

Research Article

Characterization of Thin Layer Hot Air Drying of Celery Root

Xiaohong Wei, Kai Fan, Jie He and Fengwei Yan

Department of Food Science and Technology, College of Life Science, Yangtze University, Jingzhou, Hubei Province 434025, China

Abstract: The hot air drying characteristics of celery root were evaluated in a laboratory scale dryer at the drying temperatures of 50, 60, 70 and 80°C. The effect of hot air drying on drying time, drying rate, moisture content, moisture ratio and effective moisture diffusivity of celery root was investigated. Fifteen thin layer drying models were fitted by using experimental drying data. The fitting effect of model predictions was evaluated by using the values of coefficient of determination, sum squared error, root mean square error and chi-square. The results showed fitting accuracy of model 15 (Hii *et al.*, 2009) gave a better fit for all drying conditions applied. The average values of effective moisture diffusivities of celery root ranged from 1.957×10^{-9} to 9.016×10^{-9} within the given drying temperature range. With in a certain temperature range (50-70°C), the average effective moisture diffusivities of celery root increased with increased temperature. The activation energy was estimated as 21.817 KJ/mol using an exponential expression based on the Arrhenius equation.

Keywords: Activation energy, celery root, effective moisture diffusivity, hot air drying, thin layer drying models

INTRODUCTION

Celery (*Apium graveolens* L.) which belongs to umbrelliferae plant is an annual or biennial herb. It is native to Mediterranean coastal marshes and now has been widely cultivated in the world. Celery is rich in a variety of vitamins, inorganic salts, calcium, phosphorus, iron and essential oils with different limonenes and terpenes such as p-cimol, a-limonen, a-santalol and b-pinen (Engindeniz, 2008). It's recognized as a edible and medicinal high-grade pollution-free herbaceous vegetable. The aromatic meat of its callous celeriac and aromatic leaf are the eatable parts of celery. It has the function of clean blood and lower blood pressure as well as blood lipid and is also used as stimulants, antispasmodics, aphrodisiacs and so on (Kapoor and Bhatnagar, 2007).

Fresh celery contains high moisture content to cause rot easily. It's difficult to control storage condition. Hot air drying is one of the most commonly used preservation method for the agricultural products (Yanishlieva-Maslarova, 2001). After dehydration, celery has the capability of extending the consumption period, minimizing packaging requirements and reducing transportation costs. The dehydrated vegetables can maximize retain its original color, lustre, nutrition and flavor (Maroulis and Saravacos, 2003).

Drying is a technology of simultaneous heat and mass transfer in the product. Water in the forms of liquid and vapor transported from the inside of food to the interface and then spread into the air. Whereas the heat conduct from the air to the interface of food and then into food. The drying process involving the composition and structure of material, drying temperature, drying time and water activity and some others (Bialobrzewski and Markowski, 2004). The efficiency of the process is a challenging problem that requires the optimization of the conditions. Thus, it is of great significant to establish the mathematical model of drying technology and equipment. The reliable model is also helpful to understand the transmission mechanism of drying process and accurately control operating conditions to meet the desired final product characteristics (Demir *et al.*, 2007). Some previous studies of the drying kinetics of food were reported. The investigators researched the thin layer drying models of parsley (Soysal, 2004), basil (Demirhan and Ozbek, 2010), tomato (Celmaa *et al.*, 2012) in the literatures. However, the relationship between the effective moisture diffusion coefficient and the drying temperature of celery root is less reported.

The objectives of the present study was to investigate the effect of drying temperature on the water ratio and the effective moisture diffusivity, to select the celery thin layer drying kinetics model, to calculate the effective moisture diffusivity and the activation energy under different drying conditions.

Corresponding Author: Xiaohong Wei, Department of Food Science and Technology, College of Life Science, Yangtze University, Jingzhou, Hubei Province 434025, China, Fax: +867168066257

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Table 1: Mathematical models applied by various researchers for the drying curves

