and saturating tower; (5) cold water tank and evaporator; (6), (9), (11), (15) thermocouples (T type); (7) circulation pump; (8) cold water shower; (10) electric heaters;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

cooling tower at the top and leaves from the bottom. The cooling and saturating tower was operated when it was necessary to cool the ambient air to the required dew point temperature to set the relative humidity of air to the chosen value during the drying tests.

3.2.3. *Heating unit*

The air was heated while flowing through eight spiral type electric heaters, each having 1 kW capacity.

3.2.4. *Humidifier unit*

The humidifier unit consists of a steam tank, solenoid valve and injector. This unit was operated when it was necessary to add some extra water vapour to the air to reach the desired relative humidity.

3.2.5. *Drying unit*

The drying unit has two parts: a mixing chamber; and three drying channels of 104 mm inside diameter, which were insulated with glass wool to prevent heat losses to the surroundings during the experiments. Air enters the drying channels from the mixing chamber.

3.2.6. *Measurement and control units*

Air temperature and humidity were measured by a humidity transducer with an internal temperature and humidity sensor (Hygrotest 600 ver.4, Testo GmbH&Co, Germany) in the drying channel. The accuracy of the temperature sensor is $\pm 0{\cdot}5°C$ and that for the humidity sensor is $\pm 3\%\ R_H$. Temperatures were also measured at the cooling and saturating tower outlet, air channels, cold water tank and steam tank by T type thermocouples.

Measurement of all points were centralised and logged on a data acquisition system (PCL-818HG and PCLD-8115, Advantech Automation Corp., USA). Temperature control and data acquisition as well as the general supervision of the unit, start-up and shut down electric heaters, injecting hot water into the air stream and circulating cold water through the cooling and saturating tower were all done by relay output board (PCLD-885, Advantech Automation Corp. USA), and GENIE data acquisition software.

3.3. *Experimental procedures*

Two different groups of drying experiments were planned to determine the effects of air temperature and relative humidity of the airflow, on the drying characteristics of bay leaves.

Fresh bay leaves picked for drying tests were separated randomly in three groups as the weight of each group was 13 g ($\pm$0·5 g). The whole leaves in each group were strung by thin wire so that they would not touch each other. Then each group was hung in a vertical drying channel, as the surfaces of the leaves were held parallel to the direction of airflow. The weight of the wires was taken into consideration during the calculations of net weight loss for each group of leaves.

The experiments to determine the effect of air temperature on the drying constant were carried out at temperatures of 40, 50 and 60°C. During these tests, the relative humidity of air flow was kept constant at 15%.

The tests related to the effect of the air relative humidity R_H on the drying rate were conducted at 50 and 60°C at R_H of 5, 15 and 25%. The drying test planned at 50°C air temperature and 5% relative humidity was carried out at 6·5% $\pm$0·5 relative humidity since the temperature of air in cooling tower was hardly brought down to 4·5°C. During the drying tests of 40 and 50°C, the weight losses of the samples were measured with 30 min intervals but 15 min intervals were considered for the tests at 60°C since drying at high-temperature takes less than those run at 40 and 50°C. The initial moisture content of bay leaves was determined by leaving the samples in an air-circulated oven for 5 h at 105°C. All of the tests mentioned above were achieved in triplicate.

Following the procedure of Yagcioglu *et al.* (1999), during the tests, airflow rate was kept constant at 1·5 m s^{-1}. The drying tests were terminated when the weights of the samples were stabilised, which was assumed to be the stage of dynamic equilibrium.

For the determination of essential oil changes, the sample leaves were dried to 10–12% wet basis moisture level at 40, 50 and 60°C, and relative humidity was kept constant at 15% for all temperature steps (Ceylan, 1987). Sample leaves were also dried at natural conditions under sun and shade.

The amount of essential oil of fresh and dried bay leaves was determined by using a Neo-Clevenger distillation apparatus advised by the Official Analytical Methods of the American Spice Trade Association (ASTA, 1997). For distillation, 40 g of dried and 80 g of fresh leaves were used and the results were expressed as the volume of oil per unit weight of dried leaves. Distillation process was carried out in triplicate for each test.

