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INFLUENCE OF DRYING AIR TEMPERATURE, AIR VELOCITY AND SURFACE LOAD ON DRYING KINETICS AND COLOR OF JEW'S MALLOW LEAVES

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ABSTRACT

The effect of drying air variables including: temperature (50, 60 and 70 ºC), velocity (0.2, 0.4 and 0.6 m/s) and surface load (125 – 500 g/ 0.22 m^2) on the drying kinetics and color of Jew's mallow leaves under hot – air drying was determined. All studied variables affected the drying time. Seven drying models were fitted to drying data and evaluated by using the coefficient of determination (R^2). The Thomson and modified Page models showed a better fit to experimental data as compared to other models. In the ranges studied, the obtained values of the effective moisture diffusivity (D_{eff}) ranged from 3.9167 x 10^{-11} to 9.3118 x 10^{-11} m^2/s for Jew's mallow leaves calculated using the Fick's diffusion model. Using D_{eff}, the activation energy (E_a) was determined assuming the Arrhenius – type temperature relationship and was found to be 35.01 KJ/ mol. From the results of color quality, drying at 60 ºC, 0.4 m/s and surface load of 250 g/ 0.22 m^2 (i.e. about 1200g/ m^2) were found to be the optimum conditions for drying Jew's mallow leaves.

Keywords: Jew's mallow, Drying models, Effective moisture diffusivity, Activation energy, Color quality

INTRODUCTION

Jew's mallow (*Corchorus olitorius* L.) is a leafy summer vegetable that grows in Egypt and many other countries in the Middle East. It is known by several names including Jew's mallow, Jute mallow, bush okra, saluyot, tugabang Molokhia (Melokiyah) and sometimes as Egyptian spinach. The leaves are very nutritious, rich in protein, thiamin, riboflavin, niacin, folate, calcium, iron and dietary fiber. Consumption of Jew's mallow leaves regularly controls blood pressure, cholesterol, lowers the risk of cancer, diabetes and heart disease. Jew's mallow is harvested 30- 60 days after planting, once or several times. The leaves are used fresh or dried (Palada and Chang, 2003 and Agriculture and Fisheries Information Service, 2009).

Like other agricultural products, Jew's mallow is subject to waste due to respiration and microbial spoilage during handling and storage. Drying of foods is one of the oldest and most common processes of food preservation. In this regards, the goals of drying process in the food can be classified in: 1) economic considerations, 2) environmental concerns, 3) product quality aspects. Drying can be achieved by sun solar, hot-air, freeze-drying or osmotic dehydration. Open-air sun drying had been used since a long time to dry different food products. However, it is not always suitable for a large-scale production due to various reasons including, lack of ability to control the drying process, length of drying time and unhygienic drying conditions. Thus, hot-air drying has been used as a simple and common drying method for drying of vegetables and fruits. There are some reports on the hot-air drying characteristics of fruits and vegetables with high moisture content such as tomato, apple, garden beet, carrots, pepper and others (Doymaz, 2006; Fatouh *et al.*, 2006; Saleh and Badran, 2009; Mota *et al.*, 2010; Arslan and Özcan, 2011; Babetto *et al.*, 2011 and Vega-Gálvez *et al.*, 2012).

Drying is a complex thermal process involving simultaneous heat and mass transfer in a hygroscopic system. In air drying process two important phases are usually observed: initially pure water evaporation occur a constant rate period, followed by a falling rate period in which the moisture transfer is essentially limited by internal resistances. The moisture removal during drying process is affected by a number of internal and external parameters. External parameters include temperature, velocity and relative humidity of the drying air, while internal parameters include density, permeability, porosity and thermo-physical properties of the materials (Rizvi, 1986; Guine, 2005; Kaya *et al.*, 2007 Vega *et al.*, 2007 and Mota *et al.*, 2010).

The moisture removal and its dependence on the process variable is expressed in terms of drying kinetics. Many mathematical models have been proposed to describe the drying process. These models can be categorized as theoretical, semi-theoretical and empirical. Most of these models derive from the diffusional model of Fick's second law for different geometries. When hot-air drying process is controlled by the internal mass transfer, modeling of drying is carried out through diffusion equations based on Fick's second law. Empirical equations used to model the drying kinetics of foods include: Newton (Lewis), Page, Henderson-Pabis, Page modified, Logarithmic, Diffusion approach, Verma, Henderson-pabis modified models and others (Barrozo *et al.*, 2004; McMinn, 2006; Kuitche *et al.*, 2007; Vega *et al.*, 2007 and Doymaz, 2012).

Recently, there have been many studies of the drying behavior of various leafy vegetables such as mint (Doymaz, 2006; Kaya and Aydin, 2009 and Saleh and Badran, 2009), parsley (Doymaz *et al.*, 2006 and Soysal *et al.*, 2006), nettle (Kaya and Aydin, 2009), bay (Demir *et al.*, 2004 and Gunhan *et al.*, 2005), rosemary (Derya and Özcan, 2008) and dill (Doymaz *et al.*, 2006). However, studies on the hot-air drying kinetics of Jew's mallow leaves, either in terms of empirical models or in terms of diffusivity models are scarce.

Therefore the objectives of this study are to: determine the effect of hot-air drying variables (air temperature, air velocity and surface load) on drying time and color of Jew's mallow leaves, fit the experimental data to seven mathematical models, and calculate effective moisture diffusivity and activation energy for hot-air drying of Jew's mallow leaves.

