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Verification of a novel Thin-Layer Drying Mathematical Model of air Dried Mint leaves

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Abstract

Mentha leaves were dried in hot-air drying using 3 different air temperatures (60, 70 and 80°C) with velocity of 1 m/s. In this study, measured values were compared with predicted values obtained from twenty one thin layer drying theoretical/ semi empirical/ empirical equations. Also a novel model of kinetics of thin layer drying is tested in this study. Models with highest coefficient of correlation (R^2) values were chosen as the best models. According to this, the introduced model showed the best coefficient of correlation for all of temperatures.

Keywords: Mentha leaf, Moisture Ratio, Thin-layer Drying Models, Hot-air drying.

M	initial moisture content, kg(moisture) kg^{-1}(dry matter)
W_0	initial weight of sample, kg
W	amount of evaporated water, kg
W_1	dry matter content of sample, kg
MR	moisture ratio
M_e	equilibrium moisture content, kg(moisture) kg^{-1}(dry matter)
k, k_0, k_1, k_2	drying constant, min^{-1}
a, a_0, b, c, d, g, h	coefficients, dimensionless
N	exponent, dimensionless
t	drying time, min
L	sample thickness, m
R^2	coefficient of correlation, decimal
χ^2	chi square
RMSE	root mean square error
$MR_{exp,i}$	stands fort the experimental moisture ratio found in any measurement
$MR_{pre,i}$	predicted moisture ratio for this measurement
N	total number of observations
n_i	number of constants
SEE	standard error of estimated

Introduction

Mentha (also known as mint) is a genus of plants in the family Lamiaceae (mint family) (Harley et al., 2004). The genus has a sub cosmopolitan distribution across Europe, Africa, Asia, Australia, and North America (Brickell and zuk, 1997). Mints are aromatic, almost exclusively perennial, rarely annual, herbs. They have wide-spreading underground and over ground stolon's (Aflatuni et al., 2005) and erect, square (Rose, 1981), branched stems. The leaves are arranged in opposite pairs, from oblong to Lanceolate, often downy, and with a serrated margin. The species that make up the Mentha genus are widely distributed and can be found in many environments, most grow best in wet environments and moist soils. Mints will grow 10–120 cm tall and can spread over an indeterminate area. Due to their tendency to spread unchecked, some mints are considered invasive (Brickell and cole, 2002). Menthes are regarded as one of the most important spices throughout the world. The essential oils of mints are widely used as flavorings in the food, spicing, tea infusions, cosmetic and pharmaceutical industries (Özbek and Dadali, 2007).

Drying is a complex process involving heat and mass transfer phenomena and frequently used in food processing industry (Cohen and Yang, 1995). Mathematical modeling and simulation of drying curves under different conditions is important to obtain better control of this unit operation and overall improvement of the quality of the final product. Models are often used to study the variables involved in the process, predict drying kinetics of the product and optimize the operating parameters and circumstances (Karathanos and Belessiotis, 1999).

Drying is one of the widely used methods of fruit and vegetable preservation. Thin-layer drying equations are used to estimate drying time of several products and also to generalize drying curves. Several investigators have proposed numerous mathematical models for thin-layer drying of many agricultural products (Meisami-asl, Rafiee, 2009). For example, carrot (Aghabashlo et al., 2008), apple (Wang et al., 2006), rough rice (Cihan et al., 2007), red chili (Kaleemullah and Kailappan, 2005), bitter orange leaves (Ait Mohamed et al., 2005), organic apple (Sacilik and Elicin, 2005), prickly pear peel (Lahsasni et al., 2004), eggplant (Ertekin and Yaldiz, 2004), plum (Doymaz, 2004), apricot (Togrul and Pehlivan, 2002; Togrul and Pehlivan, 2003), grape (Yaldiz et al., 2001), green pepper, stuffed pepper, pumpkin, green bean and onion (Yaldiz and Ertekin, 2001).