The composition of the essential oil of bay leaves was determined using Carlo Erba Fractovap series 2350 gas chromatography apparatus. The column temperature was 110°C, and the detector and injector temperature was 225°C. The length and inner diameter of capillary column are 2·65 m and 1·5 mm, respectively. The carrier gas was N_2 with a flow rate of 25 ml min^{-1}.

The colour analysis of the fresh and dried leaves was made by Minolta Spectrophotometer CM-508d (Minolta Camera Co., Ltd., Japan) and based on the method of ICI (Uren, 1999; Chua *et al.*, 2002). Colour measurements of each drying condition were made on randomly selected 12 leaves and at four different locations on each leaf before and after drying to determine colour coordinate (L^*, a^* and b^* values). The L^* value is the degree of lightness, a^* value is the degree of redness and greenness, and b^* value is the degree of yellowness and blueness. Colour densities C and recognisable colour difference ΔE values were calculated from the following relations:

$$C = \sqrt{a^{*2} + b^{*2}} \tag{1}$$

$$\Delta E = \sqrt{(L_0^* - L_i^*)^2 + (a_0^* - a_i^*)^2 + (b_0^* - b_i^*)^2} \tag{2}$$

where: the subscripts 0 and i refer the colour parameters of fresh and dried leaves, respectively. Initial colour coordinates on the leaves are: L_0^* of 31·16; a_0^* of −4·73; and b_0^* of 10·18.

3.4. *Modelling of the kinetics of convection drying of bay leaves*

Convection drying of biological products is a complex process that involves heat and mass transfer properties between the airflow and the product. Therefore mathematical modelling of the convection drying of these products is difficult. Nevertheless, highly successful theoretical and semi-theoretical mathematical models of single grains not touching each other were developed. For the mathematical modelling of convection drying of the grain, only the falling rate of the drying period is taken into consideration as a parameter because the initial moisture content is low, size reduction is negligible during drying and there is no stage of constant rate of drying period. Due to these factors, it is assumed that the drying is determined by internal diffusion of water during the process of the convection drying of grain. Consequently using equations of the diffusion of mass and heat diffusion were found to be satisfactory in developing mathematical models. Most of these models have been defined by Sherwood (1929, 1936), Van Arsdel (1947), McEwen *et al.* (1954), McEwen and O'Callaghan (1955), Hustrulid and Flikke (1959), Henderson and Pabis (1961, 1962), Pabis and Henderson (1961, 1962) and in the review articles of Sharp (1982), Parry (1985) and Jayas *et al.* (1991).

However, mathematical modelling of the process of convection drying of vegetables, fruits and grass is far more difficult than modelling of the convection drying of grain because initial moisture content is higher and shrinkage occurs during drying. There are mainly two approaches to this complex phenomena. One group of the researchers assume that the first period of drying does not occur in drying of such products because the first period terminates in a very short time, thus the changes in water content cease to be linear after a short period from the beginning of drying. Due to this behaviour, the researchers prefer to model the convection drying of vegetables, fruit, and grass by using differential equations of internal mass diffusion or semi-empirical exponential equations developed to account for the second period of drying of grain (Tulasidas *et al*., 1993; Cronin & Kearny, 1998; Yaldiz & Ertekin, 2001; Yaldiz *et al*., 2001; Kemp *et al*., 2001; Togrul & Pehlivan, 2002; Krokida *et al*., 2002; Gupta *et al*., 2002; Kabganian *et al*., 2002; Midilli *et al*., 2002; Togrul & Pehlivan, 2003 and the review article of Jayaraman & Das Gupta, 1992).