MATERIALS AND METHODS

Materials

Fresh harvested Jew's mallow (*Corchorus olitorius* L.) was purchased from a local market (Ismailia city, Egypt) during August and September 2011. The Jew's mallow was processed firstly by separating green leaves, washing with tap water and then draining and leaving to dry on a cheese cloth for 15 minutes at room temperature (31± 2 ˚C). The initial moisture content of the Jew's mallow leaves was immediately determined by drying according to the AOAC (1990). The initial moisture content of the Jew's mallow leaves was 84.77± 0.82% on wet basis (5.568 on dry basis). The thickness of the fresh leaves was measured using a digital caliper (Mitutoyo Corp., Japan) and an average value of 60 measurements was recorded (0.16± 0.02 mm). After drying, the samples were packed in sealed polyethylene bags and stored at 4 ºC in the refrigerator.

Methods

Drying process:

To study the effect of drying air temperature on the drying kinetics and color of the dried product, 250 g of Jew's mallow leaves were spread uniformly onto stainless steel trays of size 0.365 m x 0.60 m. The leaves were dried in a convective dryer (WT-binder, Type F115, Germany) at 50, 60 and 70 ºC at a constant air velocity (0.6 m/s) and ambient relative humidity (Doymaz, 2012).

To study the effect of air velocity, 125 g of Jew's mallow leaves were spread onto stainless steel trays, and dried in an oven at 0.2, 0.4 and 0.6 m/s at a constant air temperature (60 ºC) and ambient relative humidity (Kaya and Aydin, 2009).

To study the effect of surface load, 125, 250, 375 and 500 g of Jew's mallow leaves were spread uniformly onto stainless steel trays of size 0.365 m x 0.60 m, and dried at 60 ºC, a constant air velocity (0.6 m/s) and ambient relative humidity (Fatouh *et al.*, 2006).

The dryer was switched on 30 min before drying experiments to achieve steady-state conditions (Doymaz, 2012). The sample under drying was weighed at regular time intervals (15 min) during the drying process using a digital balance, with an accuracy of 0.01 g. A tray with the sample was taken out from the oven, weighed and placed back into the drying chamber. The weighing process took about 10 seconds (Arslan and Özcan, 2011). Drying was continued until the equilibrium moisture content was reached, and a constant weight of the samples was registered (Vega-Gálvez *et al.*, 2012). The drying experiments were conducted in triplicate and the average of the moisture ratio at each value was used for drawing drying curves (Doymaz *et al.*, 2006 and Doymaz, 2012).

Mathematical modeling of drying curves:

The moisture ratio (MR) and drying rate of the Jew's mallow leaves during the drying experiments were calculated using the following equations:

$$MR = (M - M_e)/(M_o - M_e) \quad \text{(Eq. 1)}$$

$$\text{Drying rate} = (M_{t+dt} - M_t)/(dt) \quad \text{(Eq. 2)},$$

Where , M, M_o, M_e, M_t and M_{t+dt} are the moisture contents at any time, initial moisture content, equilibrium moisture content, moisture content at t and moisture content at t+dt (g moisture/ g dry matter), respectively, (t) is the drying time (min) and (dt) is the time difference (min).

For mathematical modeling, the equations in Table (1) were tested to select the best model for describing the drying curves of Jew's mallow leaves. Regression analysis was performed using the Statistica computer program.

The correlation coefficient (R^2) was used, in this study, to select the best equation to describe the drying curves of the dehydrated samples.

Table 1: Mathematical models applied to the Jew's mallow leaves drying curves

Model name	Model equation	Reference
Lewis	$MR= \exp(-kt)$*	Ayensu (1997)
Page	$MR= \exp(-kt^n)$	Diamante and Munro (1993)
Modified Page	$MR= \exp[-(kt)^n]$	Özdemir and Devres (1999)
Modified Page equation-II	$MR= \exp[-k(t/L^2)^n]$	Diamante and Munro (1993)
Henderson and Pabis	$MR= a \exp(-kt)$	Henderson and Pabis (1961)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
Thomson	$MR = a (\ln MR) + b (\ln MR)^2$	Thomson *et al.* (1968)

*** a, b, k, n are empirical constants in drying models; (t) is the drying time (min)**

Calculation of the effective moisture diffusivity and activation energy:

The effective moisture diffusivity is an important property in food drying processes modeling, being a function of temperature and moisture content in food (Doymaz, 2012). Fick's second law of diffusion equation, symbolized as a mass-diffusion equation for drying food products in a falling rate period. This equation is solved by Crank (1975), and can be used for various products. For a long drying period, this solution can be simplified by taking the first term of series solution and expressed in a logarithmic form as follows (Falade and Solademi, 2010):

$$\ln MR= \ln (8/ \pi^2) - (\pi^2 D_{eff}/4L^2)t \qquad \text{(Eq. 3)}$$

Where, D_{eff} is the effective diffusivity (m^2/s), (L) is the half thickness of the leaves (m).

From Eq. (3), a plot of ln MR versus drying time gave a straight line with a slope of ($\pi^2 D_{eff}/4L^2$).

