Vacuum Drying Characteristics of Some Vegetables

Zakipour, Esmaeil; Hamidi, Zohreh*[+]
Department of Food Science and Technology, Faculty of Agriculture, Tarbiat Modares University,
P.O. Box 14115-336 Tehran, I.R. IRAN

ABSTRACT: *In this research the drying of four kinds of vegetables was investigated in a vacuum dryer. The effect of temperature on drying rate of samples at various temperatures (30, 35 and 45 °C) was studied. Six thin-layer drying models were fitted to drying data and suitable model was selected from them. Then effective moisture diffusivity and activation energy of samples were calculated. The Diffusion approximation model gave excellent fit for fenugreek and mint leaves and vegetative parts of leek and the page model was considered adequate to describe the thin-layer drying behavior of parsley leaves. The effective diffusivity values changed from* 2.92×10^{-10} *to* 9.81×10^{-10}, 1.77×10^{-10} *to* 5.99×10^{-10}, 9.3×10^{-11} *to* 1.7×10^{-10} *and* 1.27×10^{-9} *to* 3.4×10^{-9} *for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively. An Arrhenius type of equation was used to evaluate the effect of temperature on the effective diffusivity and the activation energy values was found 66.36, 66.34, 32.27 and 51.16 kJ/ mol for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively.*

KEY WORDS: *Vacuum drying, Mathematical modeling, Effective diffusivity.*
1-methyl-3,4,

INTRODUCTION

Fenugreek (*Trigonella foenum-graecum* L.) is an erect annual herb native to southern Europe and Eastern Mediterranean and subtropical climate countries. Undoubtedly, fenugreek is one of the oldest cultivated medicinal plants and is widely grown today as a food, condiment, medicinal, dye, and forage plant (*Makai et al*, 2004) [1].

Leek (*Allium porrum* L.) is classified in the family liliaceae. The vegetative parts of its are odor-free, and only during tissue damaging the volatile flavor principles are generated. This family is distributed throughout most regions of the temperate world including Europe, Asia, North America and Africa and has a long history as sources of therapeutic principles (*Rose et al*, 2005) [2].

Mint (*Mentha spicata* L.) is a perennial crop grown primarily for its oil, called menthol. This is widely used in the food, flavorings, pharmaceutical and cosmetic industries. Also, the cooling and soothing effect of natural menthol made it a useful ingredient in pharmaceuticals and cosmetics (*Albaugh et al*, 2002) [3].

Parsley (*Petroselinum crispum* L.) is a nutritious herb, grows in Europe and Asia. The fresh or dried leaves, roots and seeds of this plant are used in the food, cosmetic and pharmaceutical industries to produce drugs, essential oil and spices (*Akpinar et al*, 2006) [4].

Drying is the oldest method of preserving food. The main aim in drying agricultural products is to decrease water content to certain level, at which, microbial spoilage and deterioration chemical reaction are greatly minimized (*Krokida & Marinos-Kouris*, 2003) [5]. Dried foods are tasty, lightweight, easy-to-prepare and

---

* *To whom correspondence should be addressed.*

+ *E-mail: Hamidy_z@modares.ac.ir*

1021-9986/11/4/97 9/$/2.90

easy-to-store and use (*Okos et al*, 1992) [6]. Throughout history, the sun, the wind, and fire were used to remove water from fruits, meats, grains, and herbs. These are classical drying procedures.

Vacuum drying is another process, in which moist materials dried under sub-atmospheric pressures. The lower pressures allow drying temperature to be reduced and higher quality to be obtained than with classical processes (*Jaya & Das,* 2003) [7].

A mathematical model is a mathematical analog of the physical reality, describing the properties of a real system in terms of mathematical variables and operations. The exceptional growth in the computing power and its availability have allowed models to be more realistic and have fueled rapid growth in the use of models in product, process, and equipment design and research (*Sablani et al*, 2006) [8]. Knowledge of the drying kinetics of some vegetables is presented (*Akpinar*, 2006, [4,9]; *Doymaz et al*, 2006, [10]; *Kaya & Aydin,* 2009, [11]; *Ozbek & Dadli*, 2007, [12]). But vacuum drying behaviors of them are not available.

The objectives of this experiment are to determine the effect of drying temperature on drying characteristics of four kinds of vegetables, to evaluate a suitable drying model for describing this drying process and to calculate effective moisture diffusivity and activation energy of samples.

EXPERIMENTAL SECTION

Materials

All fresh vegetables (fenugreek, leek, mint and parsley) used for the drying experiments were obtained from Mazandaran region, north part of Iran. The samples were stored in closed plastic bag at 4°C refrigerator before they were used in this study. Before the drying process, the samples were taken out of the refrigerator and leaves of the leafy vegetables were separated from stems and vegetative parts of leek were chopped to the pieces with 2 cm length. To determine the initial moisture content, three 10 g of samples were dried in an oven at 105 °C for 24 h and averages were reported. The initial moisture contents of fenugreek, mint and parsley leaves and vegetative parts of leek were calculated 5.51, 5.06, 4.71 and 11.5 (kg water/kg dry matter) respectively.