Pabis (1999), who presented an alternative approach to the convection drying of the products with high initial moisture content, such as vegetables and mushrooms, found the former approach flawed and argues that non-linearity of changes in water content that occur during the initial period of convection drying of these products cannot justify the claim that the first period of drying does not exist. He maintained that non-linearity is primarily due to drying shrinkage. He concluded that the mathematical models developed for the convection drying of grain do not account for the processes involved in the convection drying of vegetables from initial to final moisture content. Instead, Pabis (1999) and Pabis and Jaros (2002) developed a mathematical model that includes the shrinkage of the product for the initial phase of convection drying of vegetables. In a similar vein, Cao *et al*. (2003) pointed out the necessity of developing a model to simulate the drying of vegetables with high moisture contents. To this end, they modify the plate drying model for mushroom intermittent drying simulation by introducing a parameter, the surface mass transfer coefficient.

Nevertheless, the approach adopted by the first group of researchers is still strong and there are many studies conducted in recent years on the convection drying of vegetables and fruits that takes into consideration only the second period of drying. Thus, well-known semi-empirical models that account for the drying behaviour of grain were applied to describe the convection drying kinetics of vegetables and fruit. The models widely employed to describe the convection drying kinetics of vegetables are shown in Table 1. Left-hand side of the models is a dimensionless number known as moisture ratio M_R as written in the following form:

$$M_R = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

where: M_R is the moisture ratio (dimensionless); M_t is the moisture content in decimal dry basis at any time t; M_0 is the initial moisture content in decimal dry basis; M_e is the equilibrium moisture content in decimal dry basis.

This study takes its impetus from the semi-empirical mathematical models shown in Table 1 in order to account for the observations made on the experimental data obtained for the following reasons.

(a) During the convection drying process, no significant shrinkage of bay leaves was observed although some leaves were slightly waved.
(b) The experimental data indicates that there is no constant rate of drying.
(c) In previous studies on bay leaves, it was concluded that the effect of the velocity of airflow on the convection drying of bay leaves was not significant (Yagcioğlu *et al*., 1999).

The effect of relative humidity was also investigated in this study. Among the previous studies which provided impetus for introducing relative humidity as

Table 1
Mathematical models widely used to describe the convection drying kinetics

Model name	*Model*	*References*
Lewis	$M_R = \exp(-kt)$	Krokida *et al*. (2002); Kabganian *et al*. (2002); Yaldiz and Ertekin (2001)
Page	$M_R = \exp(-kt^n)$	Gupta *et al*. (2002); Yaldiz and Ertekin (2001); Tulasidas *et al*. (1993); Midilli *et al*. (2002); Kabganian *et al*. (2002); Cronin and Kearny (1998)
Modified Page	$M_R = \exp[-(kt)^n]$	Yaldiz and Ertekin (2001); Midilli *et al*. (2002)
Henderson and Pabis	$M_R = a\exp(-kt)$	Kabganian *et al*. (2002)
Logarithmic	$M_R = a\exp(-kt) + c$	Yagcioglu *et al*. (1999); Togrul and Pehlivan (2002)

M_R, moisture ratio (dimensionless), k, drying rate constant in h^{-1}, t, time in h, a and c, experimental constants (dimensionless), n, exponent.

a parameter, Togrul and Pehlivan (2002) may be cited. The authors reported that the logarithmic model introduced by Yagcioglu *et al.* (1999) was assumed to satisfactorily represent the solar drying behaviour of apricots in thin layers by taking into account the effects of temperature, velocity and relative humidity of air on the coefficients and constants. While Menzies and O'Callaghan (1971) who investigated the effect of relative humidity of the airflow in the course of drying of ryegrass concluded that the drying constant does not depend on the relative humidity of the airflow, an earlier study of Mitchell and Potts (1958) implicitly suggested that the drying rate constant may be affected if the moisture ratio of vegetables is above 30%. Van Arsdel (1947) and Westerman *et al.* (1972), on the other hand, explicitly state that the drying rate constant is affected by the temperature and relative humidity of airflow. Authors concluded that if relative humidity increases, than rate constant decreases. Based on these studies, the present study is built on the assumption that the introduction of the relative humidity of air as a parameter in addition to the temperature of airflow would increase the goodness of fit of the semi-empirical models in the determination of the drying constant of bay leaves in the course of convection drying. In the evaluation of various well-known semi-empirical models, which take into account only temperature as a parameter comparisons were made to determine the best model for the pattern of drying curves of bay leaves.