The dependence of the effective diffusivity on the temperature can be determined by the Arrhenius equation (Xiao *et al.*, 2010):

$$D_{eff}= D_o \exp(-E_a/ RT) \qquad \text{(Eq. 4)}$$

Where, E_a is the activation energy of the moisture diffusion (KJ/mol), (D_o) is the diffusivity value for an infinite moisture content, (R) is the universal gas constant (KJ/mol K), and (T) is the drying air temperature (˚K).

Color measurement:

Fresh and dried samples were homogenized to fine particles in a kitchen blender. The samples were evaluated for color using a Minolta colorimeter (Minolta Co. Ltd., Osaka, Japan) on the basis of the CIELAB color system (L^*, a^* and b^*). The L^*, a^*, b^* values are average of 3 readings. The color brightness coordinate L^* measures the whiteness value of color and ranges from black at 0 to white at 100. The coordinate a^* measures the red when positive and green when negative and b^* coordinate measures yellow when positive and blue when negative (Doymaz *et al*., 2006). The total color change (ΔE) was determined by using the following equation (Vega-Gálvez *et al.*, 2012):

$$\Delta E= [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5} \qquad \text{(Eq. 5)}$$

Statistical analysis:

The data are presented as the mean of three determinations ± standard deviation. The data were analyzed by ANOVA and Duncan's multiple range tests by using SPSS (ver. 13) at $p < 0.05$. The statistical analyses of the drying experiments for model fitting were performed by using the software package (Statistica 6.0, Statsoft Inc., Tulsa, OK, USA) (Arslan and Özcan, 2011).

RESULTS AND DISCUSSION

Drying characteristics of Jew's mallow leaves:

There are three different types of plots used to represent the drying characteristics of foods: batch drying curve (moisture content versus time), drying rate curve (drying rate versus time), and krisher curve (drying rate versus moisture content) (Kemp *et al*., 2001 and Guiné 2005).

Variations of the moisture content (on dry basis) with the drying time (min) for varying values of the governing parameters (drying air temperature, drying air velocity and surface load) have been determined. As shown from the Fig. (1a), increasing the temperature from 50 ºC to 60 ºC decreased the total drying time needed to achieve equilibrium moisture content from about 405 min to about 300 min (a decrease of 25.93%), since heat transfer increased due to the increasing temperature difference between the drying air and the product. Similarly, a further increase in the temperature to 70 ºC decreased the total drying time to about 195 min, i.e by 35.00% and 51.85% according to those at 60 ºC and 50 ºC, respectively. These results well agree with some studies on drying various food products (Doymaz, 2006; Doymaz *et al.*, 2006; Kaya and Aydin, 2009; Arslan and Özcan, 2011; Doymaz, 2012 and Vega-Gálvez *et al.*, 2012).

As shown in Fig. (1b), increasing air velocity, at a constant air temperature and surface load, from 0.2 m/s to 0.4 m/s decreased the total drying time by 16.67%. A further increase in air velocity to 0.6 m/s, decreased the total time by 27.78% and 13.32% according to those at 0.2 m/s and 0.4 m/s, respectively. Similarly Kaya and Aydin (2009) showed that the increase of drying air velocity from 0.2 m/s to 0.6 m/s at 35 ºC decreased the total drying time by about 7.14% and 6.67% for nettle and mint leaves, respectively. Increasing the velocity of the drying air decreases the drying time as a result of increasing convective heat and mass transfer coefficients between the drying air and the product.

Fig. (1c) shows that the required drying time of Jew's mallow leaves increased with the increase of surface load. At constant values of the temperature (60 ºC) and velocity (0.6 m/s) of the drying air, increasing surface load from 125 g/ 0.22 m^2 to 250 g/ 0.22 m^2 increased the total drying time from 195 min to 300 min (an increase of 53.85%).

