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Drying of Mint Leaves: Influence of the Process Temperature on Dehydration Parameters, Quality Attributes, and Energy Consumption

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ABSTRACT

In this work, to assess the temperature effect on dehydration parameters and physicochemical characteristics of mint leaves, the samples were dried at air temperatures of 40, 50 and 60°C and constant air flow rate of 1 m s^{-1}. Energy consumption of the process was also studied. Fick's second law was used to model mass transport in the leaves during the process. Moisture diffusivity and coefficient of mass transfer were determined to vary in the range of 5.09×10^{-9}-1.73×10^{-8} m^2 s^{-1} and 1.59×10^{-5}-5.71×10^{-5} kg_{water} m^{-2} s^{-1}, respectively. Both of the mass transfer parameters were increased with increasing temperature. Higher temperatures caused more total color change and destruction of both chlorophyll and carotenoids. While the rehydration capacity of the dried leaves increased, the specific consumed energy of the process diminished with increasing drying air temperature.

Keywords: Color changes, Fick's second law, Mass transfer, Rehydration capacity.

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INTRODUCTION

Mint (*Mentha spicata* L.) is an aromatic herb widely grown for its singular characteristics. Both fresh and dried mint leaves are used for cooking. Usage of the leaves in some dishes, for example, fruit salads, vegetable curries, chutney, soups, desserts, juices, sherbets etc. has been reported in the literature (Park *et al.*, 2002; Thompson, 2003).

Drying is one of the most key unit operations often applied in different industries. It has been introduced as an effective method to preserve agricultural and food products. Generally, high moisture content is the main reason for the destruction of fresh agricultural materials. Reduction of the water content to a certain value controls enzymatic and metabolic activities and also inhibits microorganisms and bacterial growth (Beigi, 2016a; Aral and Bese, 2016). Therefore, in comparison with the moist materials, the physicochemical changes in dried products are significantly reduced during the storage and shelf-life is increased. Moreover, easy and low cost transportation and diversity of usage are the two other significant advantages of the dried materials (Dadali *et al*., 2007; Doymaz and Ismail, 2011). Despite the significance of dehydration in processing and preserving of agricultural and food materials, applying inappropriate drying methods and conditions could cause quality deterioration and high energy utilization. Therefore, an accurate knowledge of mass transfer mechanism, quality changes of dried products and also energy consumption is necessary to optimize the process (Beigi, 2017).

To comprehend the mechanism of mass transfer during drying process and also to clarify the influences of drying parameters on dehydration behavior, mathematical modelling is helpful. Furthermore, the results obtained from the modelling can be used for prediction of drying curves,

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designing more effective drying systems, and optimizing the process parameters (Torki-Harchegani *et al*., 2016b). The Fick's law-based diffusion model with and without external resistance has been employed in many cases to simulate convective drying and proven to be capable of accurate estimation of the drying kinetics (Garcia-Perez *et al*., 2012; Gamboa-Santos *et al*., 2014; Tao *et al*., 2016).

In the recent years, some works have been conducted on mint leaves drying using different dehydration methods and conditions (Table 1). As shown, although different aspects of the leaves drying have been assessed in the referred works, one or some important traits have been neglected. In fact, there is no published data or information in the open literature considering all of the main indices including mass transfer parameters, energy consumption, and the dried product quality. Therefore, regarding the previous studies reported on mint leaves drying, the aims of the present work were to: (1) Study dehydration behavior of the leaves under different drying air temperatures, (2) Model the drying curves and obtain the mass transmission parameters, (3) Investigate quality characteristics of dried leaves in terms of color, chlorophyll and carotenoids contents and rehydration capacity, and (4) Calculate energy consumption of the process.

MATERIALS AND METHODS

Drying Procedure

The fresh mints were bought from a local market in Isfahan and the leaves were parted accurately. To determine the initial moisture content (dry basis) of the mint leaves, four 50 g samples of the leaves were placed in an air-drying oven at 105°C for 24 hours (Torki-Harchegani *et al*., 2016a), and the following equation was applied:

$$M_0 = \frac{W_0 - W_d}{W_d} \qquad (1)$$

Where, M_0 is the initial moisture content ($g_{water}\ g^{-1}_{dry\ matter}$) of fresh leaves, and W_0 and W_d are the mass (g) of wet and dried leaves, respectively.