Drying experiments

The leaves and the vegetative parts of leek were dried at temperature of 30, 35, and 45 °C in a vacuum dryer oven (Vision scientific Co, model VS-1202V5, Korea.) after the dryer reached to the steady state conditions. The weight of samples was about 10 g. The thickness of fenugreek, mint and parsley leaves and vegetative parts of leek were about 0.25, 0.2. 0.12 and 0.7 mm, respectively. The samples were spread in a single layer on the glassy Petri dish and the pressure of the chamber was 25 kPa. Moisture contents of samples were determined at 15 min interval by an analytical balance an accuracy of 0.001 g. The vacuum was broken and restored before and after the weight measurements and each process took about 45 s. When the samples weights at three consecutive times were constant, the drying process was cut and the moisture content at that time was considered as the equilibrium moisture content. Drying experiments were repeated twice at each temperature and the average value was used for drawing the drying curves.

Mathematical modeling

In this study the Moisture Ratio (MR) and the drying rate of samples during the drying process were calculated using the following equations (Eqs (1,2)):

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

$$\text{Drying rate} = \frac{M_t - M_{t+dt}}{dt} \tag{2}$$

Where, MR, M_0, M_e, M_t and M_{t+dt} are the moisture ratio, initial moisture content, equilibrium moisture content, moisture content at t and moisture content at t+dt (kg moisture/kg dry matter), respectively and t is drying time (min). The equilibrium moisture content (M_e) was assumed to be zero for this experiment because it is very small as compared to M_0. To select the best model for describing the drying curve during drying process the thin layer drying equations in Table 1 were tested.

The regression (R^2), the Root Mean Square Error (RMSE) and the mean square of the deviations between the experimental and calculated values for the models or chi square (χ^2) analysis was performed using program MATLAB 7.0. When the values of the R^2 were higher and the values of the χ^2 and RMSE were lower, the goodness of the fit was better (*Akpinar et al*, 2003 [13]; *Gunhan et al*, 2005 [14]; *Yaldiz & Ertekin,* 2001 [15]).

Table 1: Selected thin-layer drying models for describing drying curve.

Model number	Model equation	Name	References
1	MR=exp(-kt)	Newton	O'Callaghan et al. (1971) [16]
2	MR=a exp(-kt)+c	Logarithmic	Yagcioglu et al. (1999) [17]
3	MR=exp(-kt^n)	Page	Page (1949) [18]
4	MR=a exp(-k$_0$t)+b exp(-k$_1$t)	Two-term	Henderson (1974) [19]
5	MR=a exp(-kt)+(1-a)exp(-kat)	Two-term exponential	Henderson (1974),Sharaf-Elden et al. (1980) [20]
6	MR=a exp(-kt)+(1-a)exp(-kbt)	Diffusion approach	Kassem (1998) [21], Ertekin and Yaldiz(2004) [22]

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

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp,i}} - \mathrm{MR}_{\mathrm{pre,i}})^2}{N-n} \quad (4)$$

Where $\mathrm{MR}_{\mathrm{exp,i}}$ is the ith experimentally observed moisture ratio, $\mathrm{MR}_{\mathrm{pre,i}}$, the ith predicted moisture ratio, N, the number of observations and n is the number constants.

Effective moisture diffusivity and activation energy

The effective moisture diffusivity was calculated by the following equation (*Crank*, 1975) [23]: (Eq. (5)):

$$\mathrm{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{\mathrm{eff}}\, t}{4L^2}\right) \quad (5)$$

Where D_{eff} is the effective moisture diffusivity (m^2/s), L is the **half** thickness of the plants leaves and the vegetative parts of leek and t is drying time (s). Some researchers simplified this equation to the following straight-line equation: (*Ozbek & Dadli,* 2007 [12]; *Sacilik*, 2007 [24]; *Sobukola et al*, 2007 [25]; *Wang et al.*, 2007 [26]):

$$\ln(\mathrm{MR}) = \ln(\frac{8}{\pi^2}) - (\frac{D_{\mathrm{eff}}\pi^2}{4L^2}t) \quad (6)$$

By plotting experimental drying data in terms of ln(MR) versus drying time, the effective moisture diffusivity was calculated from the slope of this curve.