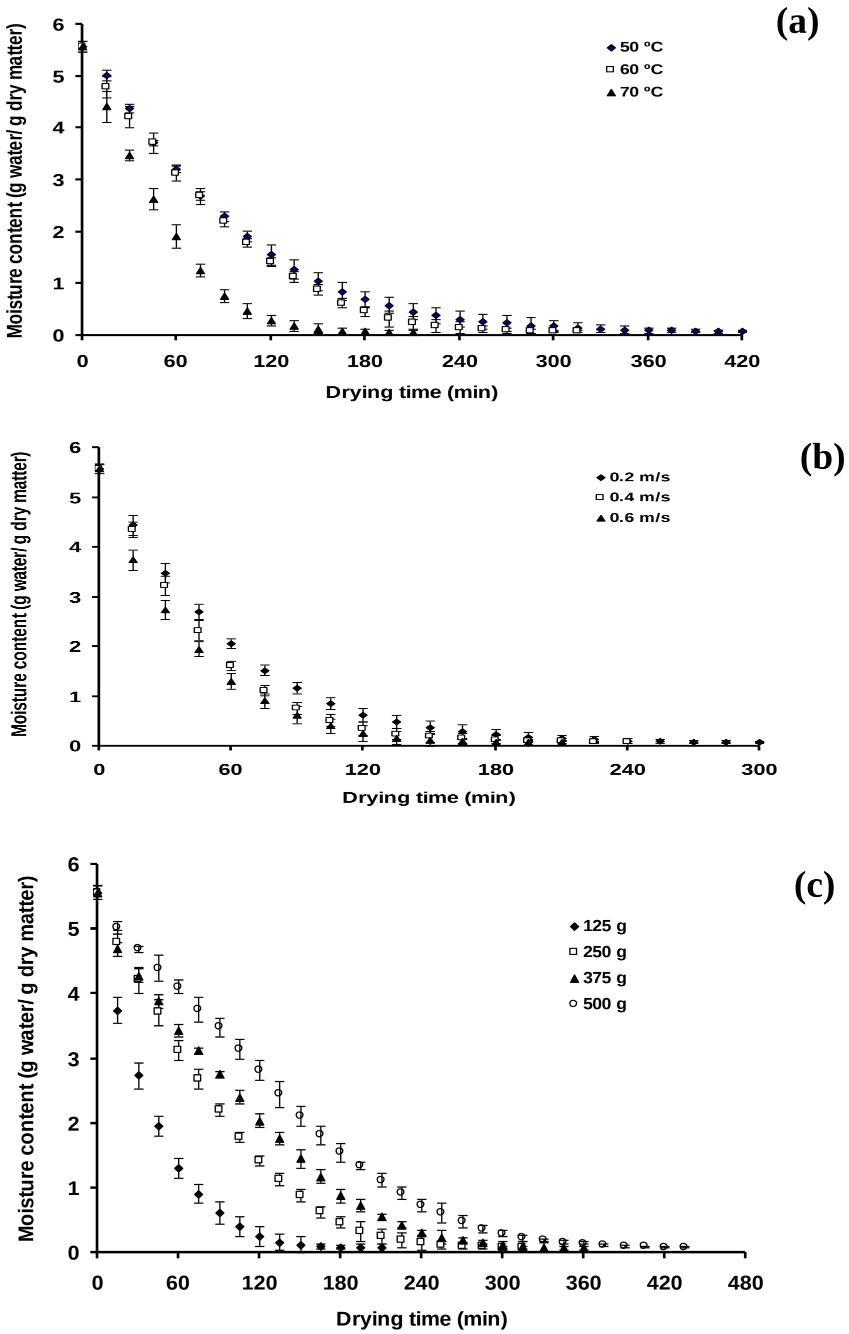

Figure (1): Moisture content in relation to time at different temperatures (a), velocities (b) and surface loads (c)

A further increase in the surface load to 375 and 500 g/ 0.22 m^2, increased the total drying time by 76.92% and 115.38% according to this at 125 g/ 0.22 m^2, respectively. Similarly, Fatouh *et al.* (2006) found that the required drying times of Jew's mallow leaves to achieve the moisture content of 6% are 4.75, 5.17 and 6.25 h for the runs of surface loads of 14, 21 and 28 Kg/ m^2, respectively. But, runs of surface loads of 3.5 and 7 Kg/ m^2 did not reach the recommended moisture content (6%) at drying air temperature of 55 ºC and velocity of 1.2 m/s using a heat pump dryer. Also, Mwithiga and Olwal (2005) showed that the drying time increased with the depth of kale leaves layer. The drying time required to decrease the moisture content of kale from 6.172 (dry basis) to about 0.15 (dry basis) at 30 ºC increased from 390 min for a 10 mm layer to about 1200 min for a 50 mm layer.

In order to gain insight into the drying characteristics of the Jew's mallow leaves, the relation of the drying rate [Eq. 2] to the moisture content (dry basis) are shown in Fig. (2a-c) for various temperatures, velocities and surface loads. Due to the moisture diffusion process, the drying rate decreases with the decrease of moisture content. As shown in Fig. (2), there is no constant drying rate period, and the entire drying process occurred in the falling - rate period. This result is in agreement with other studies on the drying of some foods (Doymaz, 2006; Doymaz *et al.*, 2006; Kaya and Aydin, 2009 and Doymaz, 2012). During the constant drying rate period, drying takes place from the material surface saturated with water and drying rate is controlled by air temperature, exposed area and air velocity conditions (Saleh and Badran, 2009). The falling drying rate period takes place as a result of the predominance of internal diffusion mechanism because of the presence of bound water. During the first part of the falling drying rate period, water in large capillaries is removed followed by that in small capillaries, resulting in a reduction in the rate of evaporation. Towards the end of drying process, water highly bound to sites of water – holding components (protein, starch, fiber,..) is removed and water extraction becomes more difficult and drying rate decreases as the drying time progresses (Baker, 2007 and Tunde-Akintunde *et al.*, 2005). From Fig. (2a), it is clear that the higher air temperature, the higher the drying rate. For higher moisture content, increasing drying – air temperature resulted in increasing drying rate and consequently decreased the drying time. This could be explained by the increasing temperature difference between the drying air and the product and accelerating water migration. Similar observations are obtained for drying – air velocity (Fig. 2b). Fig. (2c) shows that the surface load has a considerable influence on the drying rate. Increasing the surface load decreased the drying rate.