Thin layer drying is the process of drying in one layer of sample particles or slices. Many mathematical models are used in order to describe the thin layer drying process. Mathematical modeling of thin layer drying is important for performance improvements of drying systems (Cihan et al. 2007). Thin layer drying models fall into three categories as theoretical, semi-empirical an empirical (Ozdemir and Devres 1999, Midilli and Kucuk 2003).

The aim of this study is (1) to investigate the effect of drying air temperature on the drying characteristics and dehydration ratio for the Mentha drying process, (2) to compare the developed several theoretical, empirical and semi-empirical mathematical models and estimate the constant of several models, (3) to determine the best fit using statistical analysis.

Materials and Methods

Fresh Mentha

Mints were selected from a local market. The initial moisture content of Mints was obtained as 85-95 % (w.b.).

Drying equipment and drying method

The drying experiments were carried out using the laboratory dryer in the Department of Agricultural Machinery, Faculty of Bio-systems Engineering, University of Gorgan, Iran. The dryer is capable of providing any desired drying air temperature in the range of 20 to 90 °C and velocity in the range of 0.5 to 2 m/s. Figure 1 shows a schematic diagram of the dryer used for experimental work; it consisted of an electrical fan, an airflow control unit, heaters, drying chamber and instruments for various measurements. The airflow control unit regulated the velocity of the drying air flowing 10 cm diameter drying chamber. The product was spread as a thin layer on a screen. The desired drying air temperature 60, 70 and 80 ºC was attained by electrical resistance heating elements and controlled by the heating control unit. The air was forced by electrical fan to pass through the heating elements and after reaching the desired temperature chamber (60 to 80) passed through the drying chamber. Weighing of samples inside the drying chamber was carried out manually using an electronic balance with a capacity of 0-1000 g and accuracy of ±0.01 g and by connecting to the computer, the weighing program could save the weight of samples at any time interval. The temperature using a T-type thermocouple with the accuracy of ±1 °C.

Mentha leaves were dried using drying air temperatures from 60, 70 and 80 °C and drying air velocity was 1 m/s.