Average value for the initial moisture content was obtained as 5.67±0.09 $g_{water}\ g^{-1}$dry matter.

A lab scale convective dryer was used to perform the dehydration experiments. The drying air was supplied by a centrifugal fan, which was heated up to the desired temperature using an electric heater, and then passed into the samples drying chamber. The chamber had internal diameter of 20 cm, thickness of 5 mm, and height of 15 cm. To measure and control the air flow rate, a hot wire anemometer (Lutron, AM-4201 model, Taiwan) and a frequency inverter (TECO, 7300 CV model, Taiwan) were used. Temperature of the air was measured using a thermometer (PT100, 0.1°C resolution) at the inlet of the chamber and was controlled by a micro controller. To determine the consumed energy of heating coils, a digital power meter (Ziegler Delta Power, 0.1 W resolution, Germany) was used.

The experiments were carried out at three different drying air temperatures of 40, 50 and 60°C at constant air flow rate of 1 m s^{-1}. For each experiment, 100 g of leaves was distributed uniformly inside the drying chamber with a thickness of 5±0.5 cm and the process was continued until reaching approximately 0.20 $g_{water}\ g^{-1}_{dry\ matter}$. Drying experiment of the leaves at each air temperature was replicated three times and the average values were calculated and used for further analyses.

Furthermore, drying rate (*DR*, $g_{water}\ g^{-1}_{dry\ matter}\ s^{-1}$) was calculated as follows (Beigi, 2016a):

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (2)$$

In Equation (2), M_t and M_{t+dt} are the moisture contents at t and $t+dt$, respectively, and t is the drying time (s).

Modelling of Drying Kinetics

Moisture transportation in the mint leaves was modelled using the Fick's second law and effects of the air temperature on the mass

Table 1. Some studies reported in the open literature on mint leaves drying.

Drying system and conditions	Main aim(s)	Researcher(s)
Cabinet dryer at air temperatures of 35, 45, 55 and 60°C, and air velocity of 4.1 m s^{-1}	1. Studying the effect of drying temperature on the process time. 2. Fitting the experimental data to thin layer models. 3. Calculating the effective diffusivity and activation energy.	Doymaz (2006)
Microwave dryer at output powers of 180, 360, 540, 720 and 900W, and samples amount of 25, 50, 75 and 100 g	1. Investigating the effect of microwave power and sample amount on the drying kinetic of the leaves. 2. Comparing the experimental data with the predicted valued by some thin layer models. 3. Calculating effective moisture diffusivity and activation energy.	Özbek and Dadali (2007)
Microwave vacuum dryer at power intensities of 8, 9.6 and 11.2 W g^{-1} and pressure: 13.11 kPa Hot air dryer at temperatures of 60 and 70°C	1. Determining the process time and moisture diffusivity of the leaves. 2. Investigating the effects of drying on the color and structure of the dried leaves.	Therdthai and Zhou (2009)
Solar, tray and freeze dryers	1. Determining the moisture sorption isotherms of the dried leaves. 2. Determining the monolayer moisture content and some thermodynamic function of the leaves.	Dalgiç *et al.* (2012)
Infrared dryer at temperatures of 60, 70 and 80°C	1. Assessing the effect of drying temperature on dehydration behavior of the leaves. 2. Investigating the color changes of the leaves. 3. Finding the best thin layer model to describe the drying curves.	Ertekin and Heybeli (2014)
Vibro-fluidized bed heat pump drying at temperatures of 40, 50 and 60°C	1. Investigating drying kinetics of the leaves. 2. Determining the moisture diffusivity of the leaves. 3. Analyzing color, total phenolic content and antioxidant activity of the dried leaves.	Ataei Ardestani *et al.* (2015)
Fixed, semi-fluidized and fluidized bed drying at temperature of 30, 40, 50 and 60°C	1. Selecting a proper mathematical model to represent the drying kinetics. 2. Determining the moisture diffusivity values of the leaves.	Motevali *et al.* (2016)

transfer parameters were characterized. Since the thickness of mint leaves (approximately 0.22 mm) is much smaller than other two dimensions, the leaves is considered as infinite slab and the governing equation can be expressed as:

$$\frac{\partial M(x,t)}{\partial t} = D_{eff} \frac{\partial^2 M(x,t)}{\partial x^2} \qquad (3)$$