No.	Model name	Model	References
1	Newton	MR = exp(-kt)	Ayensu (1997)
2	Page	MR = exp(-kt ⁿ)	Karathanos and Belessiotis (1999)
3	Modified page	MR = exp(-(kt) ⁿ)	Overhults <i>et al.</i> (1973)
4	Henderson and Pabis	MR = a exp(-kt)	Henderson and Pabis (1961)
5	Logarithmic	MR = a exp(-kt) + c	Yaldiz <i>et al.</i> (2001)
6	Two term	MR = a exp(-k ₀ t) + b exp(-k ₁ t)	Henderson (1974)
7	Midilli and Kucuk	MR = a exp(-kt ⁿ) + bt	Midilli <i>et al.</i> (2002)
8	Wang and Singh	MR = 1 + at + bt ²	Wang and Singh (1978)
9	Modified Henderson and Pabis	MR = a exp(-kt) + b exp(-gt) + c exp(-ht)	Karathanos (1999)
10	Two term exponential	MR = a exp(-kt) + (1-a) exp(-kat)	Akpinar <i>et al.</i> (2003)
11	Thomson	t = a ln(MR) + b(ln(MR)) ²	Paulsen and Thomson (1973)
12	Verma <i>et al.</i>	MR = a exp(-kt) + (1-a) exp(-gt)	Verma <i>et al.</i> (1985)
13	Jena and Das	MR = aexp(-kt + bt ^{1/2}) + c	Jena and Das (2007)
14	Weibull	MR = exp(-(t/a) ^b)	Corzo <i>et al.</i> (2008)
15	Hii <i>et al.</i>	MR = aexp(-bt ^r) + dexp(-gt ^r)	Hii <i>et al.</i> (2009)

MATERIALS AND METHODS

Experimental material: Plants of fresh celery used for the drying experiments were purchased on the local market in Jingzhou city, Hubei province, China. Fresh celery leaves should be flat and green without rusty and insect pest. Prior to drying experiments, put the cleaned celery root on the tray to drain off the surface water and stored the samples in a refrigerator at 5.0±0.5°C for 24 h for equilibration of moisture. Remove the celery leaves from stem and then cut celery root into 0.356±0.05 cm thickness segments manually with sharp stainless steel knife. The celery root thickness was measured with vernier caliper. To determine the initial moisture content, select three samples of 25.305±0.500 g to dry in an oven (101A-3, Shanghai Experimental Instrument Co., China) at 105°C for 12 h. The average initial moisture content of celery root was calculated as 27.955 g/g (dry basis).

Drying procedure: Drying experiments were carried out at four operational temperatures: 50, 60, 70 and 80°C assisted by hot air blown at 2.0 m/s velocity. All the experiments were conducted for three replications. Set the electrothermal blowing drying oven to the specified conditions. When the dryer running stability, spread 25.305±0.500 g of the prepared samples in thin layer on the trays on a single layer to dry. During the drying process, moisture loss was measured periodically in 10 min intervals during the first 133 min and later on 15 min intervals and last in 30 min intervals by a electronic balance with a precision of 0.0001 g. All weighing processes were completed in less than 10 s. The drying process was finalized when the mass change of the sample was stabilized at a constant value, regardless of further drying duration.

Calculation of moisture ratio and drying rate: The moisture ratio and drying rate of celery root were determined using the following equations:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

$$DryingRate = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (2)$$

where,

- MR = The moisture ratio, dimensionless
- M_t = The instantaneous moisture content, g water/g dry matter
- M_e = The equilibrium moisture content, g water/g dry matter
- M_o = The initial moisture content, g water/g dry matter
- M_{t+Δt} = The moisture content at a specific time t+Δt, min
- t = Drying time, min

Drying model: Generally speaking, there are four types of thin layer drying models used to describe the drying procedure of agriculture product, namely, theoretical equation, semi-theoretical equation, empirical equation and semi-empirical equation. Theoretical model only considers the internal resistance to moisture transfer between product and heating air in the process of derivation. Semi-theoretical equation is the simplification of theoretical equation. Semi-empirical equation is based on certain theory and combined with the drying dynamics experiments, which has high fitting degree, small error and is widely used. The applicable scope of empirical equation is small (Wang *et al.*, 2007). In this study, fifteen semi-empirical or empirical equations which were widely used in published articles were selected to fit the drying curves. These mathematical models are presented in Table 1.

Correlation coefficients and statistical analyses: The software package Matlab R2009a (MathWorks Inc., Natick, MA, USA) was used to perform the nonlinear regression analysis. The fit quality of the tested mathematical models for simulating the experimental data was evaluated with determination correlation coefficient (R²), Sum Squared Error (SSE), the Root Mean Square Error (RMSE), the reduced chi-square (χ²) and mean relative percent deviation (P) (Lee and Kim, 2009; Vega-Gálvez *et al.*, 2011):

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^N (MR_{exp,i} - \overline{MR}_{exp})^2} \quad (3)$$

$$SSE = \frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2} \quad (5)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (6)$$

$$P(\%) = \frac{100}{N} \sum_{i=1}^N \frac{|MR_{exp,i} - MR_{pre,i}|}{MR_{exp,i}} \quad (7)$$

where,

$MR_{exp,i}$ = The i th experimental moisture ratio

$MR_{pre,i}$ = The i th predicted moisture ratio

\overline{MR}_{exp} = The average experimental moisture ratio

N = The number of observation

z = The number of constants

The higher the R^2 values and the lower the SSE, RMSE, χ^2 and P(%), the better the goodness of fit of the model (Cox *et al.*, 2012).