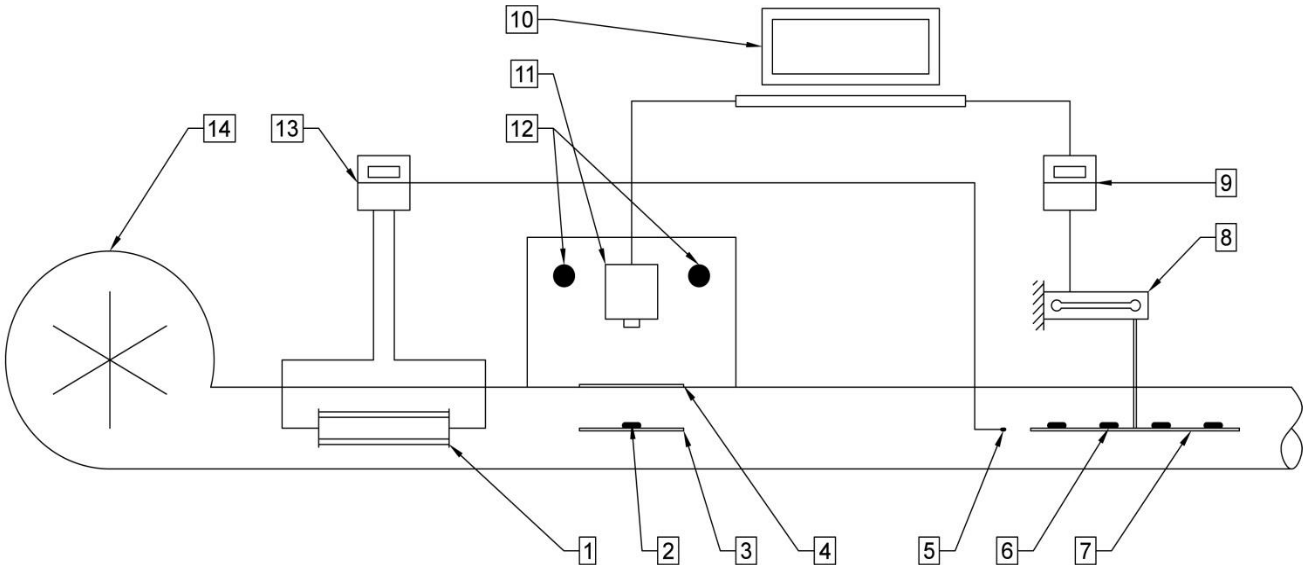

Figure 1.Schematic diagram of the drying system for measurement of parameters of Mentha
1. Heating elements; 2. Specimen; 3. Trays; 4. Protective glass; 5. Temperature sensor; 6. specimen; 7. Trays; 8. Load cell; 9. Data logger; 10. PC; 11. Camera; 12. Fluorescent lamps; 13. Contactor, 14. Fan.

Moisture content [kg (moisture) kg-1(dry matter)] was determined using the following equation:

$$M = \frac{(W_0 - W) - W_1}{M_1} \quad (1)$$

Where M is initial moisture content [kg (moisture) kg^{-1}(dry matter)], W_0 is initial weight of sample, W is amount of evaporated water, W_1 is dry matter content of sample. The moisture ratio (MR) in these model equations is defined as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (2)$$

Where M is initial moisture content [kg (moisture) kg^{-1}(dry matter)], M_e is equilibrium moisture content [kg (moisture) kg^{-1}(dry matter)].

Data Analysis

Twenty two empirical and semi empirical thin-layer drying models given in Table 1 have been taken into account in this study. Non-Linear regression analyses of these equations [Eq. (3)-Eq. (24)] were made by using ImageJ 1.46r and Excel 2010 Non-linear regression analysis was performed to estimate the parameters k, k_0, k_1, k_2, a, a_0, b, c, d, g, h, L and n of empirical and semi empirical equations in Table 1.

Table 1.Mathematical thin-layer drying models used for the approximation

No.	Model name	Model	Eq. No.	References
1	Newton	MR= exp(-kt)	(3)	(Westerman et al., 1973)
2	Page	MR = exp(-kt^n)	(4)	(Page, 1949)
3	Modified page	MR= exp[-(kt)^n]	(5)	(Yaldiz et al., 2001)
4	Henderson and Padis	MR=aexp(-kt)	(6)	(Henderson and Pabis, 1961)
5	Logarithmic	MR= aexp(-kt)+c	(7)	(Yagcioglu et al. 1999)
6	Two Term	MR= aexp(-k_0t)+ bexp(-k_1t)	(8)	(Henderson 1974)
7	Two Term Exponential	MR= aexp(-kt)+ (1-a)exp(-kat)	(9)	(Sharaf-Eldeen et al. 1980)
8	Wang and Singh	MR=a+bt+ct^2	(10)	(Wang and Singh, 1978)
9	Approximation Of Diffusion	MR= aexp(-kt)+ (1-a)exp(-kbt)	(11)	(Kasem, 1998)
10	Verma et al.	MR= aexp(-kt)+ (1-a)exp(-gt)	(12)	(Verma et al., 1985)
11	Modified Henderson and Pabis	MR= aexp(-kt)+ bexp(-gt)+cexp(-ht)	(13)	(Karathanos, 1999)
12	Aghbashlo et al.	MR=exp(-k_1t/1+k_2t)	(14)	(Aghabashlo et al., 2009)
13	Weibull	MR=exp(-(t/a)b)	(15)	(Corzo et al., 2008)
14	Midilli et al.	MR=aexp(-kt^n)+bt	(16)	(Midilli et al., 2002)
15	Simlified Ficks diffusion equation	MR=aexp[-c(t/L^2)]	(17)	(Diamante and Munro, 1991)
16	Modified Page equation-Π	MR=exp[-k(t/L^2)^n]	(18)	(Diamante and Munro, 1993)
17	Weibull distribution	MR=a-bexp[-(kt^n)]	(19)	(Babalis et al., 2006)
18	Logistic	MR=a_0/(1+aexp(kt))	(20)	(Chandra and Singh, 1995)
19	Jena and Das	MR=aexp(-kt+b√t)+c	(21)	(Jena and Das, 2007)
20	Demir et al.	MR=aexp(-kt)^n+c	(22)	(Demir et al., 2007)
21	Alibas	MR=aexp((-kt^n)+bt)+g	(23)	(Alibas, 2012)
22	Abdi-gaol	MR=aexp(-bexp(-kt))+c	(24)	**New Model**