The effective moisture diffusivity can be related with temperature by simple Arrhenius-type of equation: (Eq. (7)):

$$D_{\mathrm{eff}} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (7)$$

Where D_0 is the Arrhenius factor (m^2/s), E_a is the activation energy for the moisture diffusion (kJ/mol), R is the universal gas constant (8.314 J/mol K) and T is drying temperature (°C). The activation energy was calculated from a slope of a straight line by plotting the natural logarithm of D_{eff} versus the $1/T$.

RESULTS AND DISCUSSION

Drying characteristics

The variations of drying rate during drying time obtained in this experiment are shown in Fig 1. It is apparent that the drying rate decreased continuously throughout the drying time. Also the moisture ratio decreased incessantly. At the beginning of the drying process, the drying rate was very high, but decreased with moisture ratio reduction. Because the movement of water to the surface is not enough to maintain the surface in a saturated condition in drying process and the condition of equilibrium at the surface no longer holds and the rate of drying begins to reduce (*Brennan*, 2006) [27]. Similar results are obtainable for aromatic plants in the earlier studies (*Belghit et al*, 2000 [28]; *Doymaz et al*, 2006 [10]). As indicated in these curves, there was no constant rate period in drying of all vegetables and all the drying process took place in falling rate period and was started from the initial moisture content for fenugreek, mint and parsley leaves and vegetative parts of leek (551, 506, 471, 1150%, dry basis) to final moisture content (5, 6, 4, 14% dry basis), respectively. It is obvious from these curves that the higher the drying temperature, the greater the drying rate, so the highest values of drying rate were obtained during the experiment at 45 °C. These results are similar to the earlier studies outcomes of different vegetables (*Akpinar*, 2006 [9]; *Akpinar & Bicer,* 2004 [29]; *Doymaz*, 2006 [30]; *Doymaz et al*, 2006 [10]).

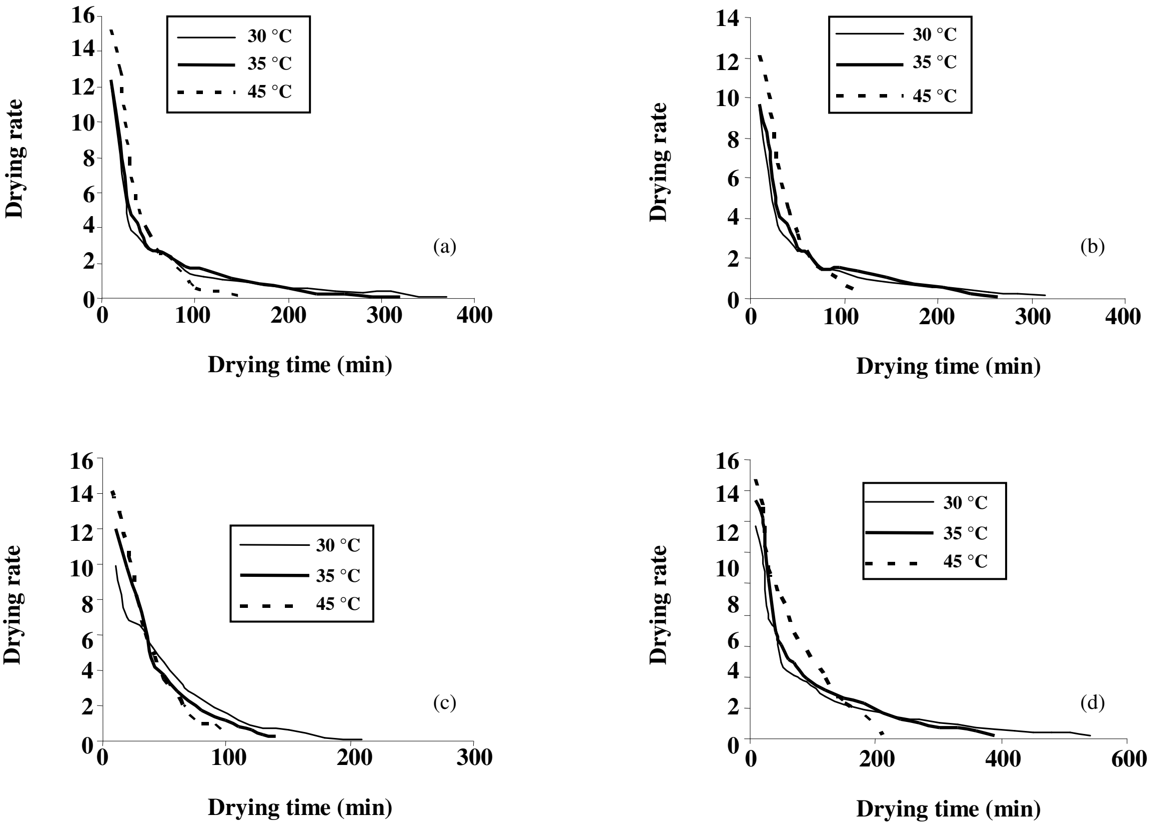

Fig. 1: Variation of drying rate with drying time at different temperatures for a: fenugreek leaves, b: mint leaves, c: parsley leaves and d: vegetative parts of leek

Due to this fact the maximum drying time occurred at 30 °C and it was 370, 315, 210 and 540 min for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively. It shows the vegetative parts of leek drying needs the times more than the other vegetables drying. This result is probably because of its different special texture.

