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Mathematical modeling of microwave dried celery leaves and determination of the effective moisture diffusivities and activation energy

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Abstract

Celery (*Apium graveolens* L. var. *secalinum* Alef) leaves with 50±0.07 g weight and 91.75±0.15% humidity (~11.21 db) were dried using 8 different microwave power densities ranging between 1.8-20 W g^{-1}, until the humidity fell down to 8.95±0.23% (~0.1 db). Microwave drying processes were completed between 5.5 and 77 min depending on the microwave power densities. In this study, measured values were compared with predicted values obtained from twenty thin layer drying theoretical, semi-empirical and empirical equations with a new thin layer drying equation. Within applied microwave power density; models whose coefficient and correlation (R^2) values are highest were chosen as the best models. Weibull distribution model gave the most suitable predictions at all power density. At increasing microwave power densities, the effective moisture diffusivity values ranged from 1.595 10^{-10} to 6.377 10^{-12} $m^2\,s^{-1}$. The activation energy was calculated using an exponential expression based on Arrhenius equation. The linear relationship between the drying rate constant and effective moisture diffusivity gave the best fit.

Keywords: activation energy; effective moisture diffusivity; microwave drying; celery; thin- layer drying models.

1 Introduction

Drying is one of the most widespread methods for post-harvest preservation of agricultural products since it allows for the quick conservation (Dadali et al., 2008; Doymaz & Kocayigit, 2011; Discala et al., 2013). Vegetables, fruits and crops normally contain a high level of moisture and microorganism. For this reason, immediate drying is a requirement in postharvest processing to avoid quality losses of these perishable agricultural products (Balbay et al., 2012; Al-Harahsheh et al., 2009; Soysal, 2004).

Several drying methods are used in the drying of plants and foodstuff. The use of microwave technique in the drying of products has become common because it minimizes the quality loss and provides rapid and effective heat distribution in the product as well (Li et al., 2009; Alibas et al., 2010; Dong et al., 2011). Besides, high quality dried product is acquired via microwave drying in addition to the reducing in drying period and energy conservation while drying (Balbay et al., 2011; Zhang et al., 2006; Li et al., 2010; Evin et al., 2012; Alibas-Ozkan et al., 2007).

Thin layer drying is the process of drying in one layer of sample particles or leaves. 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 (Kardum et al., 2011). Thin layer drying models can be categorized as theoretical, semi-empirical an empirical models (McMinn, 2006; Alibas, 2014).

The aim of this study was to (i) investigate the kinetics of the thin layer drying of orange leaves, (ii) compare the developed several theoretical, empirical and semi-empirical mathematical models and estimate the constant of several models, (iii) determine the best fit using statistical analysis, (iv) determine the effect of microwave power density on constants and coefficients in the selected models according to Arrhenius type equation, (v) calculate the activation energy and effective moisture diffusivity, vi) derive a relationship between the drying rate constant and the effective moisture diffusivity.

2 Materials and methods

2.1 Material and drying process

Celery leaves (*Apium graveolens* L. var. *secalinum* Alef) which were selected from healthy and uniform plants used for the drying experiments were bought from a manufacturer in Geyve country of Sakarya in 2013. They were stored at 4±0.5°C until the drying process. Five different 50 g samples were kept in a drying oven at 105°C for 24 h, after which the initial moisture content of celery leaves was 91.75% ±0.15.

Microwave drying trials was performed in domestic digital microwave oven (Arcelik MD 592, Turkey). The microwave oven has eight different microwave stages among 90 and 1000 W. The area on which microwave drying is carried out was 327 mm × 370 mm × 207 mm in size, and consisted of a rotating glass plate with 280 mm diameter at the base of the oven. It has a digital clock.

Microwave drying trials were carried out at six different microwave generation powers being 1000, 850, 750, 650, 500, 350, 160 and 90 W for weight of 50 g. Dried celery leaves were 50±0.07 g in weight and selected from the uniform, and healthy plants. They were removed from the microwave oven periodically (every 30 seconds) during the drying period, and the moisture loss was determined by weighing the plate

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using a digital balance (Sartorious EX 2000A, Germany) with 0.01g precision. All weighing processes were completed in 10 s during the drying process. Drying process continued until the moisture content of mallow fell down to 8.95%±0.23 (Alibas-Ozkan et al., 2007.

2.2 Mathematical formulations

The regression coefficient *(R^2)* was primary criterion for selecting the most suitable equation to describe the microwave drying curves of celery leaves. The correlation can be used to test the linear relation between measured and estimated values, which can be calculated from the following Equation 1:

$$R^2 = \frac{\sum_{i=1}^{N}(M_{R_{\exp,i}} - M_{R_{\exp_{mean,i}}})^2 - (M_{R_{pre,i}} - M_{R_{\exp,i}})^2}{\sum_{i=1}^{N}(M_{R_{\exp,i}} - M_{R_{\exp_{mean,i}}})^2} \quad (1)$$

where R^2 is called the coefficient of correlation, $M_{\text{Rexp,i}}$ stands for the experimental moisture ratio found in any measurement, $M_{\text{Rpre,i}}$ is the predicted moisture ratio fort his measurement and N is the total number of observations.

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 (Equation 2):

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}(M_{R_{\exp,i}} - M_{R_{pre,i}})^2}{N - n_i}} \quad (2)$$

where n_i is called number of constants.