Calculation of effective moisture diffusion: The effective moisture diffusion of food characterizes the intrinsic mass transfer property of moisture. Fick diffusion equation is commonly used to describe the drying characteristic. The solution of the equation put forward by Crank was under a series of assumptions (Crank, 1975), that is:

- Moisture is initially uniformly distributed throughout the mass of a sample
- Mass transfer is symmetric with respect to the center
- Surface moisture content of the sample instantaneously reaches equilibrium with the condition of the surrounding air
- Resistance to mass transfer at the surface is negligible compared to internal resistance of the sample
- Mass transfer is represented by a diffusional mechanism
- Diffusion coefficient is constant and shrinkage is negligible

The celery root was assumed as a slab because the thickness of sample was much less than its diameter. The effective moisture diffusivity was calculated by the following equation:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (8)$$

where,

D_{eff} = The effective diffusivity (m^2/s)

L = The half thickness of slab (m)

Many researchers demonstrated that for long drying period, Eq. (8) can be further simplified to the first term of series as follows (Tutuncu and Labuza, 1996):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (9)$$

Eq. (9) can be arranged in a logarithmic form as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (10)$$

The effective moisture diffusivities are typically determined by plotting experimental drying data in terms of $\ln(MR)$ versus time t .

Calculation of activation energy: Activation energy in drying process can be estimated by Arrhenius equation (Lee and Kim, 2009), that is:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad (11)$$

where,

D_0 = The pre-exponential factor of the Arrhenius equation, m^2/s

E_a = The activation energy, KJ/mol

R = The universal gas constant, KJ/mol·K

T = The absolute temperature, K

Take logarithm on both sides of the equation, the activation energy could be calculated from the slope of the linear fitting of $\ln D_{eff}$ with $1/T_a$.

RESULTS AND DISCUSSION

Analysis of hot air drying characteristics of celery root: To investigate the effect of hot air drying temperature on moisture content, four hot air drying temperatures, 50, 60, 70 and 80°C were tested for drying 25.305±0.500 g of celery root with average thickness of 0.356 cm. The initial moisture content of celery root was about 27.955±2.000 g water per g dry matter and the equilibrium moisture content was 0.013±0.001 g water per g dry matter when no more change in weight was observed, representing a 99.9% reduction in water content/g db. The moisture ratio versus drying time of celery root for different drying conditions are shown in Fig. 1. The drying times taken to reduce moisture content of celery root from the

initial moisture content to the final moisture content were about 405, 230, 165 and 180 min at 50, 60, 70 and 80°C, respectively. As it was expected, with increase in hot air drying temperature, the drying time of samples was significantly decreased within the given drying temperature range from 50 to 70°C. The steeper drying curve indicates an increase in drying rate. The patterns of variations of MR versus t obtained in the experiments were in agreement with the results others have published for garlic (Sharma and Prasad, 2001), spinach (Dadali *et al.*, 2007). In each equal increased temperature interval of 10°C from 50 to 70°C, the drying time decreased by 43.2 and 28.3% correspondingly. That is, the drying time did not

present equal decrease with the temperature increasing at equal interval. The increased temperature interval of 10°C from 50 to 60°C has the greatest effect on the decrease of drying time according to the Fig. 1. Drying at 80°C gave small differences among the drying curves, probably due to case hardening effect. This case may be attributed to the crusting phenomena occur in the surface of celery root, destroying the structure of the material, reducing the drying rate. This result is similar to the previous published article for fig (Xanthopoulos *et al.*, 2010). Therefore, with a view of optimization of energy efficiency and the product quality, the heating temperature zone between 60 to 70°C is a better option for drying celery root.