Evaluation of the models

The moisture content data at the different drying temperatures were converted to a dimensionless parameter called as moisture ratio and then the variations of moisture ratio with drying time at drying temperatures of 30, 35 and 45° C were fitted to the selected thin-layer drying models listed in Table 1. The results of statistical analyses undertaken on these models for fenugreek, mint and parsley leaves and vegetative parts of leek are given in Tables 2–5, respectively. Also the criteria used to estimate goodness of the fits (R^2, RMSE and χ^2) and the constants in models (a, b, c, n, k, k_0 and k_1) are presented in these Tables. Based on these criteria, the highest R^2 and the lowest RMSE and χ^2, the best model was selected. From the all Tables, R^2, RMSE and χ^2 values were varied between 0.9624–0.9998, 0.0039075–0.0547202 and 0.00016997–0.0538054, respectively. From Table 2, the highest R^2 values and the lowest values of RMSE and χ^2 were obtained from the diffusion approximation model for fenugreek leaves and vary between 0.9991–0.9993, 0.0073105–0.0111023 and 0.00086081–0.0011093, respectively. Similar results were obtained for vegetative parts of leek and mint leaves, as it shown in Tables 3, 4. But for parsley leaves (Table 5) the highest R^2 values and the lowest values of RMSE and χ^2 values were obtained from page model and vary between 0.9995–0.9998, 0.0039075–0.0071106 and 0.00016997–0.00056073, respectively. The best fitting curves between experimental data and predicted values by diffusion approximation model for fenugreek, mint leaves and vegetative parts of leek and by page model for parsley leaves, drying at 30, 35 and 45°C, were shown in Fig 2.

Table 2: Modeling of moisture ratio according to drying time for fenugreek leaves.

Model number	Temperature(T),°C	Coefficients	R^2	χ^2	RMSE
1	30	k=0.01605	0.9646	0.0504102	0.0529031
	35	k=0.01779	0.9841	0.0223001	0.0373209
	45	k=0.03616	0.9989	0.0012017	0.0103029
2	30	k=0.01599,a=0.8774,c=0.04157	0.9822	0.0225032	0.0375307
	35	k=0.01732,a=0.9205,c=0.02066	0.9894	0.0139301	0.0305001
	45	k=0.03645,a=1.008,c=7.47*10^{-8}	0.9989	0.0011321	0.0104109
3	30	k=0.05168,n=0.7197	0.9980	0.0027401	0.0125030
	35	k=0.04038,n=0.7987	0.9980	0.0026209	0.0131001
	45	k=0.03286,n=1.027	0.9990	0.0010149	0.0100309
4	30	k_0=0.01173,k_1=10.46,a=0.7998,b=0.2001	0.9930	0.0084089	0.0236061
	35	k_0=0.0145,k_1=10.5,a=0.8559,b=0.1442	0.9966	0.0039021	0.0172198
	45	k_0=0.03642,k_1=0.03988,a=1.006,b=0.000975	0.9986	0.0011310	0.0116045
5	30	k=0.06069,a=0.2051	0.9893	0.0144239	0.0291287
	35	k=0.07419,a=0.1901	0.9977	0.0030011	0.0140301
	45	k=19.36,a=0.001864	0.9988	0.0012221	0.0110001
6	30	k=0.0776,a=0.3152,b=0.1285	0.9993	0.00086081	0.0073105
	35	k=0.09092,a=0.2273,b=0.1441	0.9993	0.00087637	0.0079111
	45	k=0.03315,a=1.459,b=0.8343	0.9991	0.0011093	0.0111023

Table 3: Modeling of moisture ratio according to drying time for vegetative parts of leek.