In Equation (3), the effective Diffusivity (D_{eff}) embodies the overall moisture transfer process including, liquid and vapor diffusion, and all the other effective factors controlling drying behaviors (Tao *et al*., 2016). Supposing isotropic and homogenous material, uniform moisture and temperature distribution, constant diffusivity and insignificant shrinkage of the samples through the process, Equation (3) with the

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following initial and boundary conditions was numerically solved by the PDEPE function in Matlab, R2012a (MathWorks, Inc., Natick, MA).

Initial condition:

$$M(x,t)\big|_{t=0} = M_0 \qquad 0<x<L \tag{4}$$

Boundary conditions:

$$\frac{\partial M(x,t)}{\partial x}\Big|_{x=0} = 0 \tag{5}$$

$$-D_{eff}\,\rho_{dm}\,\frac{\partial M(x,t)}{\partial x}\Big|_{x=L} = h_m(M_s - M_\infty) \tag{6}$$

Where, h_m is the convective mass transfer coefficient (m s^{-1}) and L is the sample thickness (m). Also, M_s and M_∞ are moisture content (g_{water} $g^{-1}_{dry\ matter}$) of drying samples surface and surroundings, respectively.

Equations (5) and (6) indicate the symmetry moisture distribution in the leaves and the external mass transfer resistance, respectively. Minimizing the Root Mean Square Error (RMSE) between the experimental and predicted data, effective Diffusivity (D_{eff}) and surface mass transfer coefficient (h_m) were calculated (Tao *et al.*, 2016).

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(M_{pre,i} - M_{\exp,i}\right)^2\right]^{\frac{1}{2}} \tag{7}$$

After determination of D_{eff} and h_m, the goodness of fit was assessed based on coefficient of determination (R^2) and mean relative deviation modulus (E).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(M_{\exp,i} - M_{pre,i}\right)^2}{\sum_{i=1}^{n}\left(M_{\exp,i} - \overline{M}\right)^2} \tag{8}$$

$$E(\%) = \frac{\sum_{i=1}^{n}\frac{\left|M_{\exp,i} - M_{pre,i}\right|}{M_{\exp,i}}}{n}\times 100 \tag{9}$$

Where, $M_{exp,i}$ and $M_{pre,i}$ are the *i-th* experimental and predicted moisture content, respectively, $\overline{M}$ is the average of all experimental moisture contents, and n is the number of observation.

Furthermore, the activation energy was calculated by relating the obtained moisture diffusivities with drying temperature using an Arrhenius type equation as follows (Amiri Chayjan, 2012):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_{abs}}\right) \tag{10}$$

Where, D_0 is Arrhenius constant (m^2 s^{-1}), R is the universal gas constant (8.314×10^{-3} kJ mol^{-1} K^{-1}), T_{abs} is the absolute temperature (K), and E_a is the activation energy (kJ mol^{-1}).

Color Assessment

A color difference meter (Spectraflash 600-Datacolor) was used to investigate the color values of fresh and dried mint leaves based on the CIELab. L^* represents the brightness of lightness (ranges from 0 for black to 100 for white), a^* shows chromaticity on a green (-) to red (+) axis, and b^* specifies chromaticity on a blue (-) to yellow (+) axis. Measurements were taken for ten replications and the mean values were calculated. The total color differences (ΔE), Chroma (C), and Browning Index (BI) were determined as follows (Aral and Bese, 2016):

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \tag{11}$$

$$C = \sqrt{a^{*2} + b^{*2}} \tag{12}$$

$$BI = \frac{100\times(x-0.31)}{0.17} \tag{13}$$

$$x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \tag{14}$$

Chlorophyll and Carotenoids Estimation

Estimation of chlorophyll and total carotenoids (including β–Carotene and Xanthophhyl) of the fresh and dried mint leaves was carried using the procedure described by Lichtenthaler (1994). According to the procedure, the chopped samples (0.5-1 g) were filled in a 50 mL conical Erlenmeyer flask containing 20 mL