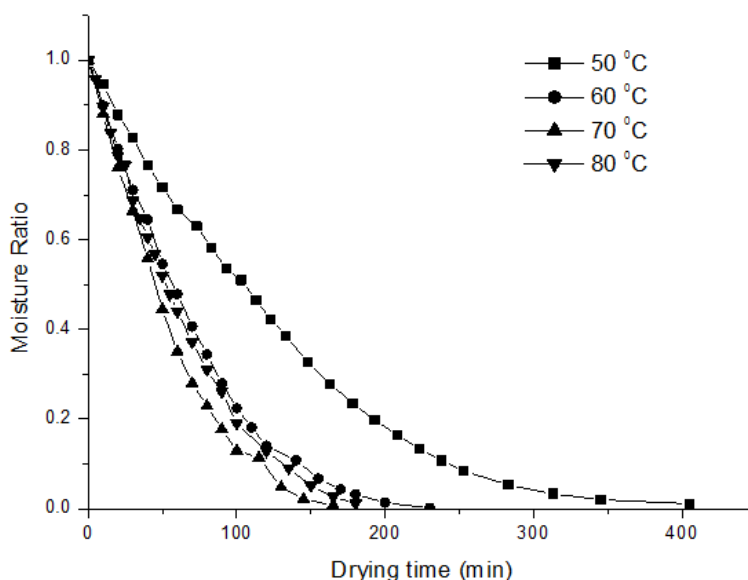


Fig. 1: Variation of moisture ratio for celery root dried at different temperatures

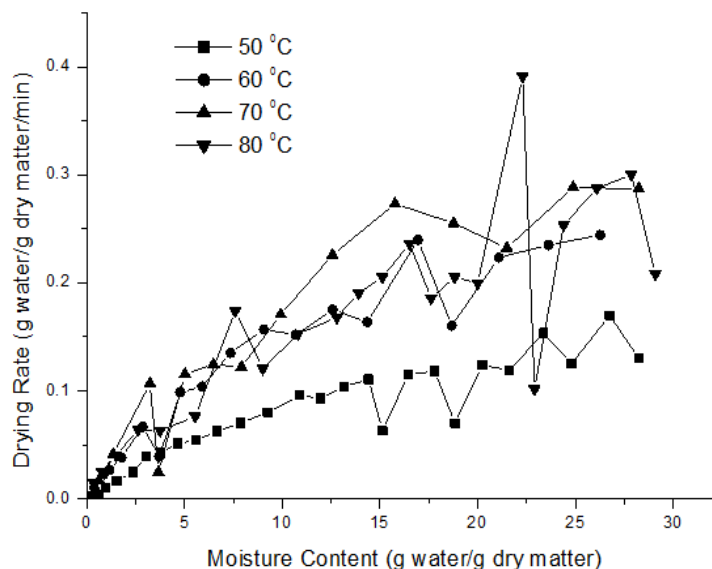


Fig. 2: Effect of moisture content on the drying rate of celery root at different temperatures

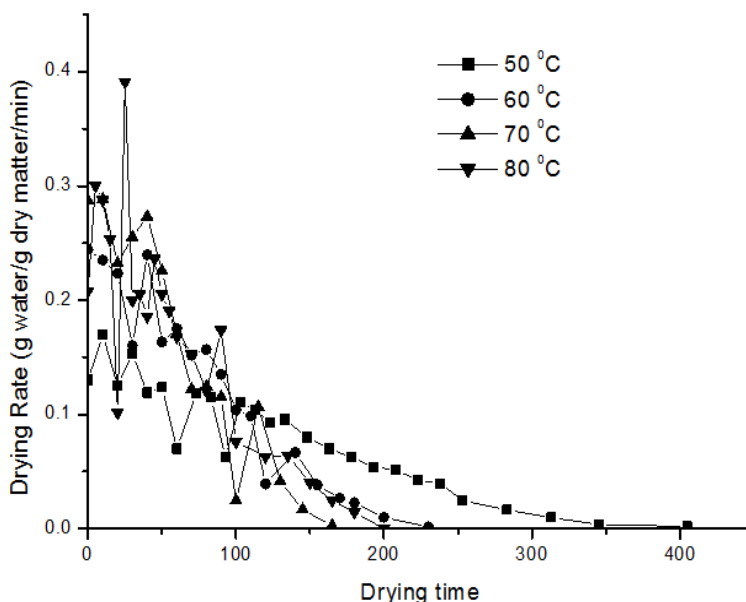


Fig. 3: Drying rate versus drying time of celery root at different temperatures

As can be seen from Fig. 2 and 3, there is no constant rate period observed in drying the celery root samples and the drying process were detected in a falling rate during drying period. The moisture loss rate of celery root was faster at the early stage than that at the end. This is because at the beginning of the drying, moisture content is larger and the celery root has more bulk water and formed a larger moisture gradient between the surrounding hot air, thus strengthen the ability of moisture transfer from inside of celery root to the surface. As drying continued, moisture content in celery decrease, the cell bulk water cuts, moisture gradient gradually become smaller; in addition, the bound water contacted by hydrogen bond binding force is difficult to precipitate from the cells, all these lead to the slow in drying process (Wang *et al.*, 2007).