The root mean square error (*RMSE*) may be computed from the following equation which provides information on the short term performance (Equation 3).

$$RMSE = \sqrt{\frac{[\sum_{i=1}^{N}(M_{R_{\exp,i}}) - \sum_{i=1}^{N}(M_{R_{pre,i}})]^2}{N}} \quad (3)$$

Chi square (χ^2) is the mean square of the deviations between the experimental and predicted moisture levels. The lower the value of the reduced χ^2, the better is the goodness of fit (Equation 4).

$$\chi^2 = \frac{[\sum_{i=1}^{N}(M_{R_{\exp,i}}) - \sum_{i=1}^{N}(M_{R_{pre,i}})]^2}{N - n_i} \quad (4)$$

2.3 Effective moisture diffusivity and activation energy

Experimental results can be interpreted by using Fick's diffusion equation. Fick's second law of unsteady state diffusion given in Equation 5 (Al-Harahsheh et al., 2005; Evin, 2012; Alibas, 2014; Sarimeseli, 2011).

$$M_R = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2.D_{eff}.\pi^2}{4L_s^2}.t\right) \quad (5)$$

where: M_R is the moisture ratio; M is the moisture content at a specific time [$kg_{(moisture)}\ kg^{-1}{}_{(drymatter)}$]; M_o is the initial moisture content [$kg_{(moisture)}\ kg^{-1}{}_{(drymatter)}$], M_e is the equilibrium moisture content [$kg_{(moisture)}\ kg^{-1}{}_{(drymatter)}$], D_{eff} is the effective moisture diffusivity ($m^2\ min^{-1}$), L_s is the half thickness (drying from both sides) of celery leaves (m) (L_s=0.18±0.010 mm), and t is drying time (min). For long drying times, n=1, Equation 6 can be written as:

$$M_R = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{D_{eff}.\pi^2}{4L_s^2}.t\right) \quad (6)$$

$$\ln(M_R) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}.\pi^2}{4L_s^2}\right)t \quad (7)$$

Diffusivities are typically determined by plotting experimental drying data in terms of *lnMR* versus drying time t in Equation 7, because the plot gives a straight line with a slope as $(\pi^2 D_{eff})/(4L_s^2)$.

In this study, the Arrhenius equation was used in a modified form to illustrate the relationship between the kinetic rate constant and ratio of the microwave output power density to sample amount instead of the temperature for calculation of the activation energy as the temperature is not measurable variable in standard microwave oven used for drying process. The activation energy was calculated using the Equation 8 and Equation 9 (Demirhan & Ozbek, 2011; Sarimeseli, 2011; Dadali et al., 2007a).

$$k = k_o \exp\left(\frac{-E_a.m}{P}\right) \quad (8)$$

$$D_{eff} = D_o \exp\left(\frac{-E_a.m}{P}\right) \quad (9)$$

where: k is the drying rate constant obtained by using Weibull distribution's thin-layer drying model (min^{-1}), k_o is the pre-exponential constant (min^{-1}), D_{eff} is effective diffusivity ($m^2\ min^{-1}$), D_0 is the pre-exponential factor ($m^2\ min^{-1}$), E_a is the activation energy ($W\ g^{-1}$), P is microwave output power (W) and m is the mass of raw sample (g).

The predicted values of drying rate constant (k_{th}), obtained from Equation 8 and the theoretical values of effective moisture diffusivity ($(D_{eff})_{th}$) obtained from Equation 9 for this study were fitted sufficiently to Equation 10.

$$k_{th} = A.(D_{eff})_{th} \quad (10)$$

where: k_{th} is the theoretical drying rate constant (min^{-1}), $D(_{eff})_{th}$ is theoretical effective diffusivity ($m^2\ s^{-1}$), A is the stabilization constant ($min^{-1}\ m^2 s$) (Özbek & Dadali, 2007).

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

Model no	Model name	Model equation	Eq no
1	Lewis (Doymaz & Ismail, 2011)	$M_R = \exp(-kt)$	(11)
2	Page (Jangam et al., 2008)	$M_R = \exp(-kt^n)$	(12)
3	Modified Page (Akpinar, 2006)	$M_R = \exp[-(kt)^n]$	(13)
4	Henderson and Pabis (Pehlivan & Toğrul, 2004)	$M_R = a\exp(-kt)$	(14)
5	Logarithmic (Kingsly et al., 2007)	$M_R = a\exp(-kt)+c$	(15)
6	Two-term (Demirhan & Ozbek, 2011)	$M_R = a\exp(-k_0t)+b\exp(-k_1t)$	(16)
7	Two-term exponential (App. of diff.) (Alibas, 2014)	$M_R = a\exp(-kt)+(1-a)\exp(-kat)$	(17)
8	Wang and Singh (Demirhan & Ozbek, 2011)	$M_R = 1+at+bt^2$	(18)
9	Thomson (Alibas, 2014)	$t = a.\ln(M_R)+b[\ln(M_R)]^2$	(19)
10	Diffusion approach (Kassem, 1998)	$M_R = a\exp(-kt)+(1-a)\exp(-kbt)$	(20)
11	Verma et al. (Alibas, 2014)	$M_R = a\exp(-kt)+(1-a)\exp(-gt)$	(21)
12	Modified Henderson and Pabis (Karathanos, 1999)	$M_R = a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	(22)
13	Simlified Fick's diffusion (SFFD) eq. (Diamante & Munro, 1991)	$M_R = a\exp[-c(t/L^2)]$	(23)
14	Modified Page equation-II (Diamante & Munro, 1993)	$M_R = \exp[-k(t/L^2)^n]$	(24)
15	Midilli et al. (Midilli et al., 2002)	$M_R = a\exp(-kt^n)+bt$	(25)
16	Weibull distribution (Babalis, 2006)	$M_R = a-b\exp[-(kt^n)]$	(26)
17	Aghlasho et al. (Aghlasho et al., 2009)	$M_R = \exp(-k_1t/1+k_2t)$	(27)
18	Logistic (Alibas, 2014)	$M_R = a_0/(1+a\exp(kt))$	(28)
19	Jena and Das (Jena & Das, 2007)	$M_R = a\exp(-kt+b\sqrt{t})+c$	(29)
20	Demir et al. (Demir et al., 2007)	$M_R = a\exp(-kt)^n+c$	(30)