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of 80% acetone, which was sealed with a silicon stopper. After filtering the crude extracts through Whatman filter papers (Grade 40: 8 μm), absorptions at wave lengths of 663.2, 646.8 and 470 nm were determined using a spectrophotometer (Unico2100, A0509089 model) and contents of Chlorophyll *a* (Chl_a), Chlorophyll *b* (Chl_b), total Chlorophyll (Chl_t) and Carotenoids (C_{X+C}) were calculated as follows:

$$Chl_a = 12.25A_{663.2} - 2.79A_{646.8} \quad (15)$$

$$Chl_b = 21.50A_{646.8} - 5.10A_{663.2} \quad (16)$$

$$Chl_t = Chl_a + Chl_b \quad (17)$$

$$C_{X+C} = \frac{(1000A_{470} - 1.82Chl_a - 85.02Chl_b)}{198} \quad (18)$$

Rehydration

To determine the rehydration capacity of the mint leaves, five g of the dried leaves was weighed accurately and placed into a 250 mL beaker containing 150 mL distilled water (maintained at 80°C), agitated and allowed to rehydrate for 6 hours. Rehydration Capacity (RC) of the leaves was calculated (Aral and Bese, 2016):

$$RC = \frac{Weight\ of\ rehydrated\ sample\ (g)}{Weight\ of\ dried\ sample\ (g)} \quad (19)$$

RC=Rehydration capacity

Energy Analysis

The obtained data for Consumed Energy (CE) during the process was used and the Specific Energy Consumption (SEC) for the mint leaves was determined as follows (Torki-Harchegani *et al*., 2016a):

$$SEC = \frac{CE}{m_w} \quad (20)$$

In Equation (20), E is the consumed energy (kW h) and m_w is the mass of removed water (kg) from the leaves during the drying process and calculated by using the following equation:

$$m_w = \frac{W_0(M_i - M_f)}{1 - M_f} \quad (21)$$

Where, M_i and M_f is the initial and final moisture contents of drying samples ($g_{water}\ g^{-1}$dry matter), respectively

RESULTS AND DISCUSSION

Dehydration Behavior

Figure 1 represents the variations in moisture content ($g_{water}\ g^{-1}_{dry\ matter}$) of the mint leaves with the process time at the different applied air temperatures. The figure represents the variations in moisture content ($g_{water}\ g^{-1}_{dry\ matter}$) of the leaves with the process time at the different applied drying temperatures. As shown, drying temperature influenced drying duration of the leaves significantly ($P< 0.05$) and the required drying time at temperatures of 40, 50 and 60°C was found to be 100, 60 and 26 min, respectively. The observation was in agreement with the findings reported for hot air drying of biological products such as apple slices (Kaya *et al.,* 2007), green bell peppers (Doymaz and Ismail, 2010), oyster mushroom (Tulek, 2011) and pomegranate arils (Minaei *et al*., 2012). Higher drying temperatures increase the vapor pressure in the products leading to faster moisture removal from the inside of the drying sample to its surface. Furthermore, increasing temperature enhances heat transfer rate between the thermal source and the product that accelerates moisture evaporation from the product surface. These phenomena result in lower drying duration.

Variations of drying rate ($g_{water}\ g^{-1}_{dry\ matter}\ min^{-1}$) with the process time for the applied drying temperatures are shown in Figure 2. From the figure, at all applied drying temperatures, drying process of the mint leaves was in the falling rate entirely and constant drying rate was not seen. Falling rate drying shows that molecular diffusion controls the moisture removal from the product interior to the surface and Fick's