Celery hot air drying thin layer model:

Select the optional model: On the basis of related literature, fifteen kinds of empirical or semi-empirical mathematical models were used to describe the effect of various drying temperature on the drying kinetics. The estimated parameters and statistical analysis of these thin layer drying models for different conditions are presented in Table 2.

To evaluate the goodness of fit of the tested mathematical models, the coefficient and the comparison criteria R^2 values were higher than 0.982 and SSE, RMSE and χ^2 values were respectively lower than 1.7×10^{-3} , 0.042 and 2.0×10^{-3} in all cases. The statistical values show that all of the models used provide a good agreement with the experimental data, but the applicability of the fifteen models are different.

The reason is that the property of models is related to material structure, composition and shape, such as apple pomace for the Logarithmic model (Wang *et al.*, 2007), celery leaves for the Midilli *et al.* model (Demirhan and Ozbek, 2011). From Table 2, R^2 , SSE, RMSE and χ^2 values of the Hii *et al.* model were 0.9990-0.9998, 2.565×10^{-5} - 9.622×10^{-5} , 0.0046-0.0098 and 2.565×10^{-5} - 1.400×10^{-4} at the drying temperatures of 50, 60, 70 and 80°C, respectively. With the highest value for the coefficient of determination (R^2) and the lowest Sum of Squared Residuals (SSE), Root Mean Square Error (RMSE) and chi-square (χ^2) among the statistical values obtained for all models, the Hii *et al.* model was found to be the most suitable for all the experimental data.

Validation of the model: To test and verify the accuracy of the Hii *et al.* model fitting for celery root in the drying temperatures, a comparison of the measured and predicted moisture ratio values using this mathematical expression is illustrated in Fig. 4. The mean relative percent deviation (P) of model 15 were 3, 2.3, 3.5 and 3.7%, respectively at the drying temperatures of 50, 60, 70 and 80°C, respectively. The values calculated according Eq. (7) for the Hii *et al.* model were obviously lower than the acceptable limit of 10% (Kumar *et al.*, 2006). The close approximation shows that the model has a very good consistency of calculated and experimental data, which indicates that the Hii *et al.* model could adequately describe the drying behavior of celery root.

Determination of effective moisture diffusivity: The values of average effective moisture diffusivity (D_{eff}) was plotted against moisture content under different