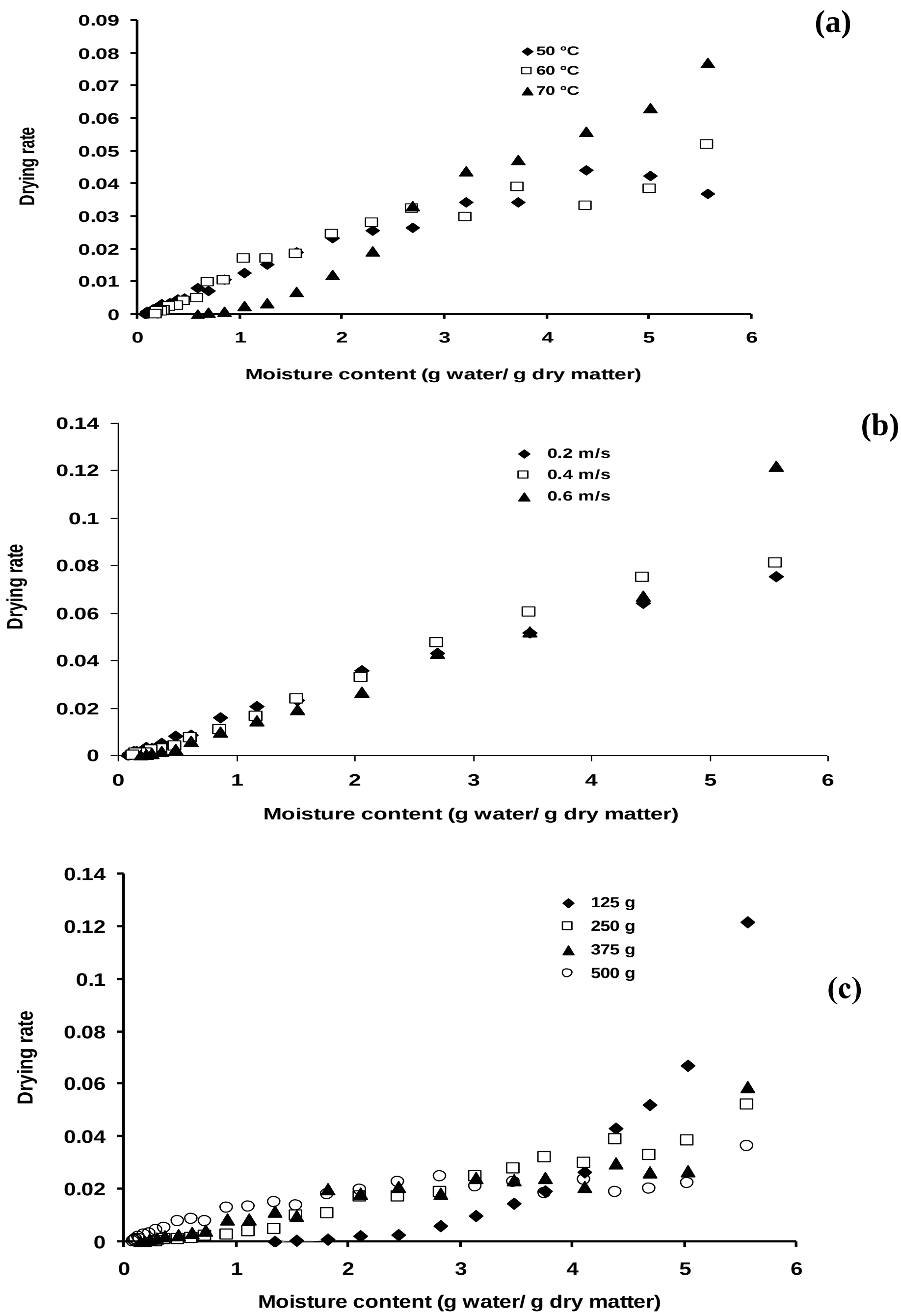

Figure (2): Variations of drying rate in relation to moisture content at different temperatures (a), velocities (b) and surface loads (c)

Modeling of drying curves:

The moisture content data obtained at different air temperatures, air velocities and surface loads were converted to dimensionless ratio [Eq. 1] and then, curve (moisture ratio versus time) fitted to seven drying models (Table 1). The non – linear regression analysis was used to estimate the parameters of those models. The statistical results from models are summarized in Tables (2, 3, 4) for the studied drying variables. The best model describing the drying characteristics of Jew's mallow leaves was chosen as the one with the highest coefficient of determination (R^2) values. The highest R^2 values are obtained by using the Thomson model and the modified Page model for all drying variables studied. Generally, R^2 values of the selected models varied between 0.9899 – 0.9981 and 0.9811 – 0.9967 for drying air temperatures (Table 2), 0.9976 – 0.9995 and 0.9838 – 0.9997 for drying air velocities (Table 3), and 0.9746 – 0.9995 and 0.9477 – 0.9838 for surface loads (Table 4) for the Thomson model and the modified Page model, respectively. Accordingly, the Thomson and the modified Page models were selected as suitable models to represent the drying characteristics of Jew's mallow leaves.

Table 2: Results of statistical analysis on the modeling of moisture ratio and drying time for Jew's mallow leaves as affected by air temperature