MR, moisture ratio; a, a_0, b, c, d, g, h, coefficients and n, air drying exponent specific to each equation; k, k_0, k_1, k_2, drying coefficient specific to each equation; t, time; L, thickness.

Mathematical Formulations

The reduced chi-square (χ^2), root mean square error (RMSE), Standard error of estimated (SEE) and increased the regression coefficient (R^2) were used as the primary criteria to select the best equation to account for variation in the drying curves of the dried samples (Goyal et al., 2007; Menges and Ertekin, 2006; Yaldiz, 2001; Alibas, 2012).

The regression coefficient (R^2) was primary criterion for selecting the most suitable equation to describe the air drying curves of Mentha leaves. The correlation can be used to test the linear relation between measured and estimated values, which can be calculated from the equation:

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp,mean,i}\right)^2 - \left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp,mean,i}\right)^2} \quad (25)$$

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

Chi square (χ^2) is the mean square of the deviations between the experimental and predicted moisture levels. The lower are the values of the reduced χ^2, the better is the goodness of fit.

$$\chi^2 = \frac{\left[\sum_{i=1}^{N}(MR_{exp,i}) - \sum_{i=1}^{N}(MR_{pre,i})\right]^2}{N - n_i} \quad (26)$$

The root mean square error (RMSE) may be computed from the following equation which provides information on the short term performance.

$$RMSE = \left[\frac{1}{N}\left[\sum_{i=1}^{N} MR_{exp,i} - \sum_{i=1}^{N} MR_{pre,i}\right]^2\right]^{1/2} \quad (27)$$

Standard error of estimated (SEE) 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 SEE is “zero”. The SEE is given as:

$$SEE = \left[\frac{1}{N - n_i}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \quad (28)$$

Where n_i is called number of constants.

Mathematical Modeling of Air Drying Curves

The thin-layer drying models, describing the drying process, can be distinguished in three main categories, namely the theoretical, the semi theoretical and the fully empirical ones (Sharaf-Eldeen and Hamdy 1979). In this study, experimental data which were measured 60°C, 70°C and 80°C air drying levels were measured theoretical/ semi-empirical/ empirical thin-layer drying models defined in Table 1 and statistical data of these models such as SEE, R^2, RMSE and χ^2 and constant and coefficients (a, a_0, b, c, d, g, h, n, k, k_0, k_1, k_2, and L) were determined. The model in which R^2 was highest was chosen to be the best model in the study where air drying levels of 60°C, 70°C and 80°C were used.

Results and Discussion

Value of moisture ratio (MR) depending on time (t) of Mentha leaves dried with 60°C, 70°C and 80°C air drying levels were given in Fig 2, a reduction in drying time occurred with the increasing temperature. The time required for the lowering of moisture content of Mentha leaves to 85-95 % on wet basis varied between 17 and 24 minute air drying curves depending on temperature level. Drying time at 60, 70 and 80 °C temperature was found as 24, 20, 17 min, respectively. Increase in temperature level in air drying had an important effect on the reduction of drying time. The extent of drying realized at 60 °C temperature with the longest drying period was 1.412 times higher compared with the drying process realized at 80 °C, with the shortest drying period. Similar findings was found by several researchers (Alibas 2007, Alibas 2009, Alibas 2012; Arévalo-Pinedo and Murr 2006, Jena and Das 2007, Wu et al. 2007, Arévalo-Pinedo and Murr 2007, Lee and Kim 2009, Bazyma et al. 2006, Artnaseaw et al. 2010).

