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Effect of Infrared Drying on Drying Kinetics and Color Changes of Wild Sage Seed Mucilage

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Abstract

In this study, the effects of infrared (IR) dryer system parameters such as IR power, the distance of mucilage from lamp surface, mucilage thickness on drying kinetics and, color indexes (L*, a*, b* and ΔE) of wild sage seed mucilage (WSSM) were investigated in an IR dryer system. Experimental moisture ratio (MR) data were fitted to 7 various empirical thin-layer models. It was found that the Page model has the best fit to show the kinetic behavior and acceptably described the IR drying behavior of WSSM with the lowest mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), and standard error (SE) values and the highest correlation coefficient (r) value. The values of MSE, RMSE, and MAE for all experiments were in the range of 0.1×10^{-3}-1.1×10^{-3}, 1.04×10^{-2}-3.25×10^{-2} and 8.7×10^{-3}-27.1×10^{-3}, respectively. The average effective moisture diffusivity (D_{eff}) increased from 4.61×10^{-9} m^2s^{-1} to 15.8×10^{-9} m^2s^{-1} with increasing lamp power from 150 W to 375 W, while it was decreased from 14.4×10^{-9} m^2s^{-1} to 5.16×10^{-9} m^2s^{-1} and 13.2×10^{-9} m^2s^{-1} to 4.31×10^{-9} m^2s^{-1} with increasing the distance of mucilage from 4 to 12 cm and the reduction of mucilage thickness from 1.5 to 0.5 cm, respectively. Increasing in IR radiation power has a positive influence on the yellowness (increasing 19.78% in b^* index) of dried WSSM. Also, it increased the color changes index (ΔE) from 16.05 to 17.59.

Keywords: Color indexes, Effective moisture diffusivity, Gum, Moisture ratio, Page model

Introduction

Fruits and vegetables drying is a commonly used process for improving product safety as it greatly decreases the microbial activity and enzymatic changes during the storage period, hence, increasing the shelf life of the product. One of the best ways to reduce the drying time is to provide heat by infrared (IR) radiation. IR methods could be used as a substitution to the current drying methods for producing high-quality dried hydrocolloids. IR heating has many advantages including high heat transfer rate, uniform heating, short processing time, high efficiency (80-90%), lower energy consumption, lower energy costs, and improving final product quality (Salehi, 2020a). In addition, the use of IR dryers in combination with other dryers helped to decrease the drying time by rising the drying rate that leads to reduced energy utilization. Also, symmetrical temperature sharing by IR improved final product quality (Baeghbali *et al.*, 2019).

The dispersion of water-soluble hydrocolloids (gums) in the aqueous system provides great technical importance, since they can improve the gelling or thickening properties of food products (Zameni *et al.*, 2015). The genus *Salvia* (*Labiatae*) contains more than 700 species of mucilaginous

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(*- Corresponding Author Email: m.rasouli@basu.ac.ir) endemic plant. Wild sage (*Salvia macrosiphon* L.) is the mucilaginous native plant that is grown in different regions of Asia, Europe, and Middle East, especially in various regions of Iran and its seeds have a high content of mucilage (gums or hydrocolloids) with outstanding useful characteristics that is comparable with marketable food gums. Wild sage seeds are round small seeds, with a mucilage layer on their surface, which could swell in water, giving a viscous suspension. Wild sage seed mucilage (WSSM) is a gum extracted from the wild sage seed. Salehi and Kashaninejad (2015) reported that the apparent viscosity of WSSM solution (0.6% w/w), was varied from 0.162 to 0.344 Pa.s (60 s^{-1}), and freeze-dried WSSM exhibited the highest viscosity value among all dried gums. Also, the amounts of hardness, stickiness, consistency and adhesiveness of WSSM gel (3% w/w) were changed from 45.7 to 78.2 g, 9.8 to 17.0 g, 340.4 to 794.8 g.s, and 91.4 to 159.2 g.s at different drying conditions. In the bakery products gums have been used to improve dough performance, breads and cakes characteristics, textural and sensorial quality and extend the shelf life of the products (Salehi, 2019a). For example, the effect of the WSSM (at four levels of 0, 0.5, 1 and 1.5%, w/w) on physicochemical characteristics and sensorial properties of apple cake was studied by Salehi (2017). The authors reported that adding WSSM to apple cake batter reduced the density and improved its volume, lightness (L*), and sensorial parameters (appearance, crumb color lightness, porosity, flavor, texture, and overall acceptance).