Model name	Temperatures (°C)	Model constants*	Coefficient of determination (R^2)
Lewis	50	*k*= 0.0144	0.9370
	60	*k*= 0.0173	0.9114
	70	*k*= 0.0299	0.9237
Page	50	*k*= 0.0034, *n*= 1.2510	0.9967
	60	*k*= 0.0032, *n*= 1.2975	0.9811
	70	*k*= 0.0048, *n*= 1.3592	0.9891
Modified Page	50	*k*= 0.0106, *n*= 1.2510	0.9967
	60	*k*= 0.0121, *n*= 1.2975	0.9811
	70	*k*= 0.0198, *n*= 1.3592	0.9891
Modified Page equation - II	50	*k*= 6.1E-06, *n*= 1.2510	0.9967
	60	*k*= 4.6E-06, *n*= 1.2975	0.9811
	70	*k*= 5.1E-06, *n*= 1.3592	0.9891
Hendeson and Pabis	50	*a*= 1.7194, *k*= 0.0165	0.957
	60	*a*= 1.9788, *k*= 0.0208	0.9482
	70	*a*= 1.9858, *k*= 0.0354	0.9556
Wang and Singh	50	*a*= -0.0071, *b*= 5E-05	0.9792
	60	*a*= -0.0083, *b*= 2E-05	0.9986
	70	*a*= -0.0138, *b*= 1E-05	0.9972
Thomson	50	*a*= -96.957, *b*= -5.9068	0.9981
	60	*a*= -88.680, *b*= -7.2472	0.9899
	70	*a*= -50.462, *b*= -3.6519	0.9909

*** a, b, k, n are empirical constants in drying models**

The drying constant *k* (min^{-1}) in the modified Page model indicates that the relative magnitude of the parameter accurately reflects the drying behavior. The increase in the drying constant with increasing the air temperature during the process indicates enhancement of drying potential (Table 2). A similar trend is found with drying air velocity (Table 3). The drying constant (*k*) decreased with increasing the surface load from 0.0256 min^{-1} for 125 g/ 0.22 m^2 to 0.0077 min^{-1} for 500 g/ 0.22 m^2 (Table 4). McMinn (2006) found that the drying constant (*k*) of the Midilli *et al*., Page and Logarithmic models increased with increasing temperature and velocity of drying air.

Table 3: Results of statistical analysis on the modeling of moisture ratio and drying time for Jew's mallow leaves as affected by air velocity

Model name	Air velocity (m/s)	Model constants*	Coefficient of determination (R^2)
Lewis	0.2	*k*= 0.0209	0.9819
	0.4	*k*= 0.0263	0.9865
	0.6	*k*= 0.0320	0.9436
Page	0.2	*k*= 0.0100, *n*= 1.1378	0.9985
	0.4	*k*= 0.0093, *n*= 1.2048	0.9997
	0.6	*k*= 0.0155, *n*= 1.1364	0.9838
Modified Page	0.2	*k*= 0.0174, *n*= 1.1378	0.9985
	0.4	*k*= 0.0206, *n*= 1.2048	0.9997
	0.6	*k*= 0.0256, *n*= 1.1364	0.9838
Modified Page equation - II	0.2	*k*= 31.8E-06, *n*= 1.1378	0.9985
	0.4	*k*= 21.2E-06, *n*= 1.2048	0.9997
	0.6	*k*= 49.8E-06, *n*= 1.1364	0.9838
Hendeson and Pabis	0.2	*a*= 1.3279, *k*= 0.0225	0.9890
	0.4	*a*= 1.3696, *k*= 0.0285	0.9945
	0.6	*a*= 1.6346, *k*= 0.0359	0.9595
Wang and Singh	0.2	*a*= -0.0111, *b*= 3E-05	0.9640
	0.4	*a*= -0.0135, *b*= 4E-05	0.9736
	0.6	*a*= -0.0156, *b*= 6E-05	0.9565
Thomson	0.2	*a*= -59.779, *b*= -2.7754	0.9989
	0.4	*a*= -46.483, *b*= -1.9199	0.9976
	0.6	*a*= -44.261, *b*= -2.6572	0.9995

*** a, b, k, n are empirical constants in drying models**

Table 4: Results of statistical analysis on the modeling of moisture ratio and drying time for Jew's mallow leaves as affected by surface load

Model name	Surface load (g/ 0.22 m²)	Model constants*	Coefficient of determination (R^2)
Lewis	125	*k*= 0.0320	0.9436
	250	*k*= 0.0173	0.9114
	375	*k*= 0.0151	0.833
	500	*k*= 0.0119	0.8553
Page	125	*k*= 0.0155, *n*= 1.1364	0.9838
	250	*k*= 0.0032, *n*= 1.2975	0.9811
	375	*k*= 0.0034, *n*= 1.2407	0.9477
	500	*k*= 0.0015, *n*= 1.3406	0.9615
Modified Page	125	*k*= 0.0256, *n*= 1.1364	0.9838
	250	*k*= 0.0121, *n*= 1.2975	0.9811
	375	*k*= 0.0104, *n*= 1.2407	0.9477
	500	*k*= 0.0077, *n*= 1.3406	0.9615
Modified Page equation - II	125	*k*= 49.8E-06, *n*= 1.1364	0.9838
	250	*k*= 4.6E-06, *n*= 1.2975	0.9811
	375	*k*= 6.5E-06, *n*= 1.2407	0.9477
	500	*k*= 1.7E-06, *n*= 1.3406	0.9615
Hendeson and Pabis	125	*a*= 1.6346, *k*= 0.0359	0.9595
	250	*a*= 1.9788, *k*= 0.0208	0.9482
	375	*a*= 2.3745, *k*= 0.0189	0.8827
	500	*a*= 2.4111, *k*= 0.0151	0.9111
Wang and Singh	125	*a*= -0.0156, *b*= 6E-05	0.9565
	250	*a*= -0.0083, *b*= 2E-05	0.9986
	375	*a*= -0.0068, *b*= 1E-05	0.9963
	500	*a*= -0.0052, *b*= 7E-06	0.9976
Thomson	125	*a*= -44.261, *b*= -2.6572	0.9995
	250	*a*= -88.680, *b*= -7.2472	0.9899
	375	*a*= -106.700, *b*= -8.7934	0.9809
	500	*a*= -137.470, *b*= -12.2940	0.9746