Model number	Temperature(T),°C	Coefficients	R^2	χ^2	RMSE
1	30	k=0.008065	0.9727	0.0538054	0.0494002
	35	k=0.0111	0.9881	0.0203102	0.0335076
	45	k=0.01579	0.9990	0.0012009	0.0099302
2	30	k=0.008022,a=0.8825,c=0.03836	0.9892	0.0192098	0.0310221
	35	k=0.01082,a=0.9285,c=0.01994	0.9933	0.0101011	0.0251109
	45	k=0.01588,a=1.005,c=7.63*10^{-11}	0.9990	0.0011222	0.0101096
3	30	k=0.02542,n=0.7663	0.9979	0.0040301	0.0138325
	35	k=0.02258,n=0.8418	0.9979	0.0034002	0.0141237
	45	k=0.0136,n=1.036	0.9993	0.00073543	0.0082041
4	30	k_0=0.05265,k_1=0.005849,a=0.2349,b=0.7707	0.9996	0.00074706	0.0063085
	35	k_0=0.009562,k_1=3.088,a=0.9011,b=0.09882	0.9964	0.0051052	0.0185304
	45	k_0=3.111,k_1=0.01589,a=0.0001754,b=1.005	0.9988	0.0011090	0.0112207
5	30	k=0.03594,a=0.1805	0.9946	0.0102107	0.0220351
	35	k=0.05623,a=0.1597	0.9989	0.0018296	0.0103001
	45	k=5.627,a=0.002795	0.9989	0.0012021	0.0106093
6	30	k=0.05105,a=0.2306,b=0.1145	0.9996	0.00078166	0.0063271
	35	k=0.06514,a=0.1649,b=0.1356	0.9989	0.0012154	0.0095205
	45	k=0.01596,a=0.002463,b=0.989	0.9987	0.0015076	0.0108154

Table 4: Modeling of moisture ratio according to drying time for mint leaves.

Model number	Temperature(T),°C	Coefficients	R^2	χ^2	RMSE
1	30	k=0.01546	0.9624	0.0479003	0.0547202
	35	k=0.01713	0.9820	0.0222221	0.0399145
	45	k=0.03571	0.9982	0.0018104	0.0135076
2	30	k=0.01628,a=0.8729,c=0.05646	0.9826	0.0195320	0.0373302
	35	k=0.01718,a=0.9182,c=0.02971	0.9881	0.0125154	0.0323148
	45	k=0.0362,a=1.014,c=1.06*10^{-9}	0.9983	0.0016307	0.0133321
3	30	k=0.04906,n=0.7253	0.9978	0.0027098	0.0134104
	35	k=0.03817,n=0.8044	0.9968	0.0037333	0.0168260
	45	k=0.02961,n=1.053	0.9987	0.0012012	0.0116307
4	30	k_0=10.62,k_1=0.01152,a=0.1887,b=0.8113	0.9913	0.0090090	0.0264091
	35	k_0=0.01414,k_1=9.901,a=0.8657,b=0.1343	0.9942	0.0056231	0.0226005
	45	k_0=0.03616,k_1=0.03745,a=0.9674,b=0.04709	0.9978	0.0016198	0.0150003
5	30	k=0.05891,a=0.2039	0.9895	0.0126104	0.0290359
	35	k=0.07019,a=0.1926	0.9969	0.0035205	0.0164021
	45	k=0.04118,a=1.446	0.9985	0.0014003	0.0125111
6	30	k=0.07253,a=0.3109,b=0.1342	0.9994	0.00071317	0.0071043
	35	k=0.08045,a=0.2302,b=0.1566	0.9987	0.0019035	0.0142184
	45	k=0.03006,a=2.697,b=0.9069	0.9990	0.0016341	0.0127106

Table 5: Modeling of moisture ratio according to drying time for parsley leaves.

Model number	Temperature(T),°C	Coefficients	R^2	χ^2	RMSE
1	30	k=0.02205	0.9992	0.00099866	0.0088098
	35	k=0.02849	0.9994	0.00070165	0.0076210
	45	k=0.0379	0.9982	0.0022095	0.0135100
2	30	k=0.02226,a=1.009,c=4.12*10^{-8}	0.9993	0.00087455	0.0085014
	35	k=0.02907,a=0.9936,c=0.007393	0.9994	0.00055277	0.0074392
	45	k=0.03872,a=1.021,c=4.78*10^{-12}	0.9987	0.0015213	0.0116021
3	30	k=0.01827,n=1.048	0.9997	0.00031733	0.0051002
	35	k=0.03093,n=0.9777	0.9995	0.00056073	0.0071106
	45	k=0.02826,n=1.086	0.9998	0.00016997	0.0039075
4	30	k_0=1.938,k_1=0.02226,a=0.00029,b=1.009	0.9991	0.00087987	0.0094290
	35	k_0=0.02495,k_1=0.04175,a=0.7151,b=0.2892	0.9995	0.00044396	0.0070301
	45	k_0=0.03873,k_1=0.03933,a=1.012,b=0.00899	0.9984	0.0015245	0.0128063
5	30	k=0.02575,a=1.46	0.9998	0.00022634	0.0043333
	35	k=4.206,a=0.006724	0.9994	0.00068293	0.0079065
	45	k=47.81,a=0.0007919	0.9980	0.0022309	0.0142108
6	30	k=0.0221,a=0.9102,b=0.975	0.9991	0.00099959	0.0095048
	35	k=0.0381,a=0.3849,b=0.6324	0.9995	0.00046543	0.0068139
	45	k=0.03793,a=0.774,b=0.9968	0.9979	0.0022109	0.0147206