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

2.4 Data analysis

Twenty 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(11) – Eq(30)] were made by using SPSS statistics 17.0. Non-linear regression analysis was performed to estimate the parameters *k*, k_0, k_1, k_2, *a*, a_0, *b*, *c*, *g*, *h*, *L* and *n* of theoretical, empirical and semi empirical equations in Table 1.

3 Result and discussion

3.1 Curves and mathematical modeling

In this study, apart from 20 thin-layer drying models [Eq. (11) – Eq. (30)] defined by various researchers in Table 1. Values of moisture ratio (M_R) depending on time (*t*) of celery leaves were given in Figure 1. The drying periods of celery leaves

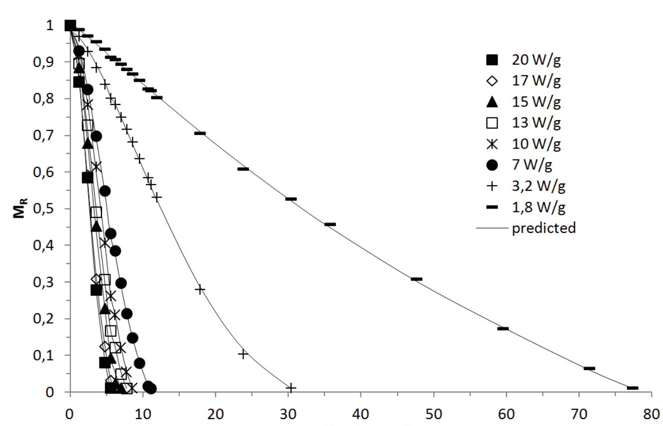

Figure 1. Moisture ratio versus time, comparing experimental curve with the predicted one (—) through Weibull distribution's model (model no:16) for all microwave densities.

from an initial moisture content of 91.75% ± 0.15 to 8.95% ± 0.12 were 5.5, 6, 7, 8, 9, 11, 30 and 77 min in microwave power densities of 20, 17, 15, 13, 10, 7, 3.2 and 1.8 W g^{-1}, respectively. As the microwave power density increase drying time decreases profoundly. Similar findings were found by several researchers (Al-Harahsheh et al., 2009; Evin 2012; Alibas 2014; Demirhan & Ozbek 2011; Sarimeseli 2011; Alibas, 2012; Karaaslan & Tunçer 2008). Moreover data obtained experimentally in Figure 1 and data of estimation obtained with "Weibull distribution model" whose coefficient of correlation (R^2) is highest within 20 models defined in Table 2 were also given. Since the value of the coefficient of correlation (R^2) in drying tests is too close to value "1", data of model and estimation on Figure 1 seemed to coincide with each other. The value of "1" for coefficient of correlation (R^2) means that estimation data corresponded well with the experimental data.

Apart from Weibull distribution model which is defined for the first time in this study, values of standard error of estimate (*SEE*), coefficient of correlation (R^2), root mean square error (*RMSE*) and chi-square (χ^2) about thin-layer drying models that were defined in the literature were also given in Table 2. In the study thin-layer drying model in which (R^2) value is closest to "1" and *RMSE*, (χ^2) and (*SEE*) values are smallest was chosen to be the most optimum model. Within microwave drying values dried of 20, 17, 15, 13, 10, 7 and 3.2 W g^{-1} microwave power density, coefficient of correlation (R^2) of Weibull distribution model is more close to values "1" compared with other thin-layer drying model. Therefore, Weibull distribution Model was the most optimal model in which estimation values were closest to experimental data for microwave power density levels. In the microwave drying test at 1.8 W g^{-1} microwave power density dosage, coefficient of correlation (R^2) of Weibull distribution's equation was equal to the coefficient of correlation (R^2) of Jena and Das Model 0.9998 (98%). Drying constant and coefficient values (*n*, *k*, *a* and *b*) calculated for each microwave power density of Weibull distribution's equation were given in Table 3. The highest coefficient of correlation (R^2) was at the level of 17 and 1.8 W g^{-1} microwave power density with a value of 0.9998, whereas the lowest value recorded at 20 W g^{-1} microwave power density level with a value of 0.9992. Weibull distribution model's coefficient of correlations (R^2) were found to 0.9985, 0.9996, 0.9996, 0.9997 according to microwave power density levels 15, 13, 10, 7 and 3.2 W g^{-1} respectively. Moreover *k*, *n*, *a* and *b* coefficients of Weibull distribution's equation were given in Table 3 for all microwave power density.

Demirhan & Ozbek (2011) determined that the semi-empirical Midilli et al. model gave a better fit for all drying conditions applied of microwave dried celery leaves among the eight thin-layer drying models proposed. Evin (2012) found that the experimental moisture loss data were fitted to the 14 thin layer drying models. Among the models proposed, the Midilli model precisely represented the microwave drying behavior of *G. tournefortii*. Sarimeseli (2011) found that the coriander leaves were dried with microwave radiation and the semi-empirical Midilli et al. model was the best model of six thin-layer drying models. Dadali et al. (2007b) determined that Page's model gave a better fit for all drying conditions applied of microwave dried spinach leaves among of the eight thin-layer drying models proposed.