Table 2: Statistical results obtained from different thin-layer drying models

T (°C)	No.	Constants	R ²	SSE	RMSE	χ ²
50	1	$k = 0.0076$	0.9826	1.6×10^{-3}	0.0404	1.7×10^{-3}
	2	$k = 0.0023 \ n = 1.2409$	0.9962	3.5257×10^{-4}	0.0188	3.8195×10^{-4}
	3	$k = 0.0076 \ n = 1.2409$	0.9962	3.5257×10^{-4}	0.0188	3.8195×10^{-4}
	4	$a = 1.0531 \ k = 0.0080$	0.9866	1.3×10^{-3}	0.0354	1.4×10^{-3}
	5	$a = 1.1595 \ k = 0.0061$ $c = -0.1381$	0.9958	3.9158×10^{-4}	0.0198	4.4266×10^{-4}
	6	$a = -72.6904$ $k_0 = 0.0138$ $b = 73.6684 \ k_1 = 0.0137$	0.9970	2.8555×10^{-4}	0.0169	3.3748×10^{-4}
	7	$a = 0.9754 \ k = 0.0021$ $b = 1.2459$ $c = -0.0001$	0.9978	2.0157×10^{-4}	0.0142	2.3822×10^{-4}
	8	$a = -0.0057 \ b = 8.259 \times 10^{-6}$	0.9988	1.0845×10^{-4}	0.0104	1.1748×10^{-4}
	9	$a = 1.0580 \ k = 0.0044$ $b = -1.9398 \ g = 0.0032$ $c = 1.8998 \ h = 0.0045$	0.9967	3.0965×10^{-4}	0.0176	4.0254×10^{-4}
	10	$a = 1.7677 \ k = 0.0107$	0.9960	3.7878×10^{-4}	0.0195	4.1034×10^{-4}
	11	$a = -138.4507$ $b = -12.1928$	0.9904	8.9653×10^{-4}	0.0299	9.7124×10^{-4}
	12	$a = -397.8517 \ k = 0.0134$ $g = 0.0134$	0.9966	3.1860×10^{-4}	0.0178	3.6016×10^{-4}
	13	$a = 1.082$ $k = 0.007546$ $b = 0.01497$ $c = -0.09795$	0.9968	2.9645×10^{-4}	0.0172	3.5035×10^{-4}
	14	$a = 132.2266 \ b = 1.2409$	0.9962	3.5257×10^{-4}	0.0188	3.8195×10^{-4}
	15	$a = 0.1689 \ b = 0.004612$ $c = 1.676$ $d = 0.8261$ $g = 0.0002116$	0.9998	2.5646×10^{-5}	0.0046	2.5646×10^{-5}
60	1	$k = 0.0139$	0.9825	1.7×10^{-3}	0.0415	1.8×10^{-3}
	2	$k = 0.0041 \ n = 1.2761$	0.9982	1.7924×10^{-4}	0.0134	2.0033×10^{-4}
	3	$k = 0.0136 \ n = 1.2762$	0.9982	1.7924×10^{-4}	0.0134	2.0033×10^{-4}
	4	$a = 1.0609 \ k = 0.0147$	0.9870	1.3×10^{-3}	0.0357	1.4×10^{-3}
	5	$a = 1.1437 \ k = 0.0115$ $c = -0.1134$	0.9960	3.9054×10^{-4}	0.0198	4.6376×10^{-4}
	6	$a = -125.6114$ $k_0 = 0.0254$ $b = 126.5959 \ k_1 = 0.0253$	0.9984	1.6045×10^{-4}	0.0127	3.7979×10^{-4}
	7	$a = 0.9842$ $k = 0.0041$ $b = 1.2657$ $c = -0.0001$	0.9990	9.8087×10^{-5}	0.0099	1.2424×10^{-4}
	8	$a = -0.0102 \ b = 2.613 \times 10^{-5}$	0.9976	2.3326×10^{-4}	0.0153	2.6070×10^{-4}
	9	$a = 1.5665 \ k = 0.0230$ $b = -2.9282$ $g = 0.0285$ $c = 2.3463 \ h = 0.0228$	0.9983	1.6744×10^{-4}	0.0129	2.4473×10^{-4}
	10	$a = 1.813 \ k = 0.01976$	0.9976	2.3213×10^{-4}	0.0152	2.5944×10^{-4}
	11	$a = -75.3911$ $b = -6.2776$	0.9897	1.0×10^{-3}	0.0318	1.1×10^{-3}
	12	$a = -282.3697 \ k = 0.0250$ $g = 0.0250$	0.9982	1.7675×10^{-4}	0.0133	2.0989×10^{-4}
	13	$a = 1.0595$ $k = 0.0150$ $b = 0.0270$ $c = -0.06994$	0.9979	2.0515×10^{-4}	0.0143	2.5986×10^{-4}
	14	$a = 73.6321 \ b = 1.2762$	0.9982	1.7924×10^{-4}	0.0134	2.0033×10^{-4}
	15	$a = 0.1084 \ b = 0.02698$ $c = 1.515$ $d = 0.8915$ $g = 0.001267$	0.9996	3.5004×10^{-5}	0.0059	4.7506×10^{-5}
70	1	$k = 0.0175$	0.9829	1.7×10^{-3}	0.0415	1.8×10^{-3}
	2	$k = 0.0054 \ n = 1.2850$	0.9985	1.5471×10^{-4}	0.0124	1.7682×10^{-4}
	3	$k = 0.0171 \ n = 1.2850$	0.9985	1.5471×10^{-4}	0.0124	1.7682×10^{-4}
	4	$a = 1.0613 \ k = 0.0186$	0.9875	1.3×10^{-3}	0.0355	1.4×10^{-3}
	5	$a = 1.1229 \ k = 0.0154$ $c = -0.0836$	0.9942	5.8960×10^{-4}	0.0243	7.2566×10^{-4}