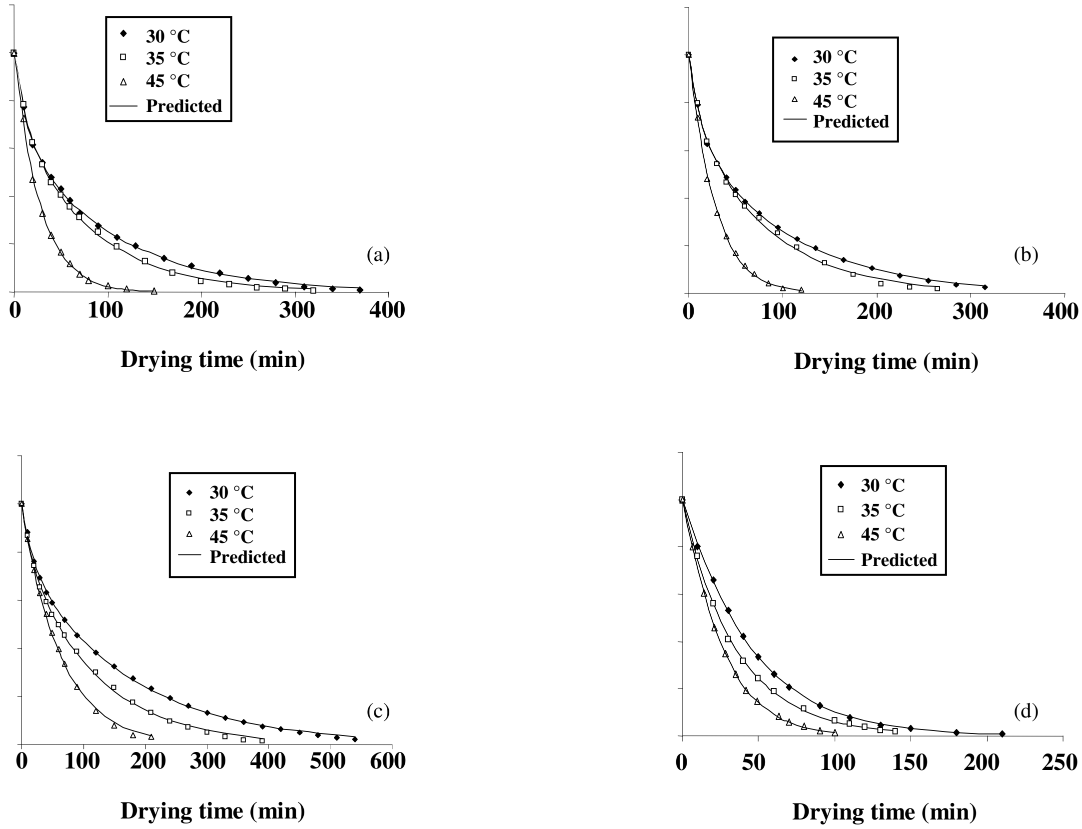

Fig 2: Experimental data and predicted values by diffusion approximation model for a: fenugreek leaves, b: mint leaves, c: vegetative parts of leek and d: parsley leaves drying at 30, 35 and 45°C.

Effective diffusivity and activation energy

The values of effective diffusivity (D_{eff}) at different drying temperatures calculated with using Eq. (6). By plotting the natural logarithm of moisture ratio values, ln(MR), versus drying time, the effective moisture diffusivity was calculated from the slope of this graph with following equation:

$$D_{eff} = -\frac{4L^2\alpha}{\pi^2} \tag{8}$$

Where α is the slop of curve and L is the half thickness of the leaves and the vegetative parts of the vegetables. The values of effective diffusivities of fenugreek, mint and parsley leaves and vegetative parts of leek in the drying process at 30, 35 and 45°C are presented in Table 6. As indicated in this table, the values of D_{eff} increased incessantly as the drying temperature increased. This result closely agreed with those for aromatic plants (*Doymaz et al*, 2006 [10]; *Ozbek & Dadli,* 2007 [12]), Asian white radish slices (*Lee & Kim* 2009, [31]) and coconut presscake (*Jena & Das*, 2007, [32]). Also this table shows, the vegetative parts of leek and the parsley leaves have the highest and the lowest D_{eff}, respectively. This result is due to high thickness of vegetative parts of leek and low thickness of parsley leaves. Also, more drying time needing to dry vegetative parts of leek is another reason for its highest D_{eff}.