3.2 Estimation of effective moisture diffusivity and activation energy

The effective moisture diffusivity of celery leaves was described using the drying data. Non-linear regression technique was used to estimate the effective moisture diffusivity (D_{eff}) of Fick's diffusion equation Equation 9. Depending on the drying conditions, effective moisture diffusivities of celery leaves ranged from 1.595 10^{-10} to 6.377 10^{-12} m^2 s^{-1} for the microwave output power density between 20 and 1.8 W g^{-1}, respectively. According to Eq.(9) which is calculated, the effective moisture diffusivities, the corresponding values of the coefficient of determination (R2) were presented in Table 4 for various microwave output power densities.

In this study, as the temperature is not measurable variable in standard microwave oven used for drying process, the Arrhenius equation was used in a modified form to illustrate the relationship between the kinetic rate constant and the ratio of the microwave output power density to sample amount instead of the temperature for calculation of the activation energy. After evaluation of the data, the dependence of kinetic rate constant on the ratio of microwave output power densities to sample amount was represented with Dadali et al. exponential Equation 8 (Evin, 2012; Sarimeseli, 2011; Dadali et al., 2007a, b; Özbek & Dadali, 2007). The drying rate constant (k) is obtained by using Weibull distribution equation. The values of k versus m/P shown in Figure2 accurately fit Eq.(8) with a coefficient of determination (R2) of 0.9221 and the standard error of estimated (SEE) of 0.0148725. Then pre-exponential constant (k0) and activation energy (Ea) values were estimated as 0.2933 min-1 and 14.1978 W.g^{-1}.

The activation energy were also calculated using Equation 9 derived by Dadali et al. (2007a, b) and Özbek & Dadali

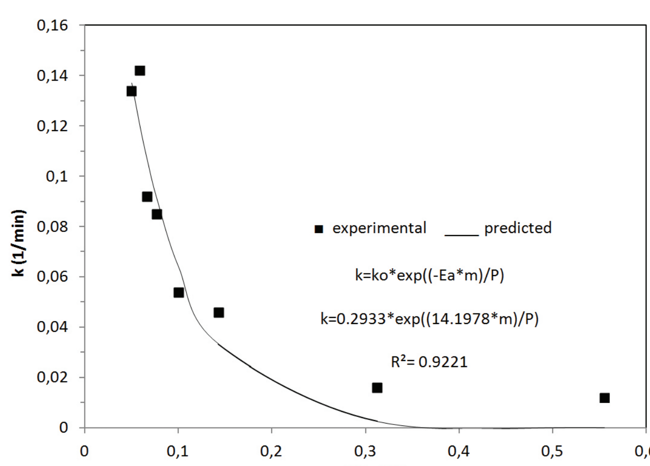

Figure 2. The relationship between the values of *k* (Weibull distribution model) versus sample amount/power.

Table 2. Statistical results obtained from different thin-layer drying models for the different microwave power density.