In this study, the drying rate constants and the coefficients of the equations of the semi-empirical drying models shown Table 1, were generated by using the software called Statistica, windows version of 6·0. The coefficient of correlation r was one of the primary criterion for selecting the best model to define the convection drying curves of bay leaves. In addition to r, there are several statistical test methods to evaluate the goodness of fit of the models. Among these, mean bias error E_{MB}, root mean square error E_{RMS} and reduced chi-square χ^2 are the ones widely used in many drying-related studies (Yaldiz & Ertekin, 2001; Togrul & Pehlivan, 2002; Krokida *et al.*, 2002; Gupta *et al.*, 2002; Kabganian *et al.*, 2002; Midilli *et al.*, 2002; Togrul & Pehlivan, 2003). These statistical test methods are defined as follows.

$$E_{MB} = \frac{1}{N}\sum_{i=1}^{N}(M_{R_{pre,i}} - M_{R_{exp,i}}) \tag{4}$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}(M_{R_{pre,i}} - M_{R_{exp,i}})^2\right]^{1/2} \tag{5}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(M_{R_{exp,i}} - M_{R_{pre,i}})^2}{N - n_1} \tag{6}$$

where: $M_{R_{exp,i}}$ is the ith experimental moisture ratio; $M_{R_{pre,i}}$ is the ith predicted moisture ratio; N is the number of observations; n_1 is the number of constants. The higher the values of the r, and lowest values of the E_{MB}, E_{RMS} and χ^2, the better the goodness of the fit.

4. Results and discussion

4.1. *Mathematical modelling of air-dried bay leaves*

For modelling purposes, the data obtained in the laboratory using the apparatus shown in *Fig. 1.* were used. The changes in the moisture content of bay leaves with drying time for 40, 50 and 60°C air temperatures at 15% relative humidity are given *Fig. 2.* The changes in moisture content with respect to drying time at 5; 15 and 25% relative humidities at 60°C are depicted in *Fig. 3.*

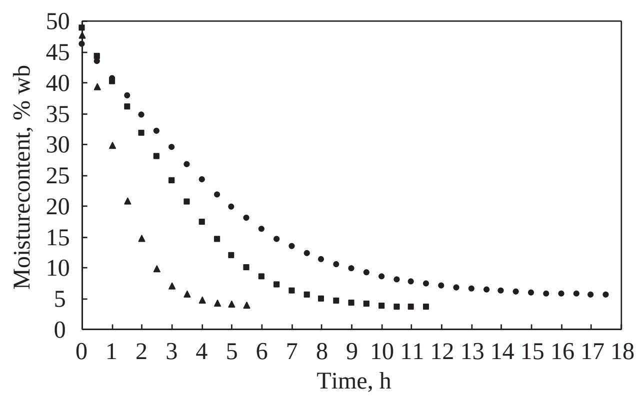

Fig. 2. Relationship between the moisture content (wb) and drying time at different air temperatures at 15% relative humidity; ●, 40°C; ■, 50°C; ▲, 60°C

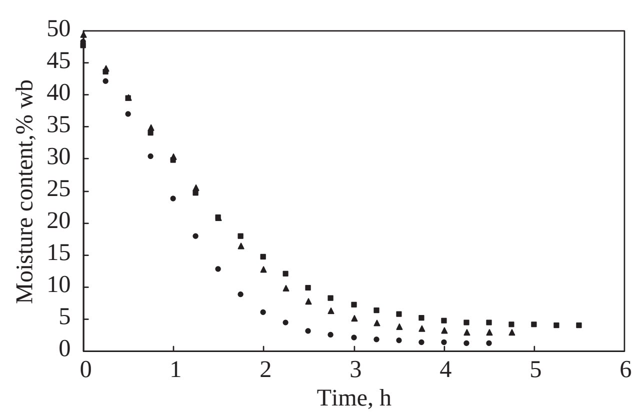

Fig. 3. Relationship between the drying moisture content (wb) and drying time at different relative humidities at 60°C air temperature; ●, 5%; ■, 15%; ▲, 25%