The physicochemical properties and rheological behavior of dried seed gums depend on the method and condition of drying. Also, the color of the dried products is an important quality factor, which is affected by the drying conditions. For example, the effect of different drying methods (oven drying with temperature changes 40-80°C, freeze-drying and, vacuum oven-drying) on rheological behavior, color and physicochemical characteristics of basil seed mucilage was investigated by Salehi and Kashaninejad (2017). The color of oven-dried gum was darker (lower L* index values) in comparison to the freeze-dried or vacuum oven dried gums. In addition, the drying procedure can provide a broad range of molecular weight depending on the type and condition of drying. Nep and Conway (2011) reported that the grewia gum demonstrated the various degrees of viscosity varying from 0.2 to 0.32Pa.s depending on the drying method. However, there is no study available in the literature regarding the effect of IR drying techniques on the drying kinetics, D_{eff} and color changes of WSSM. Therefore, this study aimed to investigate the effect of IR drying on the drying kinetics, D_{eff} and color changes of WSSM.

Materials and Methods

Gum extraction

Wild sage seeds were purchased from a local market in Hamedan, Iran. They were physically cleaned and all foreign materials were removed. Then, the pure wild sage seeds were immersed in water for 20 min at a seed/water portion of 1:20 at 25°C. In the next step, the gum was separated from the inflated seeds by passing the seeds through an extractor (M-J-376-N, Nikko Electric Industry Company, Iran) with a rotating disc that scratched the mucilage layer on the seed surface. The initial moisture content (MC) of the WSSM was 99.4% (wet basis). The moisture content of WSSM was determined in an atmospheric oven at 105°C for 4 h (AOAC, method no. 934.06). Finally, the obtained WSSM was immediately placed into the IR dryer (Figure 1).

IR drying

The extracted WSSM was transferred in the cylindrical aluminum containers and then dried in an IR dryer (length 44 cm, width 20 cm, and height 40 cm). The effect of IR lamp (IR radiation lamp (NIR), Noor Lamp Company, Iran) power (at three levels 150, 250 and 375 W), the distance of sample from lamp (at three levels 4, 8, and 12 cm), mucilage thickness (at three levels 0.5, 1 and 1.5 cm) and time on the drying kinetics of WSSM was investigated (Amini *et al.*, 2021).

The weight changes of WSSM were measured using a LutronGM-300p digital balance (Taiwan, sensitivity of ±0.01 gr).

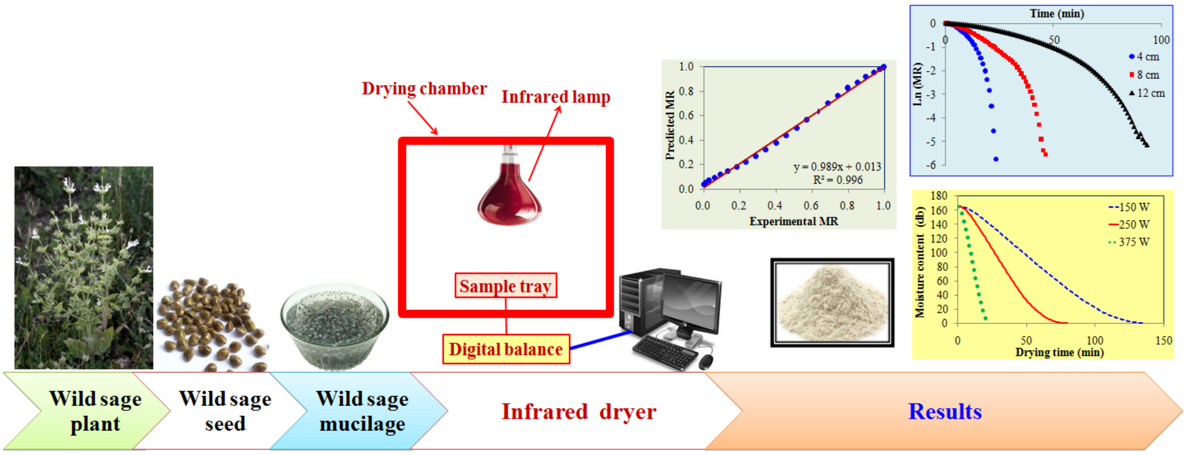

Fig.1. Schematic of Wild sage seed mucilage drying in an infrared dryer

Drying kinetics

Numerical modeling is one of the appropriate methods for describing the drying kinetics of food products (Salehi, 2020b). For numerical modeling the drying kinetic behavior of WSSM, 7 commonly used thin-layer models including Quadratic, Page, Newton, Midilli, Logarithmic, Verma, and Two terms were examined (Akpinar and Bicer, 2005; Doymaz, 2011). In these models, dimensionless MR were defined as equation (1):