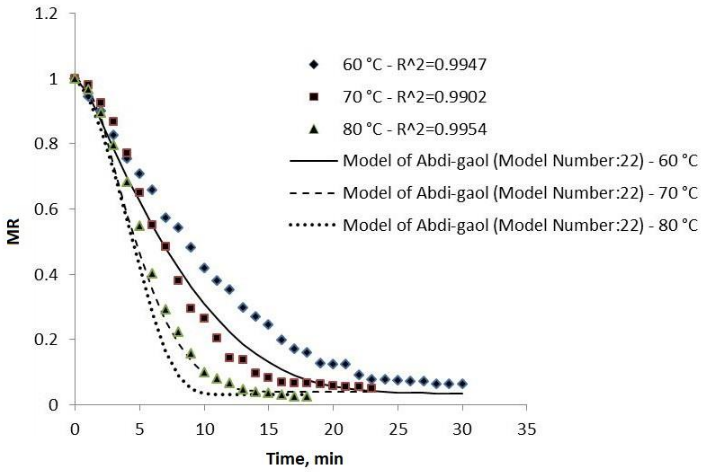

Figure 2. Moisture ratio versus time, comparing experimental curve with the predicted one (——) through "Abdi-gaol" model's equation (model no: 22) for 60 °C, (- - - - -) through "Abdi-gaol" model's equation (model no: 22) for 70 °C and (··········) through

Mathematical Modeling

In this study, twenty two thin-layer drying models defined by various researchers in Table 1. Coefficient of correlation (R^2), Standard error of estimated (SEE), Root mean square error (RMSE) and Chi-square (χ^2) in the air drying of thin layer drying models, shown in Table 2. The coefficient of correlation (R^2) was one of the primary criterions for selecting the best model to define the air drying curves of Mentha leaves. In this study thin-layer drying model in which (R^2) value is most close to "1.0000" and (RMSE), (χ^2) and (SEE) values are smallest was chosen to be the most optimum model. According to Table 2, among all drying tests, Within air drying trials dried of 60°C, 70°C and 80°C drying levels, coefficient of correlation (R^2) of Abdi-gaol model is more close to values "1.0000" compared with the other twenty-one thin-layer drying model defined in the literature. Therefore Abdi-gaol's Model was defined as the most optimal model in which estimation value are closest to experimental data for 60, 70 and 80°C air drying levels. The air drying constants and the coefficients of the thin-layer drying Abdi-gaol's Model, shown in Table 3. Mathematical modeling of air drying was conducted by several researchers in drying literature (Meisami-asl, Rafiee, 2009;Yadollahinia, 2006; Alibas 2007, Alibas 2009, Alibas 2012; Arévalo-Pinedo and Murr 2006, Jena and Das 2007, Wu et al. 2007, Arévalo-Pinedo and Murr 2007, Lee and Kim 2009, Bazyma et al. 2006, Artnaseaw et al. 2010).

Table 2. Average values of the statistical parameters of drying for different models for Mint leaves