As seen from the figures, the moisture content decreases continuously with the drying time. Drying of bay leaves takes about 2·5–9 h in the dryer for 10–12% wb, while it takes about 8 and 15 days in September under sun and shade in outdoor conditions. As seen from *Figs 2* and *3*, one of the main factors influencing the drying kinetics of the bay leaves is the air temperature. An increase in air temperature results in a decrease in drying time.

The moisture content data obtained at different air temperatures and relative humidities were converted to the moisture ratio expression and then curve fitting procedure was performed for five well-known semi-empirical models.

The coefficients and drying rate constant k equations were found and the drying rate constant equations and the results from the statistical analysis depending only on the temperature between 40 and 60°C and on both the air temperature and relative humidity are shown in Table 2.

The statistical results from five semi-empirical models such as correlation coefficient r, mean bias error E_{MB}, root mean square error E_{RMS} and reduced chi-square χ^2 along with the drying rate constants considering air temperature only and both, air temperature and relative humidity are given Table 3.

The results indicated that the highest values of r and the lowest values E_{MB}, E_{RMS} and χ^2 could be

Table 2

Statistical results of drying coefficient k models using only air temperature in °C, and using both air temperature in °C and relative humidity in % with respect to different semi-empirical mathematical models; standard error in brackets

Model name	*Intercept (b_1)*	*Temperature coefficient (b_2)*	*Humidity coefficient (b_3)*	*Correlation coefficient, r*
Temperature-dependent drying coefficient				
Lewis	−4·0852 (0·2405)	0·06744 (0·0045)		0·960
Page	−4·5712 (0·2712)	0·07455 (0·0051)		0·959
Modified Page	−4·0266 (0·2225)	0·06584 (0·0042)		0·964
Henderson and Pabis	−4·0882 (0·2481)	0·06799 (0·0047)		0·958
Logarithmic	−4·0768 (0·2667)	0·06622 (0·0050)		0·950
Temperature- and humidity-dependent drying coefficient				
Lewis	−3·9769 (0·2347)	0·06744 (0·0043)	−0·00718 (0·0039)	0·966
Page	−4·4647 (0·2699)	0·07455 (0·0049)	−0·00714 (0·0045)	0·964
Modified Page	−3·9384 (0·2213)	0·06584 (0·0040)	−0·00590 (0·0037)	0·968
Henderson and Pabis	−3·9748 (0·2416)	0·06799 (0·0044)	−0·00749 (0·0041)	0·965
Logarithmic	−3·9235 (0·2549)	0·06622 (0·0046)	−0·00879 (0·0043)	0·960

Table 3

Comparison of different drying models using drying coefficient as a function of air temperature in °C, and of both air temperature in °C and relative humidity in %

Model name	*Exponent (n)*	*Coefficient (a)*	*Coefficient (c)*	*Correlation coefficient, (r)*	*Mean bias error*	*Root mean square error*	χ^2
Temperature-dependent drying coefficient							
Lewis				0·9909	0·004720	0·038045	0·001450
Page	1·14222			0·9927	0·001763	0·034121	0·001169
Modified Page	1·12849			0·9927	0·001565	0·034157	0·001171
Henderson and Pabis		1·02796		0·9912	0·005838	0·037448	0·001408
Logarithmic		1·03787	−0·01909	0·9920	0·004024	0·035851	0·001293
Temperature- and humidity-dependent drying coefficient							
Lewis				0·9917	0·004826	0·036296	0·001320
Page	1·14325			0·9936	0·001874	0·032005	0·001028
Modified Page	1·13132			0·9935	0·001636	0·032091	0·001034
Henderson and Pabis		1·02835		0·9920	0·005968	0·035651	0·001276
Logarithmic		1·03849	−0·01940	0·9929	−0·000001	0·033681	0·001141