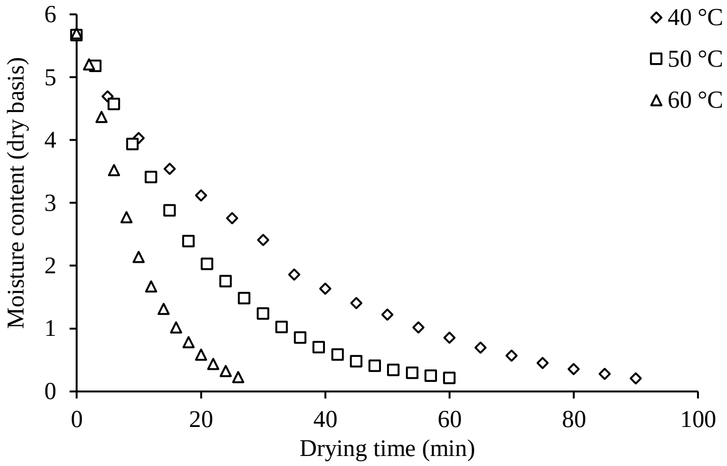

Figure 1. Variation in moisture content of the mint leaves with drying time at different drying air temperatures.

second law of diffusion can be effectively used to represent the moisture transfer phenomenon.

Modeling of Drying Curves

Diffusion model was used to simulate the experimental dehydration curves and explain the influence of drying temperature on the mass transfer parameters (D_{eff} and h_m) of the mint leaves. Table 2 presents the obtained results for the mathematical modeling. From the table, the moisture Diffusivity (D_{eff}) values for the mint leaves varied from 5.09×10^{-9} to 1.73×10^{-8} m^2 s^{-1} which generally is within the range of 10^{-11}-10^{-6} m^2 s^{-1} given for food products. Some researchers have determined moisture diffusivity for mint leaves under different drying treatments. Doymaz (2006) studied thin layer drying of mint leaves by conducting dehydration experiments at air temperatures of 35, 45, 55, and 60°C, and determined the parameter to be in the range of 3.07×10^{-9}-1.94×10^{-8} m^2 s^{-1}. Özbek and Dadali (2007) studied thin layer drying characteristics of

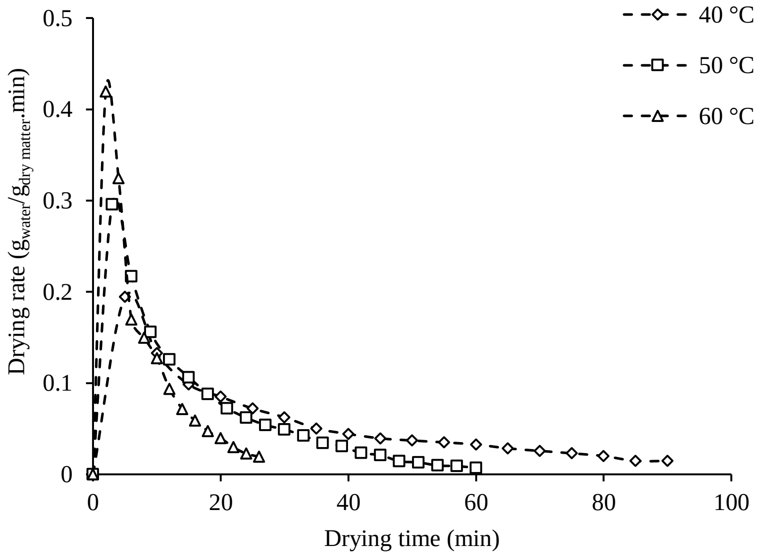

Figure 2. Variation in drying rate of the mint leaves with drying time at different drying air temperatures.