An Arrhenius type of equation (Eq. (7)) was used to evaluate the effect of temperature on the effective diffusivity. The activation energy was calculated from a slope of a straight line by plotting the natural logarithm of D_{eff} versus the 1/ T value and was found 66.36, 66.34, 32.27 and 51.16 kJ/ mol for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively. These values are similar to other literature for similar vegetables: 43.92 kJ/mol for parsley leaves (*Doymaz et al*, 2006, [10]), 62.96 kJ/mol for mint leaves (*Doymaz*, 2006, [30]). Other literature values for various vegetables are: 406.02 for black tea (*Panchariya et al*, 2002, [33]), 42.8 for red pepper (*Kaymak-Ertekin,* 2002) [34], 26.2 kJ/mol for broccoli drying (*Simal et al*, 1998) [35].

Table 6: Values of effective diffusivity at various temperatures on vacuum drying of fenugreek, mint and parsley leaves and vegetative parts of leek.

Vegetable	Drying temperature (°C)	Effective diffusivity (m^2/s) $\times 10^{-10}$
Fenugreek	30	2.92
	35	3.85
	45	9.81
Mint	30	1.77
	35	2.42
	45	5.99
Parsley	30	0.93
	35	1.13
	45	1.70
Leek	30	12.72
	35	20.28
	45	33.99

CONCLUSIONS

In this study the drying kinetics of four types of plant were investigated in a vacuum dryer at the temperatures of 30, 35, 45° C with thickness of 0.25, 0.2. 0.12 and 0.7 mm for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively. Drying process for all of these vegetables occurred in the falling rate period and no constant rate period was observed. Drying time decreased continuously with temperature increasing. To explain the drying kinetic of these herbs 6 thin-layer drying models were used. Based on non-linear regression analysis, the Diffusion approximation model gave excellent fit for fenugreek and mint leaves and vegetative parts of leek. But page model was considered adequate to describe the thin-layer drying behavior of parsley leaves. The effective diffusivity increased with temperature increasing and the vegetative parts of leek and the parsley leaves have the highest and the lowest D_{eff}, respectively. The activation energy was found 66.36, 66.34, 32.27 and 51.16 kJ/ mol for fenugreek, mint and parsley leaves and vegetative parts of leek, respectively.

Received : Jan. 20, 2010 ; Accepted : Feb. 28, 2011

REFERENCES

[1] Makai P.S., Makai S., Kismanyoky A., Comparative Test of Fenugreek (*Trigonella foenum-graecum* L.), *Journal of Central European Agriculture*, **5**, p. 259 (2004).

[2] Rose P., Whiteman M., Moore P.K., Zhu Y.Z., Bioactive *S*-alk(en)yl Cysteine Sulfoxide Metabolites in the Genus *Allium*: the Chemistry of Potential Therapeutic Agents, *Published as an Advance Article on the Web (www.rsc.org/npr)*, Cambridge, UK (2005)

[3] Albaugh A., Eggers D., Crowe F., Morris M., Reerslev J., Passmore K., Pest Management Strategic Plan for Pacific Northwest Mint Production, *Summary of a Workshop*, Portland, Oregon (2002).

[4] Akpinar E.K., Bicer Y., Cetinkaya F., Modeling of Thin Layer Drying of Parsley Leaves in a Convective Dryer and under Open Sun, *Journal of Food Engineering*, **75**, p. 308 (2006).

[5] Krokida M.K., Marinos-Kouris D., Rehydration Kinetics of Dehydrated Products, *Journal of Food Engineering*, **57**(1), p. 1 (2003).

[6] Okos M.R., Narsimhan G., Singh R.K., Witnauer A.C., Food dehydration. In: D.R. Heldman & D.B. Lund (Eds.), "Handbook of Food Engineering", Marcel ekker, New York (1992).

[7] Jaya S., Das H., A Vacuum Drying Model for Mango Pulp, *Drying technology*, **21**(7), p. 1215 (2003).

[8] Sablani S.S., Datta A.K., Rahman M.S., Mujumdar, A.S., Mathematical Modeling Techniques in Food and Bioprocesses. In: Taylor & Francis (Eds.), "Handbook of Food and Bioprocess Modeling Techniques", Boca raton, London, New York (2006).

[9] Akpinar E.K., Mathematical Modeling of Thin Layer Drying Process under Open Sun of Some Aromatic Plants, *Journal of Food Engineering*, **77**, p. 864 (2006).

[10] Doymaz I., Tugrul N., Pala M., Drying Characteristics of Dill and Parsley Leaves, *Journal of Food Engineering*, **77**, p. 559 (2006).

[11] Kaya A., Aydın O., An experimental Study on Drying Kinetics of Some Herbal Leaves, *Energy Conversion and Management*, **50**, p. 118–124 (2009).

[12] Ozbek B., Dadali G., Thin-Layer Drying Characteristics and Modeling of Mint Leaves Undergoing Microwave Treatment, *Journal of Food Engineering*, **83**, p. 541 (2007).