Model	20 W g^{-1}				17 W g^{-1}				***15 W g^{1}***				***13 W g^{1}***			
	SEE	R^2	RMSE	χ^2	SEE	R^2	RMSE	χ^2	SEE	R^2	**RMSE**	χ^2	**SEE**	R^2	**RMSE**	χ^2
1	0.1281	0.9015	2.1687 10^{-03}	5.6438 10^{-06}	0.1180	0.9135	6.1499 10^{-03}	4.4125 10^{-05}	0.1289	0.8930	5.2569 10^{-04}	3.1583 10^{-07}	0.1165	0.9041	4.1661 10^{-03}	1.9526 10^{-05}
2	0.0203	0.9980	1.4390 10^{-02}	3.1060 10^{-04}	0.0153	0.9988	1.2730 10^{-02}	2.2688 10^{-04}	0.0283	0.9956	2.2814 10^{-02}	6.9397 10^{-04}	0.0184	0.9979	1.5900 10^{-02}	3.2504 10^{-04}
3	0.1432	0.9015	2.1687 10^{-03}	7.0548 10^{-06}	0.1292	0.9135	6.1499 10^{-03}	5.2950 10^{-05}	0.1392	0.8930	5.2571 10^{-04}	3.6850 10^{-07}	0.1245	0.9041	4.1661 10^{-03}	2.2315 10^{-05}
4	0.1335	0.9144	4.6391 10^{-02}	3.2282 10^{-03}	0.1194	0.9261	5.3759 10^{-02}	4.0460 10^{-03}	0.1276	0.9101	5.7938 10^{-02}	4.4758 10^{-03}	0.1121	0.9223	5.3145 10^{-02}	3.6314 10^{-03}
5	0.0661	0.9843	7.0199 10^{-10}	9.8557 10^{-19}	0.0543	0.9878	7.3204 10^{-11}	9.3780 10^{-21}	0.0509	0.9881	5.3395 10^{-01}	4.5616 10^{-01}	0.0462	0.9887	3.6781 10^{-10}	2.0293 10^{-19}
6	0.1888	0.9144	4.6391 10^{-02}	6.4563 10^{-03}	0.1542	0.9261	5.3759 10^{-02}	6.7434 10^{-03}	0.1562	0.9101	5.7938 10^{-02}	6.7137 10^{-03}	0.1327	0.9223	5.3145 10^{-02}	5.0839 10^{-03}
7	0.0590	0.9833	2.9403 10^{-02}	1.2968 10^{-03}	0.0493	0.9874	3.1792 10^{-02}	1.4150 10^{-03}	0.0648	0.9768	4.1209 10^{-02}	2.2642 10^{-03}	0.0511	0.9838	3.5191 10^{-02}	1.5923 10^{-03}
8	0.0609	0.9822	1.9989 10^{-02}	5.9932 10^{-04}	0.0515	0.9862	1.9812 10^{-02}	5.4951 10^{-04}	0.0505	0.9859	2.0236 10^{-02}	5.4599 10^{-04}	0.0476	0.9860	2.3160 10^{-02}	6.8965 10^{-04}
9	0.4979	0.9405	4.0619 10^{-01}	2.4749 10^{-01}	0.4305	0.9596	3.7520 10^{-01}	1.9708 10^{-01}	0.5964	0.9304	5.4818 10^{-01}	4.0066 10^{-01}	0.5674	0.9439	6.0529 10^{-01}	4.7106 10^{-01}
10	0.0519	0.9871	2.6981 10^{-02}	1.4559 10^{-03}	0.0424	0.9907	2.8431 10^{-02}	1.4146 10^{-03}	0.0579	0.9815	3.8276 10^{-02}	2.3441 10^{-03}	0.0443	0.9879	3.1822 10^{-02}	1.5190 10^{-03}
11	0.0596	0.9872	2.6895 10^{-02}	1.4467 10^{-03}	0.0471	0.9908	2.8274 10^{-02}	1.3990 10^{-03}	0.0632	0.9816	3.8166 10^{-02}	2.3306 10^{-03}	0.0478	0.9879	3.1790 10^{-02}	1.5160 10^{-03}
12	0.0385	0.9982	2.2003 10^{-04}	2.9049 10^{-07}	0.0180	0.9993	1.2638 10^{-04}	1.1181 10^{-07}	0.0282	0.9978	7.9960 10^{-05}	2.5574 10^{-08}	0.0145	0.9993	9.8131 10^{-05}	2.8889 10^{-08}
13	0.1542	0.9144	4.6391 10^{-02}	4.3042 10^{-03}	0.1335	0.9261	5.3759 10^{-02}	5.0576 10^{-03}	0.1398	0.9101	5.7938 10^{-02}	5.3709 10^{-03}	0.1211	0.9223	5.3145 10^{-02}	4.2366 10^{-03}
14	0.0234	0.9980	1.4390 10^{-02}	4.1413 10^{-04}	0.0171	0.9988	1.2730 10^{-02}	2.8360 10^{-04}	0.0310	0.9956	2.2814 10^{-02}	8.3277 10^{-04}	0.0199	0.9979	1.5900 10^{-02}	3.7921 10^{-04}
15	0.0177	0.9991	8.0118 10^{-05}	1.9257 10^{-08}	0.0662	0.9864	1.6490 10^{-07}	6.3451 10^{-14}	0.0583	0.9701	3.9567 10^{-06}	3.1312 10^{-11}	0.0493	0.9893	2.5235 10^{-06}	1.1463 10^{-11}
16	**0.0180**	**0.9992**	**3.1103 10^{-11}**	**2.9022 10^{-21}**	**0.0084**	**0.9998**	**6.7939 10^{-12}**	**1.0770 10^{-22}**	**0.0202**	**0.9985**	**1.8630 10^{-11}**	**6.9413 10^{-22}**	**0.0093**	**0.9996**	**3.5378 10^{-14}**	**2.2529 10^{-27}**
17	0.0246	0.9969	1.7308 10^{-02}	4.4937 10^{-04}	0.0266	0.9963	2.1197 10^{-02}	6.2907 10^{-04}	0.0183	0.9981	1.3544 10^{-02}	2.4460 10^{-04}	0.0231	0.9967	1.7726 10^{-02}	4.0397 10^{-04}
18	0.0179	0.9989	8.6266 10^{-03}	1.4883 10^{-04}	0.0148	0.9991	8.6890 10^{-03}	1.3212 10^{-04}	0.0290	0.9961	1.5046 10^{-02}	3.6219 10^{-04}	0.0186	0.9982	9.6192 10^{-03}	1.3879 10^{-04}
19	0.0392	0.9963	7.7043 10^{-12}	1.7807 10^{-22}	0.0244	0.9981	7.6817 10^{-10}	1.3769 10^{-18}	0.0323	0.9961	8.6128 10^{-11}	1.4836 10^{-20}	0.0239	0.9975	1.5316 10^{-12}	4.2226 10^{-24}
20	0.0810	0.9843	7.6798 10^{-08}	1.7694 10^{-14}	0.0627	0.9878	1.9068 10^{-07}	8.4840 10^{-14}	0.0569	0.9881	1.0524 10^{-07}	2.2149 10^{-14}	0.0506	0.9887	9.6871 10^{-08}	1.6891 10^{-14}