Table 2: Continue

	6	$a = -83.5347$ $k_0 = 0.0100$	0.9957	4.3846×10^{-4}	0.0209	5.8462×10^{-4}
	7	$b = 84.5691$ $k_1 = 0.0101$ $a = 0.9898$ $k = 0.0052$ $b = 1.2838$ $c = -0.0001$	0.9988	1.2266×10^{-4}	0.0111	1.6355×10^{-4}
	8	$a = -0.0123$ $b = 3.677 \times 10^{-5}$	0.9920	8.0252×10^{-4}	0.0283	9.1716×10^{-4}
	9	$a = 1.5447$ $k = 0.0286$ $b = -2.7923$ $g = 0.0364$ $c = 2.2382$ $h = 0.0290$	0.9985	1.5460×10^{-4}	0.0124	2.4736×10^{-4}
	10	$a = 1.8321$ $k = 0.0252$	0.9981	1.9490×10^{-4}	0.0140	2.2275×10^{-4}
	11	$a = -56.6960$ $b = -3.9447$	0.9830	1.7×10^{-3}	0.0414	2.0×10^{-3}
	12	$a = -233.5832$ $k = 0.0319$ $g = 0.0318$	0.9985	1.5586×10^{-4}	0.0125	1.9183×10^{-4}
	13	$a = 1.036$ $k = 0.02094$ $b = 0.03959$ $c = -0.04433$	0.9976	2.4556×10^{-4}	0.0157	3.2742×10^{-4}
	14	$a = 58.4853$ $b = 1.2850$	0.9985	1.5471×10^{-4}	0.0124	1.7682×10^{-4}
	15	$a = 0.0612$ $b = 0.07179$ $c = 1.413$ $d = 0.9389$ $g = 0.002929$	0.9990	9.6217×10^{-5}	0.0098	1.3995×10^{-4}
80	1	$k = 0.0142$	0.9822	1.7×10^{-3}	0.0415	1.8×10^{-3}
	2	$k = 0.0050$ $n = 1.2543$	0.9980	1.9304×10^{-4}	0.0139	2.1234×10^{-4}
	3	$k = 0.0145$ $n = 1.2543$	0.9980	1.9304×10^{-4}	0.0139	2.1234×10^{-4}
	4	$a = 1.0593$ $k = 0.0153$	0.9879	1.2×10^{-3}	0.0342	1.3×10^{-3}
	5	$a = 1.1987$ $k = 0.0111$ $c = -0.1741$	0.9981	1.8351×10^{-4}	0.0135	2.1249×10^{-4}
	6	$a = -31.6574$ $k_0 = 0.0069$ $b = 32.6796$ $k_1 = 0.0071$	0.9985	1.4640×10^{-4}	0.0121	1.7893×10^{-4}
	7	$a = 0.9933$ $k = 0.0059$ $b = 1.1936$ $c = -0.0003$	0.9993	6.5742×10^{-5}	0.0081	8.0351×10^{-5}
	8	$a = -0.0111$ $b = 3.161 \times 10^{-5}$	0.9992	7.8158×10^{-5}	0.0088	8.5974×10^{-5}
	9	$a = 1.0075$ $k = 0.0081$ $b = -1.8080$ $g = 0.0057$ $c = 1.8229$ $h = 0.0082$	0.9985	1.4834×10^{-4}	0.0122	2.4633×10^{-4}
	10	$a = 1.7927$ $k = 0.0208$	0.9976	2.2792×10^{-4}	0.0151	2.5071×10^{-4}
	11	$a = -77.3273$ $b = -8.5385$	0.9956	4.2230×10^{-4}	0.0205	4.6453×10^{-4}
	12	$a = -84.9070$ $k = 0.0264$ $g = 0.0262$	0.9981	1.8150×10^{-4}	0.0135	2.1015×10^{-4}
	13	$a = 1.111$ $k = 0.01396$ $b = 0.01904$ $c = -0.1188$	0.9990	1.2009×10^{-4}	0.0099	1.2009×10^{-4}
	14	$a = 68.7633$ $b = 1.2543$	0.9980	1.9304×10^{-4}	0.0139	2.1234×10^{-4}
	15	$a = 0.1121$ $b = 0.02308$ $c = 1.506$ $d = 0.8863$ $g = 0.001453$	0.9993	6.3922×10^{-5}	0.0080	8.2723×10^{-5}

conditions. Figure 5 shows the curve for D_{eff} dependence on moisture content for celery root at four drying temperatures.

It can be observed that D_{eff} values increased with increasing of temperature and decreasing of moisture content. The results were in conformity with previous researches on pumpkin slices and rosehip (Doymaz, 2007; Erenturk *et al.*, 2010). The variation in moisture diffusivity with moisture content is a complex and system specific function. The D_{eff} of a food material characterizes its intrinsic moisture mass transport property that includes molecular diffusion, liquid diffusion, vapour diffusion, hydrodynamic flow and

other possible mass transport mechanisms (Karathanos *et al.*, 1990). This result may indicate that as moisture content decreased, the permeability to vapour increased, provided the pore structure remained open. In the temperature domain of 50-80°C, the D_{eff} value obtained from this study were within the general range of 1.957×10^{-9} to 9.016×10^{-9} m²/s for celery root. The values of D_{eff} for drying of banana obtained by precious researchers ranged from 7.87×10^{-10} to 2.27×10^{-9} m²/s at 65-70°C (Minh-Hue and William, 2007). Also values of D_{eff} ranging from 1.26×10^{-9} to 8.80×10^{-9} m²/s have been obtained for drying of sweet potato cube at 50-90°C (Singh and Pandey, 2012). Comparison of these values