	60°C				70°C				80°C			
No	R^2	SEE	RMSE	χ^2	R^2	SEE	RMSE	χ^2	R^2	SEE	RMSE	χ^2
1	0.9808	0.0701	0.0325	0.3945	0.9517	0.1583	0.0511	0.2708	0.9434	0.1912	0.0574	0.2367
2	0.9808	0.0701	0.0325	0.1060	0.9517	0.1583	0.0511	0.0452	0.9434	0.1912	0.0574	0.0398
3	0.8974	0.3992	0.0775	0.1222	0.9198	0.2616	0.0658	0.1170	0.9312	0.2347	0.0633	0.1355
4	0.9851	0.0546	0.0286	0.1096	0.6231	1.1732	0.1074	0.0452	0.6671	1.0188	0.1049	0.0398
5	0.9880	0.0434	0.0268	0.0290	0.9709	0.0953	0.0425	0.0057	0.9600	0.1339	0.0494	0.0047
6	0.9906	0.0358	0.0205	0.0053	0.9769	0.0752	0.0271	0.0005	0.6378	1.3343	0.1009	0.0003
7	0.9808	0.0702	0.0325	0.1172	0.9517	0.1583	0.0511	0.0452	0.9434	0.1912	0.0574	0.0398
8	0.5312	1.7339	0.1697	0.0290	0.4471	1.8167	0.1849	0.0057	0.5788	1.5218	0.1382	0.0047
9	0.9907	0.0354	0.0221	0.0176	0.9787	0.0691	0.0306	0.0057	0.9831	0.0567	0.0261	0.0047
10	0.9906	0.0358	0.0205	0.0290	0.9787	0.0691	0.0306	0.0057	0.9780	0.0722	0.0307	0.0047
11	0.9902	0.0375	0.0214	0.0001	0.9743	0.0831	0.0312	0.0001	0.9786	0.0699	0.0295	0.0002
12	0.9839	0.0599	0.0284	0.1128	0.9606	0.1288	0.0459	0.0452	0.9551	0.1513	0.0489	0.0353
13	-0.1566	4.4453	0.2248	0.1128	-0.0487	3.4295	0.2196	0.0452	0.0267	3.3415	0.2179	0.0398
14	-0.1183	4.2921	0.2422	0.0053	0.6169	1.2523	0.1050	0.0007	0.5170	1.7557	0.1472	0.0003
15	0.9851	0.0546	0.0286	0.0255	0.9614	0.1264	0.0451	0.0057	0.9573	0.1436	0.0500	0.0047
16	0.9808	0.0701	0.0325	0.0290	0.9517	0.1583	0.0511	0.0057	0.9434	0.1912	0.0574	0.0047

17	0.9880	0.0434	0.0268	0.0053	0.9709	0.0953	0.0425	0.0007	0.9600	0.1339	0.0494	0.0003
18	0.9615	0.1623	0.0378	0.0290	0.9452	0.1844	0.0442	0.0055	0.9856	0.0494	0.0198	0.0047
19	0.4629	2.0474	0.1564	0.0053	0.4795	1.7518	0.1503	0.0007	0.7303	0.9525	0.0891	0.0003
20	0.9431	0.2212	0.0589	0.0053	0.2273	2.5322	0.2189	0.0007	0.6841	1.1425	0.1197	0.0003
21	0.9880	0.0434	0.0268	0.0009	0.9709	0.0953	0.0425	0.0004	0.9600	0.1339	0.0494	0.0004
22	**0.9947**	0.0198	0.0178	0.0032	**0.9902**	0.0316	0.0238	0.0005	**0.9954**	0.0159	0.0166	0.0003

Table 3. Constant and Coefficients of Abdi-gaol model

temperature	a	b	k	c
60	4.1035	1.3998	-0.0011	0.0344
70	3.2100	1.0203	-0.0023	0.0381
80	1.2601	0.2337	-0.0054	0.0309

Conclusions

The effects of different temperature levels on the drying of Mentha leaves were evaluated based on the drying parameters such as the drying time and moisture ratio. Drying period was completed between 17 and 24 minute at combined different temperature (60, 70 and 80°C) levels. Twenty-two different drying models were used in the study and coefficient of correlation (R^2), standard error estimated (SEE), root mean square error (RMSE) and chi-square (χ^2) values and constant and coefficients of these models were calculated. Among all drying tests, the drying model where constant of coefficient (R^2) is the highest at 60°C, 70°C and 80°C drying levels was Abdi-gaol Model.

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