Model	**10 W g^{-1}**				**7 W g^{-1}**				**3.2 W g^{-1}**				**1.8 W g^{-1}**			
	SEE	R^2	**RMSE**	χ^2	**SEE**	R^2	**RMSE**	χ^2	**SEE**	R^2	**RMSE**	χ^2	**SEE**	R^2	**RMSE**	χ^2
1	0.1222	0.8889	1.3152 10^{-02}	1.9219 10^{-04}	0.1089	0.9008	1.0905 10^{-02}	1.2884 10^{-04}	0.0814	0.9194	5.0868 10^{-02}	2.7492 10^{-03}	0.0580	0.9652	6.0119 10^{-02}	3.7864 10^{-03}
2	0.0204	0.9973	2.0759 10^{-02}	5.3865 10^{-04}	0.0215	0.9965	2.5787 10^{-02}	7.8585 10^{-04}	0.0179	0.9964	2.3824 10^{-02}	6.4323 10^{-04}	0.0242	0.9942	2.8319 10^{-02}	8.8219 10^{-04}
3	0.1296	0.8889	1.3152 10^{-02}	2.1622 10^{-04}	0.1137	0.9008	1.0904 10^{-02}	1.4052 10^{-04}	0.0841	0.9194	5.0868 10^{-02}	2.9325 10^{-03}	0.0594	0.9652	6.0119 10^{-02}	3.9758 10^{-03}
4	0.1158	0.9113	5.2354 10^{-02}	3.4262 10^{-03}	0.0996	0.9238	5.5680 10^{-02}	3.6640 10^{-03}	0.0689	0.9460	3.1310 10^{-02}	1.1110 10^{-03}	0.0466	0.9785	2.6465 10^{-02}	7.7042 10^{-04}
5	0.0454	0.9881	7.1418 10^{-10}	7.2864 10^{-19}	0.0362	0.9908	1.2279 10^{-09}	1.9601 10^{-18}	0.0265	0.9925	2.4730 10^{-09}	7.4264 10^{-18}	0.0065	0.9996	3.3157 10^{-12}	1.2730 10^{-23}
6	0.1337	0.9113	5.2354 10^{-02}	4.5682 10^{-03}	0.1102	0.9238	5.5680 10^{-02}	4.4782 10^{-03}	0.0740	0.9460	3.1310 10^{-02}	1.2820 10^{-03}	0.0492	0.9785	2.6465 10^{-02}	8.5602 10^{-04}
7	0.0583	0.9775	3.9800 10^{-02}	1.9800 10^{-03}	0.0518	0.9794	4.4549 10^{-02}	2.3455 10^{-03}	0.0314	0.9888	2.8676 10^{-02}	9.3193 10^{-04}	0.0268	0.9929	2.1421 10^{-02}	5.0473 10^{-04}
8	0.0478	0.9849	2.4100 10^{-02}	7.2599 10^{-04}	0.0401	0.9876	2.6169 10^{-02}	8.0933 10^{-04}	0.0305	0.9894	3.0757 10^{-02}	1.0721 10^{-03}	0.0098	0.9991	2.0064 10^{-02}	4.4281 10^{-04}
9	0.6956	0.9251	8.1782 10^{-01}	8.3603 10^{-01}	0.7378	0.9437	9.6621 10^{-01}	1.1033 10^{+00}	1.5821	0.9480	3.1389 10^{+00}	1.1166 10^{+01}	2.1861	0.9883	5.0824 10^{+00}	2.8413 10^{+01}
10	0.0514	0.9826	3.6999 10^{-02}	1.9556 10^{-03}	0.0458	0.9839	4.1566 10^{-02}	2.2461 10^{-03}	0.0203	0.9912	2.6792 10^{-02}	8.7166 10^{-04}	0.0255	0.9938	2.0500 10^{-02}	4.8663 10^{-04}
11	0.0549	0.9826	3.6994 10^{-02}	1.9551 10^{-03}	0.0478	0.9840	4.1475 10^{-02}	2.2362 10^{-03}	0.0286	0.9913	2.6731 10^{-02}	8.6766 10^{-04}	0.0257	0.9938	2.0463 10^{-02}	4.8486 10^{-04}
12	0.0166	0.9989	2.0877 10^{-04}	1.0896 10^{-07}	0.0106	0.9994	8.7839 10^{-05}	1.4329 10^{-08}	0.0081	0.9992	1.2487 10^{-04}	2.4097 10^{-08}	0.0056	0.9997	1.3918 10^{-06}	2.6635 10^{-12}
13	0.1238	0.9113	5.2354 10^{-02}	3.9156 10^{-03}	0.1045	0.9238	5.5680 10^{-02}	4.0304 10^{-03}	0.0713	0.9460	3.1310 10^{-02}	1.1904 10^{-03}	0.0479	0.9785	2.6465 10^{-02}	8.1097 10^{-04}
14	0.0218	0.9973	2.0759 10^{-02}	6.1560 10^{-04}	0.0225	0.9965	2.5787 10^{-02}	8.6443 10^{-04}	0.0185	0.9964	2.3824 10^{-02}	6.8918 10^{-04}	0.0248	0.9942	2.8319 10^{-02}	9.2862 10^{-04}
15	0.0425	0.9910	2.2173 10^{-06}	8.1942 10^{-12}	0.0419	0.9890	2.8293 10^{-06}	1.1563 10^{-11}	0.0399	0.9843	1.6476 10^{-06}	3.5498 10^{-12}	0.0322	0.9908	4.2131 10^{-06}	2.1695 10^{-11}
16	**0.0094**	**0.9996**	**2.7114 10^{-11}**	**1.2253 10^{-21}**	**0.0072**	**0.9997**	**1.3592 10^{-11}**	**2.6683 10^{-22}**	**0.0082**	**0.9993**	**1.4847 10^{-11}**	**2.8825 10^{-22}**	**0.0048**	**0.9998**	**8.8749 10^{-14}**	**9.6266 10^{-27}**
17	0.0226	0.9966	2.1528 10^{-02}	5.7934 10^{-04}	0.0174	0.9977	1.9276 10^{-02}	4.3913 10^{-04}	0.0108	0.9987	1.5258 10^{-02}	2.6386 10^{-04}	0.0095	0.9991	4.2332 10^{-03}	1.9712 10^{-05}
18	0.0182	0.9981	1.0840 10^{-02}	1.6785 10^{-04}	0.0191	0.9975	1.4020 10^{-02}	2.5552 10^{-04}	0.0106	0.9988	6.2639 10^{-03}	4.7645 10^{-05}	0.0197	0.9963	9.5633 10^{-03}	1.0590 10^{-04}
19	0.0274	0.9963	5.1880 10^{-11}	4.4859 10^{-21}	0.0213	0.9972	3.7409 10^{-13}	2.0214 10^{-25}	0.0186	0.9966	3.9295 10^{-10}	2.0192 10^{-19}	**0.0042**	**0.9998**	**9.1568 10^{-13}**	**1.0248 10^{-24}**
20	0.0490	0.9881	1.5806 10^{-08}	4.1637 10^{-16}	0.0382	0.9908	1.5085 10^{-08}	3.2869 10^{-16}	0.0275	0.9925	1.5721 10^{-08}	3.2318 10^{-16}	0.0067	0.9996	4.0056 10^{-09}	1.9611 10^{-17}