mint leaves undergoing microwave treatment at different output power levels (180-900W) and samples amounts (25-100 g), and reported that moisture diffusivity ranged from 3.98×10^{-11} to 2.07×10^{-10} m^2 s^{-1}. Therdthai and Zhou (2009) found moisture diffusivity of the leaves to be 4.70×10^{-11}, 7.26×10^{-11}, 9.78×10^{-11}, 0.96×10^{-11} and 1.19×10^{-11} m^2 s^{-1} for microwave vacuum drying at 8.0, 9.6, 11.2 W g^{-1}, and hot air drying at 60 and 70°C. Motevali *et al.* (2016) studied dried mint leaves using different drying conditions (fixed, semi-fluidized and fluidized bed) and four temperature levels of 30, 40, 50, and 60°C, and reported the effective moisture diffusivity of the leaves to be varied between 0.91 $\times10^{-11}$ and 10.41 $\times10^{-11}$ m^2 s^{-1}. Furthermore, the diffusivity values obtained for the mint leaves in this study are comparable with the reported values for hot air drying of different plant leaves such as peppermint (1.81-4.65×10^{-9} m^2 s^{-1}) (Torki-Harchegani *et al*., 2016a), olive (1.05-4.97×10^{-9} m^2 s^{-1}) (Erbay and Icier, 2010), wild edible plant (*Allium roseum*) (2.55-8.83×10^{-12} m^2 s^{-1}) (Haj Said *et al.,* 2015), and bertoni (4.67-14.9×10^{-9} m^2 s^{-1}) (Lemus-Mondaca *et al*., 2015).

Based on the obtained results (Table 2), the surface mass transfer coefficient (h_m) for the mint leaves was obtained to be 1.59×10^{-9}, 2.65×10^{-9} and 5.71×10^{-9} kg_{water} m^{-2} s^{-1} for drying air temperature of 40, 50, and 60°C, respectively. Cárcel *et al*. (2010) conducted experiments to investigate influences of ultrasonic power on the mass transfer parameters of olive leaves during convective drying and obtained the surface mass transfer coefficient values in the range of 3.55×10^{-8}-9.26×10^{-8} kg_{water} m^{-2} s^{-1}. Tao *et al.* (2016) studied the effect of ultrasound pre-treatment (25.2-117.6 kW m^{-3}) prior to hot air drying (at temperature of 60°C) on drying behavior of mulberry leaves and reported that the surface mass transfer coefficient values varried from 0.8910^{-4} 10^{-8} to 1.25 10^{-4} 10^{-8} kg_{water} m^{-2} s^{-1}.

Generally, the obtained values for R^2, *RMSE* and *E%* (Table 2) indicated that the applied diffusion model were well suited. Moreover, to evaluate the capability of the diffusion model, the experimental values for moisture content of the leaves were plotted *versus* the model estimated values and the results are presented in Figure 3. As shown, the values are generally banded close to the 45° straight line, representing good accuracy of the estimated values by the model.

The activation Energy (E_a) value was obtained to be 52.89 kJ mol^{-1}. The obtained activation energy was within the range reported for fruits and vegetables materials (12.7-110 kJ mol^{-1}) (Aral and Bese, 2016). The obtained activation energy in the present work is comparable with the values reported for mint leaves by Motevali *et al.* (2016) (60.82-65.59 kJ mol^{-1}), Ataei Ardestani *et al.* (2015) (54.34 and 84 kJ mol^{-1}), Park *et al.* (2002) (82.93 kJ mol^{-1}) and Doymaz (2006) (62.96 kJ mol^{-1}).

Color Parameters

The color parameters obtained for the fresh and dried mint leaves are shown in Table 3. As the results show, for all drying temperatures, the lightness was decreased (the leaves color became dark green) and the

Table 2. Determined effective moisture diffusivity and surface moisture transfer coefficient for the mint leaves with the goodness of fit of the model.

Drying temperature (°C)	Effective diffusion (m^2 s^{-1})	External mass transfer coefficient (kg_{water} m^{-2} s^{-1})	R^2	*RMSE*	*E* (%)
40	5.09×10^{-9}	1.59×10^{-5}	0.989	0.055	5.274
50	8.17×10^{-9}	2.65×10^{-5}	0.998	0.035	6.438
60	1.73×10^{-8}	5.71×10^{-5}	0.992	0.061	5.361

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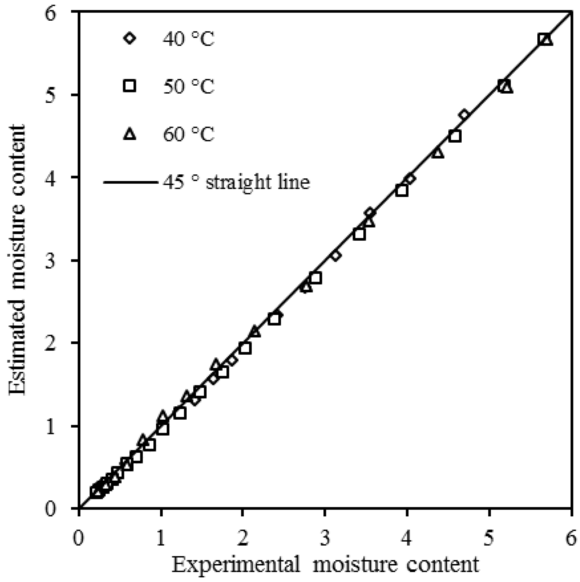