obtained when the Page model was used. This model is shown as

$$M_R = \exp(-kt^n) \quad (7)$$

$$k = \exp(b_1 + b_2 T + b_3 R_H) \quad (8)$$

where: M_R is the moisture ratio (dimensionless); k is the drying rate constant in h^{-1}; t is the time in h; n is the exponent; T is the temperature in °C; R_H is the relative humidity in %; and b_1, b_2 and b_3 are experimental constants (dimensionless). The optimum values for the coefficients are: n of 1·14325; b_1 of −4·4647; b_2 of 0·07455; and b_3 of −0·00714.

The generalised drying models are valid in the $40°C \leqslant T \leqslant 60°C$ air temperature and $5\% \leqslant R_H \leqslant 25\%$ relative humidity range. However, it can also be stated that the use of other models for the determination of drying bay leaves with an acceptable degree of accuracy is possible.

4.2. *Effects of air on the amount of essential oil of bay leaves*

Mean amount of essential oil of bay leaves under the different drying conditions (fresh and dried 10% wb) is given in Table 4. The amount of oil extracted from the fresh and dried leaves at 40, 50 and 60°C and a relative humidity kept at 15% for all temperature steps and, sun and shade conditions was analysed statistically. The results indicated no significant differences among the drying procedures at 95% probability level (Table 5).

Table 4
Mean amount of essential oil of bay leaves dried under different conditions (fresh and dried 10% wb)

Drying condition		*Mean amount of essential oil ml 100 g^{-1} dried leaves*	
Air temperature, °C	*Relative humidity, %*	*Fresh*	*Dried*
40	15	0·617	0·642
	5	0·510	0·525
50	15	0·641	0·540
	25	0·512	0·585
	5	0·489	0·501
60	15	0·568	0·619
	25	0·489	0·515
Under sun	—	0·605	0·592
Under shade	—	0·605	0·569

Table 5
Comparison of the effects of drying conditions on the amount of the essential oil of dried bay leaves

Drying condition (relative humidity = 15%)		*Mean amount of essential oil,* ml 100 g^{-1} [dried leaves]*
Air temperature, °C	*Leaves*	
40	Fresh	0·617^{a}
	Dried	0·642^{a}
50	Fresh	0·641^{a}
	Dried	0·540^{b}
60	Fresh	0·568^{ab}
	Dried	0·619^{a}
Under sun	Fresh	0·605^{ab}
	Dried	0·592^{ab}
Under shade	Fresh	0·605^{ab}
	Dried	0·569^{ab}

*Values with the same letter are not significantly different at a probability, $P < 0{\cdot}05$.

4.3. *Effects of air on the composition of essential oil of bay leaves*

The results from the gas chromatography indicated that leaves have a composition of mainly α-pinene, β-pinene, 1·8-cineole, linalool, borneol and eugenol. Mean composition of essential oil of bay leaves under different drying conditions (fresh and 10% wb) is shown in Table 6. From the point of view of the α-pinene, 1·8-cineole, linalool and eugenol there are significant differences between the fresh and dried leaves at 99% probability level. On the other hand, the analysis indicated that the differences in essential oil composition of dried leaves were not significant.

4.4. *Effects of air on the colour of bay leaves*

Mean colour values of bay leaves dried under the different drying conditions and fresh are shown in Table 7. From the point of view of colour coordinates (L^*, a^*, b^*) there are significant differences between the fresh and dried leaves at 99% probability level.