Table 3. Statistical results and coefficients obtained from Weibull distribution thin-layer drying model for the different microwave power density.

P_D (W g^{-1})	(R^2)	SEE	RMSE	χ^2	Drying constant and coefficients			
					k*	n*	a*	b*
20	0.9992	0.0180	3.1103 10^{-11}	2.9022 10^{-21}	0.1339166	1.9439840	−0.0544864	−1.0475040
17	0.9998	0.0084	6.7939 10^{-12}	1.0770 10^{-22}	0.1423951	1.8211029	−0.0515568	−1.0482103
15	0.9985	0.0202	1.8630 10^{-11}	6.9413 10^{-22}	0.0917851	1.8437386	−0.1119173	−1.1045911
13	0.9996	0.0093	3.5378 10^{-14}	2.2529 10^{-27}	0.0854332	1.7952976	−0.0869173	−1.0822232
10	0.9996	0.0094	2.7114 10^{-11}	1.2253 10^{-21}	0.0541612	1.9084683	−0.1009756	−1.0909846
7	0.9997	0.0072	1.3592 10^{-11}	2.6683 10^{-22}	0.0461380	1.7356680	−0.1175300	−1.1082083
3.2	0.9993	0.0082	1.4847 10^{-11}	2.8825 10^{-22}	0.0164425	1.5206285	−0.1115377	−1.0982806
1.8	0.9998	0.0048	8.8749 10^{-14}	9.6266 10^{-27}	0.0118011	1.0842987	−0.4746149	−1.4812530

*Means with same letter do not show significance at P < 0.01.

Table 4. Estimated effective moisture diffusivity and regression coefficient of linear model at various microwave output power densities.

P(W)	m (g)	P_D (W g^{-1})	Slope*	D_{eff} (m^2 min^{-1})*	D_{eff} (m^2 s^{-1})*	R^2
90	50	1.8	0.729385	9.57002 10^{-09}	1.59500 10^{-10}	0.9800
160	50	3.2	0.650130	8.53014 10^{-09}	1.42169 10^{-10}	0.9629
350	50	7	0.527513	6.21320 10^{-09}	1.15355 10^{-10}	0.9875
500	50	10	0.434881	5.05930 10^{-09}	9.50989 10^{-11}	0.9964
650	50	13	0.354309	4.48770 10^{-09}	7.74796 10^{-11}	0.9732
750	50	15	0.249521	3.73880 10^{-09}	5.45647 10^{-11}	0.9862
850	50	17	0.06964	9.37210 10^{-10}	1.52287 10^{-11}	0.9582
1000	50	20	0.029163	3.82639 10^{-10}	6.37731 10^{-12}	0.9703

* Means with same letter do not show significance at P < 0.01.

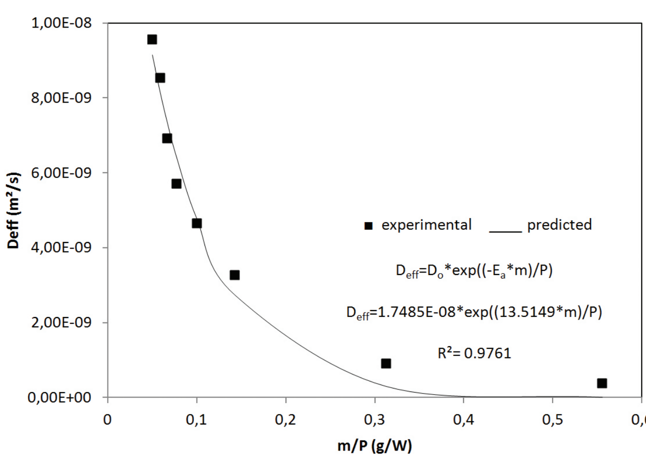

Figure 3. The relationship between the values of effective moisture diffusivity (D_{eff}) versus sample amount/power.