Figure 3. Comparison between the experimental and estimated moisture content values of the mint leaves at different drying air temperatures.

level was lower at higher drying temperatures. In fact, any increment in drying temperature caused darker mint leaves. Chlorophyll degradation is the possible reason for decrement in lightness value of the mint leaves. It is reported that drying at higher temperatures and long drying durations are the two main factors leading to decreased lightness of samples during dehydration process (Rudra *et al.*, 2008). Drying of the leaves at temperatures of 40, 50, and 60°C increased redness (a^*) about 1.61, 2.93 and 4.82, respectively. The mixture of chlorophyll, which is directly related to magnesium, is the main resource of leaves natural green color. Heating changes the magnesium molecules pyropheophytin and pheophytin and, therefore, drying at higher temperatures leads to lower greenness (Ali *et al*., 2014). Visually, due to chlorophyll degradation, dark green color of the mint leaves seemed as dull green-yellow. Furthermore, it is noticeable that, as well as the fresh leaves, all three different drying methods have negative *a** values, indicating retention of green color to some extent. Based on the obtained results (Table 3), the yellowness of the leaves decreased after drying and higher drying temperatures caused more reduction in the value. Therdthai and Zhou (2009) investigated drying effect on color of mint leaves and found the same results. The maximum and minimum total color change (ΔE) for dried leaves occurred at temperatures of 60 and 40°C, respectively, which indicated that exposing to higher temperatures caused more degradations in the leaves. Moreover, the values of Chroma (C) and Browning Index (BI) decreased in dried leaves in comparison with the fresh leaves. Also, increasing drying temperature

Table 3. Evaluation of color parameters for the fresh and dried mint leaves.

Drying temperature (°C)	L^*	a^*	b^*	ΔE	C	BI
40	42.83±0.91	-11.57±0.33	+24.55±0.64	2.74	27.14	56.24
50	41.42±0.17	-10.25±0.84	+23.38±1.09	4.99	25.34	55.75
60	39.15±0.62	-8.36±0.59	+21.29±0.73	8.73	22.67	54.83
Fresh	44.33±0.81	-13.18±0.61	+26.19±0.47	0	29.32	57.13

Table 4. Contents of total chlorophyll and carotenoids in the fresh and dried mint leaves.

Drying temperature (°C)	Total chlorophyll (mg g^{-1})	Carotenoids (mg g^{-1})
40	72.94±0.79	17.05±0.37
50	66.11±0.88	15.32±0.54
60	54.53±0.66	13.71±0.91
Fresh	85.13±1.05	19.43±0.65

decreased these parameters.

Chlorophyll and Carotenoids

Table 4 shows the values determined for chlorophyll and total carotenoids of the fresh and dried mint leaves at different drying temperatures. As shown, chlorophyll content of the fresh leaves was 85.13 mg g^{-1} and decreased significantly ($P< 0.01$) during drying process where dehydration at air temperatures of 40, 50, and 60 °C led to approximately 14, 22, and 36% loss of the value, respectively. Rudra *et al*. (2008) stated that magnesium in the chlorophyll could be replaced by hydrogen at high temperatures and, therefore, chlorophyll converted to pheophytins (Rudra *et al*., 2008). Better retention of chlorophyll content at lower drying temperatures has been reported by some researchers (Ahmed *et al*., 2001; Potisate and Phoungchandang, 2010). The influence of drying on carotenoids content of the mint leaves can be seen in Table 4, where it can be observed that dehydration caused significant destruction in carotenoids and increasing temperatures led to more reduction in the level. The observation agrees well with the results reported by Cui *et al*. (2004), and Goula and Adamopoulos (2010).