*** a, b, k, n are empirical constants in drying models**

Calculation of effective moisture diffusivity and activation energy:

The values of the effective moisture diffusivity (D_{eff}) of hot air dried Jew's mallow leaves at different air temperatures, velocities and surface loads are shown in Table (5). These values varied in the range of 3.9167 x 10^{-11} m^2/s to 9.3118 x 10^{-11} m^2/s. It is noted that the D_{eff} values increase greatly with increasing drying temperatures from 4.2798 x 10^{-11} m^2/s at 50 ºC to 9.1821 x 10^{-11} m^2/s at 70 ºC. Drying samples at higher temperatures, increased heating energy which in turn increases the activity of water molecules leading to higher moisture diffusivity (Xiao *et al.*, 2010). Furthermore, the values of effective moisture diffusivity increase with increasing drying air velocity and decrease with increasing the surface load (Table 5). The values of D_{eff} obtained lie within the range of 10^{-12} – 10^{-8} m^2/s for drying of food products (Zogzas *et al.*, 1996). The obtained values are in agreement with those reported for leafy vegetables, e.g. 1.744 – 4.992 x 10^{-9}

m^2/s for nettle leaves and 1.975 – 6.172 x 10^{-9} m^2/s for mint leaves (Kaya and Aydin, 2009), 6.693 x 10^{-10} to 1.434 x 10^{-9} m^2/s for dill leaves and 9.0 x 10^{-10} to 2.337 x 10^{-9} m^2/s for parsley leaves (Doymaz *et al.*, 2006), and 14.9 – 55.9 x 10^{-10} m^2/s for kale leaves (Mwithiga and Olwal, 2005).

The activation energy (E_a) can be determined from the slope of Arrhenius plot, ln D_{eff} versus reciprocal of absolute temperature Fig. (3). The result shows a linear relationship due to Arrhenius type dependence (R^2= 0.9432). The slope of the line is ($-E_a/R$) and the intercept equals ln D_o. The value of D_o is 18.6 x 10^{-6} m^2/s and the activation energy (E_a) for diffusion was found as 35.01 KJ/ mol. This value is similar to those reported for different fruits and vegetables such as 22.66 – 30.92 KJ/ mol for apples (Meisami-asl *et al.*, 2010), 30.46 – 35.57 KJ/ mol for strawberry (Lee and Hsieh, 2008), 35.05 KJ/ mol for dill leaves (Doymaz *et al.*, 2006), 35.43 KJ/ mol for green bean (Doymaz, 2005), and 36.115 KJ/ mol for kale leaves (Mwithiga and Olwal, 2005).

Table 5: Effective moisture diffusivity (D_{eff}) obtained for Jew's mallow leaves at different drying variables

Drying variables	Effective moisture diffusivity (m^2/s)	Coefficient of determination (R^2)
Air temperature (ºC)		
50	4.2798 x 10^{-11}	0.9570
60	5.3952 x 10^{-11}	0.9482
70	9.1821 x 10^{-11}	0.9556
Air velocity (m/s)		
0.2	5.8361 x 10^{-11}	0.9890
0.4	7.3924 x 10^{-11}	0.9945
0.6	9.3118 x 10^{-11}	0.9595
Surface load (g/ 0.22 m^2)		
125	9.3118 x 10^{-11}	0.9595
250	5.3952 x 10^{-11}	0.9482
375	4.9023 x 10^{-11}	0.8827
500	3.9167 x 10^{-11}	0.9111

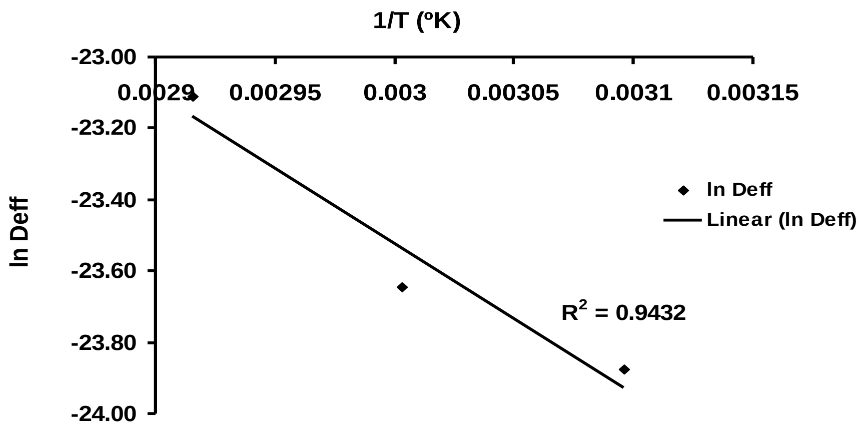

Figure (3): Correlation between effective moisture diffusivity and temperatures

Color parameters of Jew's mallow leaves:

Color influences consumer acceptability, and abnormal colors, especially those associated with deterioration in eating quality or with spoilage, cause the product to be rejected by the consumer. There are many reactions that can affect color during thermal processing of foods, the most common of them are pigment degradation (chlorophylls and carotenoids) and browning reactions such as Maillard reaction and oxidation of ascorbic acid (Maskan, 2001 and Doymaz *et al.*, 2006).