The variance analysis and Duncan's tests made by using the colour coordinates and the calculated values of C of dried leaves yielded no clear results. The statistical analysis of ΔE values of dried leaves indicated that the values of leaves dried under shade were different as compared to those dried under the sun and in the laboratory. However, the differences between the leaves

Table 6
Mean composition of essential oil of bay leaves dried under different conditions (fresh and dried 10% wb)

Drying condition		*Mean composition of essential oil, %*											
Air temperature, °C	*Relative humidity, %*	*α-Pinene***		*β-Pinene*		*1·8-Cineol***		*Linalool***		*Borneol*		*Eugenol***	
		Fresh	*Dried*	*Fresh*	*Dried*	*Fresh*	*Dried*	*Fresh*	*Dried*	*Fresh*	*Dried*	*Fresh*	*Dried*
40	15	2·13	2·76	9·27	9·06	61·34	55·77	5·54	7·01	2·82	4·16	17·89	20·04
	5	1·82	2·70	7·98	10·03	55·70	56·31	7·19	8·12	5·33	2·87	21·24	19·56
50	15	2·98	3·05	8·80	8·76	65·55	63·55	5·15	3·88	3·04	2·94	12·31	14·13
	25	2·05	3·24	9·90	9·73	59·24	55·82	5·95	6·22	4·08	4·06	18·78	19·21
	5	2·27	2·68	10·75	10·13	58·96	57·79	6·89	6·03	5·11	2·74	14·84	19·59
60	15	2·48	2·79	9·44	9·36	59·79	59·60	5·77	5·38	3·99	3·70	17·80	17·49
	25	3·34	3·12	9·51	9·29	52·13	50·88	5·91	8·48	2·53	2·90	15·85	21·58
Under sun		1·98	2·00	9·20	9·42	60·10	61·62	6·07	6·65	3·84	2·49	18·81	17·50
Under shade		1·98	2·42	9·20	9·64	60·09	57·94	6·07	5·41	3·84	3·77	18·81	20·00
LSD**		1·03				7·39		2·04				4·63	

LSD, least significant difference.
**Probability, $P<0{\cdot}01$.

Table 7
Mean colour values of bay leaves dried under different conditions (fresh and 10% wb)

Drying condition		*Mean colour values*			
Air temperature, °C	*Relative humidity, %*	*Lightness*** *(L^*)*	*Redness and greenness*** *(a^*)*	*Yellowness and blueness*** *(b^*)*	*Colour density*** *(C)*
40	15	43·79	−4·16	24·02	24·39
	5	45·99	−4·02	19·41	19·84
50	15	45·54	−4·10	18·45	18·91
	25	45·64	−3·95	19·30	19·72
	5	43·22	−2·19	18·69	18·86
60	15	43·35	−2·57	19·77	19·96
	25	47·07	−3·19	23·30	23·55
Under sun	—	46·08	−1·70	21·98	22·06
Under shade	—	51·32	−4·33	25·85	26·25
Fresh	—	31·16	−4·73	10·18	11·25
LSD**		1·68	0·99	1·64	

LSD, least significant difference.
**Probability, $P<0{\cdot}01$.

dried under the sun and in the test laboratory were not significant (Table 8).

5. Conclusions

The following conclusions were drawn from this study.

(1) Predictions by the Page model are in good agreement with the data obtained in the laboratory.
(2) There are no significant differences between the amount and composition of essential oil of fresh bay leaves and leaves dried at different conditions.
(3) Drying bay leaves down to 10% (wb) moisture content at 60°C air temperature can shorten the drying time about 80–140 times as compared to the traditional drying process under sun or nearly 4 times as compared to that at 40°C air temperature without any significant loss in the proportion of essential oil, its composition and the colour of leaves.

Table 8
Comparison of recognisable mean colour difference (ΔE) between bay leaves dried under different conditions and under the sun

Drying condition		*Recognisable mean colour difference* (ΔE)*
Air temperature, °C	*Relative humidity, %*	
40	15	$4{\cdot}45^{b}$
50	5	$3{\cdot}94^{b}$
	15	$4{\cdot}71^{b}$
	25	$4{\cdot}05^{b}$
60	5	$4{\cdot}61^{b}$
	15	$4{\cdot}04^{b}$
	25	$2{\cdot}98^{b}$
Under shade	—	$7{\cdot}25^{a}$

*Values with the same letter are not significantly different at a probability, $P<0{\cdot}01$.

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