[13] Akpinar E.K., Bicer Y., Midilli A., Modeling and Experimental Study on Drying of Apple Slices in a Convective Cyclone Dryer, *Journal of Food Process Engineering*, **26**(6), p. 515 (2003).

[14] Gunhan T., Demir V., Hancioglu E., Hepbasli A., Mathematical Modeling of Drying of Bay Leaves, *Energy Conversion and Management*, **46**(11–12), p. 1667 (2005).

[15] Yaldiz O., Ertekin C., Thin Layer Solar Drying of Some Vegetables, *Drying Technology*, **19**, p. 583 (2001).

[16] O'Callaghan J.R., Menzies D.J., Bailey P.H., Digital Simulation of Agricultural Dryer Performance, *Journal of Agricultural Engineering Research*, **16**, p. 223 (1971).

[17] Yagcioglu A., Degirmencioglu A., Cagatay F., Drying Characteristics of Laurel Leaves Under Different Drying Conditions, In: "Proceedings of the 7th International Congress on Agricultural Mechanization and Energy in Agriculture", pp 565-569. Adana, Turkey, 26–27 May (1999).

[18] Page G.E., Factors Influencing the Maximum Rates of Air Drying Shelled Corn in Thin Layers. M.S. thesis. Department of Mechanical Engineering, Purdue University, Purdue, USA (1949).

[19] Henderson S.M., Progress in Developing the Thin-Layer Drying Equation, *Transactions of the ASAE*, **17**, 1167–1168,1172 (1974).

[20] Sharaf-Elden, Y I., Blaisdell, J.L., Hamdy, M.Y., A Model for Ear Corn Drying, *Transactions of the ASAE*, **5**,1261-1265 (1980).

[21] Kassem A.S., Comparative Studies on Thin Layer Drying Models for Wheat, In: "Proceedings of the 13th International Congress on Agricultural Engineering", **6**, pp. 2–6 (1998).

[22] Ertekin Y., Yaldiz O., Drying of Eggplant and Selection of a Suitable Thin Layer Drying Model, *Journal of Food Engineering*, **63**, p. 349 (2004).

[23] Crank J., "The mathematics of Diffusion", (2nd ed.). Oxford, UK: Clarendon Press (1975).

[24] Sacilik K., Effect of Drying Methods on Thin-layer Drying Characteristics of Hull-Less Seed Pumpkin (*Cucurbita pepo* L.). *Journal of Food Engineering*, **79**(1), p. 23 (2007)..

[25] Sobukola O.P., Dairo O.U., Sanni L.O., Odunewu A.V., Fafiolu B.O., Thin Layer Drying Process of Some Leafy Vegetables under Open Sun, *Food Science and Technology International*, **13**(1), p. 35 (2007).

[26] Wang Z., Sun J., Chen F., Liao X., Hu X., Mathematical Modeling on Thin Layer Microwave Drying of Apple Pomace with and Without Hot-Air Pre Drying, *Journal of Food Engineering*, **80**(2), p. 536 (2007)

[27] Brennan J.G., Dehydration (Drying). In: WILEY-VCH Verlag GmbH & Co. KGaA (Eds.), Food Processing Handbook", (pp. 85–88), Weinheim , Germany (2006).

[28] Belghit A., Kouhila M., Boutaleb B.C., Experimental Study of Drying Kinetics of Forced Convection of Aromatic Plants, *Energy Conversion and Management*, **41**, p. 1303 (2000).

[29] Akpinar E.K., Bicer Y., Modeling of the Drying of Eggplants in Thin-Layer, *International of Journal of Food Science and Technology*, **39**, p. 1 (2004).

[30] Doymaz I., Thin-layer Drying Behavior of Mint Leaves, *Journal of Food Engineering*, **74**, p. 370 (2006).

[31] Lee J.H., Kim H.J., Vacuum Drying Kinetics of Asian White Radish (*Raphanus sativus* L.) Slices, *LWT - Food Science and Technology*, **42**, p. 180 (2009).

[32] Jena S., Das H., Modeling for Vacuum Drying Characteristics of Coconut Press Cake, *Journal of Food Engineering*, **79**, p. 92 (2007).

[33] Panchariya P.C., Popovic D., Sharma A.L., Thin-Layer Modeling of Black Tea Drying Process, *Journal of Food Engineering*, **52**, p. 349 (2002).

[34] Kaymak-Ertekin F., Drying and Rehydrating Kinetics of Green and Red Peppers, *Journal of Food Science*, **67**, p. 168 (2002).

[35] Simal S., Rossello C., Berna A., Mulet A., Drying of Shrinking Cylinder-Shaped Bodies, *Journal of Food Engineering*, **37**, p. 423 (1998).