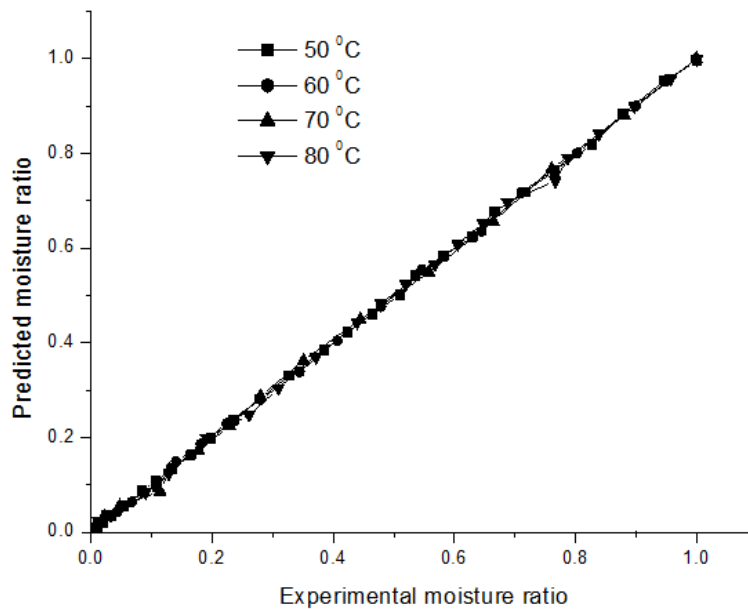


Fig. 4: Experimental and predicted moisture ratio values at different temperatures for the Eq. (15)

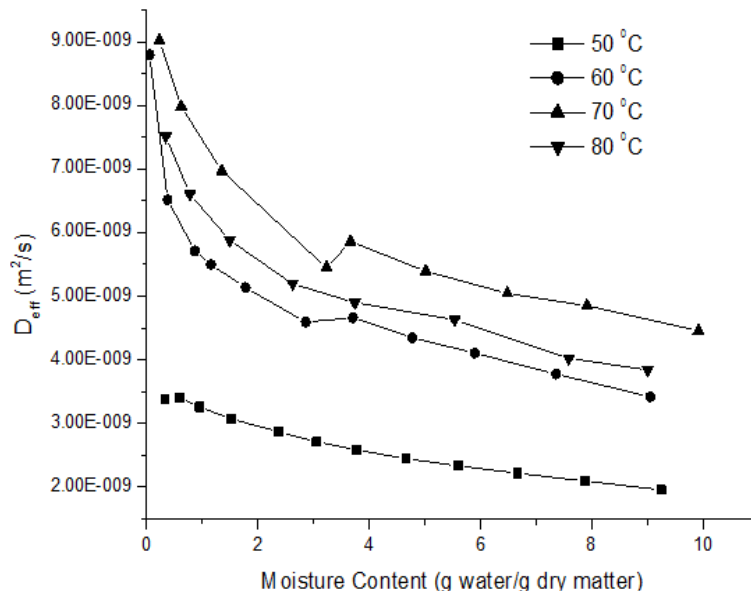


Fig. 5: Effective moisture diffusion coefficient versus moisture content of celery root at different temperatures

with the D_{eff} obtained for drying at 50-80°C in this experiment showed compatibility with the previous published data.

Determination of activation energy: The activation energies was estimated from the slopes of Arrhenius-type relationship (Eq. (11)) which found to be 21.817 KJ/mol. The E_a values of celery root obtained in this study were in close with that of chestnuts (20.46-22.58 KJ/mol) (Guine and Fernandes, 2006), apple slices (19.96-22.62 KJ/mol) (Kaya *et al.*, 2007), baggase (19.47 KJ/mol) (Vijayaraj *et al.*, 2007) and white radish slices (16.49-20.26 KJ/mol) (Lee and Kim, 2009).

CONCLUSION

The drying characterization of the celery root were investigated in hot air dryer as a single layer with thickness of 0.356 ± 0.05 cm at the drying temperatures of 50, 60, 70 and 80°C. Constant drying rate period was not observed, the celery root drying occur in the falling rate period. The moisture ratio and drying rate were influenced by the drying temperature. Drying time decreased and drying rate increased with increased drying temperature. Effective moisture diffusivity increased with increasing of drying temperature. The model 15 (Hii *et al.* model) were considered the best for

explaining the drying celery root, which gave higher R^2 and lower SSE, RMSE and χ^2 . The average values of effective moisture diffusivities of celery root ranged from 1.957×10^{-9} to 9.016×10^{-9} m²/s. The effective moisture diffusivity increased with the increase in the drying temperature. The activation energy for effective moisture diffusion coefficients was found as 21.817 KJ/mol.

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