Rehydration Capacity

Generally, rehydration is a complex phenomenon affected by the process methods and conditions as well as product characteristics. Rehydration of dried products with cellular structures is more complex where drying treatments can affect the process due to changes in the physicochemical properties of the material during water removal. The rehydration capacity for the dried mint leaves at drying air temperatures of 40, 50, and 60°C were obtained to be 5.25, 5.42 and 5.64 $g_{water}\ g^{-1}_{dry\ matter}$, respectively. As shown, increasing drying temperatures resulted in higher rehydration capacity. The observation can be associated with the samples microstructure. Higher drying temperatures may cause more porous structure in the leaves leading to higher water penetration. This observation is in agreement with the results reported in the literature for quinces (Noshad *et al.,* 2012), for hawthorn (Aral and Bese, 2016) and for amaranth leaves (Mujaffar and Loy, 2017).

Specific Energy Consumption

The Specific Energy Consumption (SEC) values for dying of the mint leaves at temperatures of 40, 50, and 60°C were obtained as 23.45, 18.65 and 10.55 kW h kg^{-1}, respectively. It can be observed that increasing air temperature decreased the specific energy consumption. Researchers have found similar observations during drying of other products such as nettle leaves (Alibas, 2007), rough rice (Zare *et al.*, 2015), apple slices (Beigi, 2016b). Furthermore, the obtained specific energy consumptions in this study are comparable to the values reported in the literature. Aghbashlo *et al.* (2008) investigated energy consumption for berberis fruit at drying temperatures of 50-70°C and air velocities of 0.5-2 m s^{-1}, and determined that the specific energy consumption varied from

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20.94 to 1110.07 kW h kg^{-1}. Motevali *et al.* (2011) dried pomegranate arils using a convective dryer at temperature in the range of 45-70°C and air velocities of 0.5, 1, and 1.5 m s^{-1} and found the *SEC* values in the range of 50.78-252.33 kW h kg^{-1}.

CONCLUSIONS

Influence of drying air temperature on dehydration characteristics and quality indices of mint leaves were studied in a convective dryer. Moisture removal of the leaves entirely occurred in the falling rate period, and increasing air temperature shortened drying duration. The modeling results revealed that both effective moisture diffusivity and surface mass transfer coefficient were increased with any increment in drying temperature. Exposing to higher temperatures caused more degradation in color parameters of the leaves. Significant destructions occurred in chlorophyll and carotenoids contents and higher temperatures resulted in more reduction in the values. Higher drying air temperature led to more rehydration capacity of the leaves and less energy consumption of the process.

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خشک کردن برگ‌های نعناع: تأثیر دمای فرآیند بر پارامترهای آب‌زدایی، شاخص‌های کیفی و مصرف انرژی

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چکیده

در این پژوهش، به منظور بررسی تأثیر دما بر پارامترهای آب‌زدایی و ویژگی‌های فیزیکوشیمیایی برگ‌های نعناع، نمونه‌ها در دماهای هوای ۴۰، ۵۰ و 60درجه سلسیوس و سرعت هوای ثابت ۱ متر بر ثانیه خشکانده شدند. مصرف انرژی فرآیند نیز مطالعه شد. انتقال جرم در برگ‌ها در طی فرآیند با استفاده از قاون دوم فیک مدل شد. ضرایب انتشار رطوبت و انتقال جرم به ترتیب در محدوده‌های ۹-۱۰×۵/۰۹-۸-۱۰×۱/۷۳ متر مربع بر ثانیه و ۵-۱۰×۱/۵۹-۵-۱۰×۵/۷۱ کیلوگرم آب بر متر مربع ثانیه به دست آمدند. هر دو پارامتر انتقال جرم با افزایش دمای هوا افزایش یافتند. دماهای بالاتر منجر به تغییرات بیشتر در رنگ و تخریب بیشتر کلروفیل و کارتئونیدها شدند. بر خلاف ظرفیت بازجذب آب برگ‌های خشک شده، مصرف انرژی ویژه فرآیند با افزایش دمای هوای خشک کردن افزایش یافت.