Table (6) shows the color parameters (L^*, a^*, b^*) of fresh and dried Jew's mallow leaves at different drying variables under study. The colorimetric coordinates for the fresh Jew's mallow leaves were 30.96 ± 1.29, -2.92 ± 0.23 and 8.04 ± 0.80 for L^*, a^* and b^*, respectively. At constant air – drying velocity and surface load, color parameters L^* and b^* values increased and a^* values decreased as drying air temperatures increased. The same observations are noted with surface load. Regarding air velocity, no notable changes were found.

The total color difference (ΔE) is a function of the three CIE L^* a^* b^* coordinates [Eq. 5]. When analyzing the ΔE values, the major changes are observed at 70 ºC, 0.6 m/ s and 500 g/ 0.22 m^2. From these results, drying at 60 ºC, 0.4 m/s and 250 g/ 0.22 m^2 produce a dried Jew's mallow leaves with less color changes.

Table 6: Color values (mean ± SD) and *ΔE* for Jew's mallow leaves at different drying variables

Drying variables	L^*	a^*	b^*	ΔE
Fresh leaves	30.96 ± 1.29	-2.92 ± 0.23	8.04 ± 0.80	-
Air temperature (ºC)				
50	50.40 ± 0.78	3.87 ± 0.32	9.93 ± 0.38	19.55^b
60	51.50 ± 0.46	4.87 ± 0.55	12.10 ± 0.46	21.03^a
70	52.33 ± 0.38	5.03 ± 0.32	13.63 ± 0.40	22.19^a
Air velocity (m/ s)				
0.2	51.30 ± 0.61	4.43 ± 0.06	11.30 ± 0.87	20.65^a
0.4	51.37 ± 0.47	5.03 ± 0.31	9.33 ± 0.85	20.56^a
0.6	51.27 ± 0.81	4.57 ± 0.50	10.90 ± 0.26	20.58^a
Surface load (g/ 0.22 m^2)				
125	51.27 ± 0.81	4.57 ± 0.50	10.90 ± 0.26	20.58^b
250	51.50 ± 0.46	4.87 ± 0.55	12.10 ± 0.46	21.03^b
375	52.07 ± 0.38	4.70 ± 0.10	13.10 ± 0.56	21.78^a
500	52.13 ± 0.45	5.13 ± 0.25	13.43 ± 0.21	21.96^a

Means of triplicates
Means having the same letter within the same category are not significantly different at $p < 0.05$

CONCLUSION

Drying kinetics and color of Jew's mallow leaves were investigated as a function of drying variables. The following conclusions can be made: Drying time decreased considerably with the increase of drying air temperature and velocity and increased with the increase of surface load. Drying curves of Jew's mallow leaves did not show a constant drying rate period, but showed only a falling rate period. The Thomson and modified Page models gave the best representation of drying data under all experimental variables. The effective moisture diffusivity values increased with the drying air temperature and velocity and decreased with increasing the surface load. The values varied between 3.9167 x 10^{-11} and 9.3118 x 10^{-11} m^2/ s, over the variables range. The activation energy for moisture diffusion was 35.01 KJ/ mol. From the results of color quality, drying at 60 ºC, 0.4 m/s and 250 g/ 0.22 m^2 were found to be optimal drying conditions of Jew's mallow leaves.

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تأثير درجة حرارة هواء التجفيف، وسرعته وحمولة الصواني في حركيات تجفيف ولون أوراق الملوخية

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تم دراسة تأثير كل من درجة حرارة هواء التجفيف (٥٠، ٦٠ و ٧٠ درجة مئوية)، وسرعته (٠,٢، ٠,٤ و ٠,٦ م/ ث) وحمولة الصواني (١٢٥ – ٥٠٠ جم/ ٠,٢٢ م٢) في حركيات تجفيف ولون أوراق الملوخية. أوضحت النتائج تأثير جميع المتغيرات تحت الدراسة في وقت التجفيف. كما تم تحليل بيانات التجفيف باستخدام سبعة نماذج رياضية وقيمت هذه النماذج باستخدام معامل التحديد (R^2). وجد أن نموذج Thomson ونموذج modified Page أفضل القياسات للبيانات التجريبية بالمقارنة مع النماذج الرياضية الأخرى. تراوحت قيم انتشار الرطوبة (D_{eff}) أثناء التجفيف ما بين ٣,٩١٦٧ X ١٠-١١ الي ٩,٣١١٨ X ١٠-١١ م٢/ث محسوبة باستخدام معادلة فيكس للانتشار. وباستخدام قيم انتشار الرطوبة المتحصل عليها، تم حساب طاقة التنشيط باستخدام معادلة أرهينيس ووجدت أنها تساوي ٣٥,٠١ كيلو جول/ مول. ومن نتائج جودة اللون، وجد أن أفضل ظروف تجفيف لأوراق الملوخية هي التجفيف عند ٦٠ درجة مئوية وسرعة هواء ٠,٤ م/ ث، وحمولة سطح تساوي ٢٥٠ جرام/ ٠,٢٢ م٢ (أي ما يعادل ١٢٠٠ جم/ م٢).

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