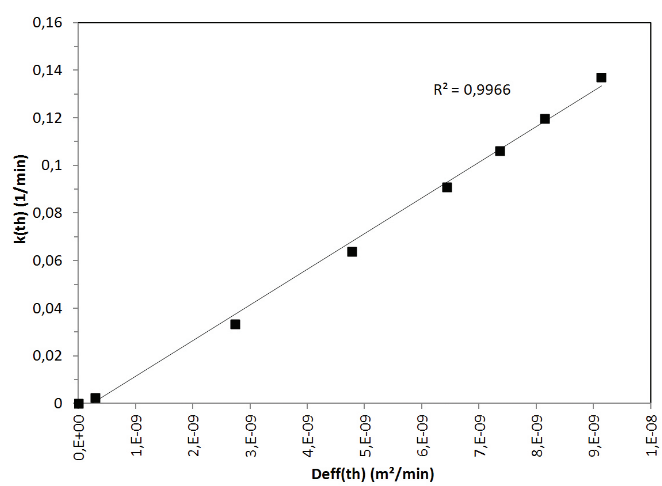

Figure 4. The relationship between the values of k_{th} (Weibull distribution model) and effective diffusivities $(Deff)_{th.}$

(2007). The relationship between the values of effective moisture diffusivity versus sample amount/power (*m/P*) is given in Figure 3 accurately fit Equation 9 with a coefficient of determination (R^2) of 0.9761 and the standard error of estimated (*SEE*) of 5.599 10^{-10}. The values of pre-exponential factor (*Do*) and activation energy (*Ea*) were estimated as 1.7485 10^{-8} m^2 min^{-1} (1.2828 10^{-10} m^2s^{-1}) and 13.5149 W.g^{-1}. In conclusion, the value of Ea found from this study was quite similar to the value (14.1978 W.g^{-1}) obtained from the previous paragraph by using Equation 8.

The theoretical values of drying rate constant (k_{th}), obtained from Equation 8 and the theoretical values of effective moisture diffusivity ($(D_{eff})_{th}$) obtained from Equation 9 for this study were fitted sufficiently to Equation 10 with the coefficient of determination (R^2) of 0.9948 and the standard error of estimated value of 0.003814. The value of constant (*A*) was obtained as 14468064.1 10^7 $min^{-1}m^{-2}s$. The relationship between the theoretical effective moisture diffusivity ($(D_{eff})_{th}$) and the drying rate constant (k_{th}) is given in Figure 4.

Demirhan & Ozbek (2011) found that the effective moisture diffusivities increased from 0.343 × 10^{-10} to 1.714 × 10^{-10} m^2 .s^{-1} with an increase in microwave output power of 25 g and the activation energy of celery leaves was found similar as 7.89 and 6.92 W.g^{-1} , respectively. Evin (2012) determined that the effective moisture diffusivities of *G. tournefortii* under microwave range of 90-800 W were in the range of 5.5 × 10^{-8} to 3.5 × 10^{-7} m^2/s. Dadali et al. (2007b) found that the effective moisture diffusivities increased from 1.99 × 10^{-10} to 5.27 × 10^{-10} $m^2.s^{-1}$ with an increase in microwave output power of 25 g and the activation energy of spinach dried was found almost similar as 10.84 and 9.62 W.g^{-1}. Sarimeseli (2011) determined that the effective moisture diffusivities were found to be 6.3 × 10^{-11}-2.19 × 10^{-10} m^2/s of microwave dried coriander leaves within the range of microwave power values, 180-360 W.

4 Conclusions

The effects of different microwave power density on the drying of celery leaves were evaluated based on the drying parameters such as the drying time, the moisture on a wet basis and the drying rate. Drying period was completed between 5.5 and 77 min at the microwave power densities between 20 W and 1.8 Wg^{-1}.

Drying tests were done at the microwave power density values of 1.8, 3.2, 7, 10, 13, 15, 17 and 20 W g^{-1}. Twenty different drying models were used in the study and chi-square and coefficient of correlation (R^2) values and constant and coefficients of these models were calculated. Weibull distribution's model was found as the best model within all drying trials.

The effective moisture diffusivity was also calculated to understand the mass transfer mechanism of celery leaves at various microwave output power densities and sample amounts. For a constant amount of 50 g sample, the effective moisture diffusivities increased from 1.595 10^{-10} to 6.377 10^{-12} m^2 s^{-1} with an increase in microwave output power density.

The activation energy of celery leaves was calculated by using the exponential expression based on Arrhenius equation and found similar as 13.515 and 14.198 W g^{-1}, respectively.

Notation

M initial moisture content, [$kg_{(moisture)}$ $kg^{-1}{}_{(drymatter)}$]
W_0 initial weight of sample, kg
W amount of evaporated water, kg
W_1 dry matter content of sample, kg
M_R moisture ratio
M_e equilibrium moisture content, [$kg_{(moisture)}$ $kg^{-1}{}_{(drymatter)}$]
k, k_0, k_1, k_2 drying constant, min^{-1}
a,a_0,b,c, 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
$M_{Rexp,i}$ stands fort the experimental moisture ratio found in any measurement
$M_{Rpre,i}$ predicted moisture ratio for this measurement
N total number of observations
n_i number of constants
SEE standard error of estimated
D_{eff} effective moisture diffusivity, m^2 min^{-1}
L_s half thickness of celery leave, m
k_o the pre-exponential constant, min^{-1}
D_0 the pre-exponential factor, m^2 min^{-1}
E_a the activation energy, W g^{-1}
P microwave output power, W
m the mass of raw sample, g
A the stabilization constant, min^{-1} m^2 s
k_{th} the theoretical drying rate constant, min^{-1}
$D(_{eff})_{th}$ theoretical effective diffusivity, m^2 s^{-1}

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