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

Where M_t is MC of the sample (gr water/gr dry matter) at time t; M_e and M_0 are equilibrium and initial MC (gr water/gr dry matter), respectively. In equation (1), since $M_e << M_t$ and $M_e << M_0$, the value of M_e is negligible and the equation was simplified to M_t/M_0 (Arunsandeep and Chandramohan, 2018; Ceylan *et al.*, 2007; Doymaz, 2011).

Regression analysis was done using Curve Expert software (Version 1.34, Hyams, D. G., Microsoft Corporation) to evaluate equations parameters. Mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), standard error (SE), and correlation coefficient (r) values were calculated using equations 2 to 6 to evaluate the accuracy of models. It is noted that the highest r-value (closer to one) and the lowest MSE, RMSE, MAE, and SE values (closer to zero) represent the best model (good fitting).

$$MSE = \frac{\sum_{i=1}^{N} (O_i - T_i)^2}{N} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (O_i - T_i)^2}{N}} \tag{3}$$

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |O_i - T_i| \tag{4}$$

$$SE = \frac{\sigma}{\sqrt{N}} \tag{5}$$

$$r = \sqrt{1 - \frac{\sum_{i=1}^{N} [O_i - T_i]^2}{\sum_{i=1}^{N} [O_i - T_m]^2}} \tag{6}$$

Where O_i is the ith actual value, T_i is the ith predicted value, N is the number of data, σ is the standard deviation, and T_m is given by:

$$T_m = \frac{\sum_{i=1}^{N} O_i}{N} \tag{7}$$

Calculation of Moisture Diffusivity (D_{eff})

Drying of food products occurs in two periods of constant and falling rates and drying of them is controlled by internal diffusion phenomenon. Fick's second law of diffusion can be used to describe the thin layer drying of these products at the falling rate (Sacilik, 2007). According to this law, MR for different geometries including cylinder, slab and sphere is defined as equation 8:

$$\frac{\partial MR}{\partial t} = D_{eff} \nabla^2 MR \tag{8}$$

Analytical solution of this equation for infinite slab geometry and with assuming a constant moisture distribution, one-dimensional moisture, negligible shrinkage, and negligible external resistance used to predict moisture diffusion in samples. The dimensionless MC values were calculated with the equilibrium moisture content determined by dynamic equilibrium data of samples. It is given as equation (9):

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp(-(2n+1)^2 \frac{\pi^2 D_{eff} t}{4L^2}) \tag{9}$$

Where t is the drying time (s), D_{eff} is the effective moisture diffusivity (m^2s^{-1}); L is half-thickness of WSSM samples which are equal to 0.25×10^{-2}, 0.5×10^{-2}, and 0.75×10^{-2} m in this study.

For long drying process period, Eq. (10) can be further simplified to:

$$MR = \frac{8}{\pi^2} \exp\left[\frac{-\pi^2 D_{eff} t}{4L^2}\right] \tag{10}$$

Hence, a logarithmic form was introduced as follows:

$$LnMR = Ln(\frac{8}{\pi^2}) - \frac{\pi^2 D_{eff} t}{4L^2} \tag{11}$$

The D_{eff} was calculated through Eq. (11) by using the method of slopes. From Eq. 12, a plot of experimental drying data in terms of lnMR versus time gives a straight line with a slope (K) of:

$$Slope(K) = -\frac{\pi^2 D_{eff}}{4L^2} \tag{12}$$

Color measurement

WSSM chromaticity was measured before and after drying in CIE lab system using the digital imaging method cited in the literature. CIE lab color parameters of L*, a* and b* represent darkness-lightness (0-100), color of greenness (-a*) to redness (+a*), and color of blueness (-b*) to yellowness (+b*), respectively (Salehi, 2019b). Therefore, the fresh and dried WSSM of each experiment were placed on the scanner surface and samples photos (RGB signals) were obtained (Hp Scanjet 300). Then, the taken photos from dried WSSM were loaded to a computer, and L*, a* and, b* indexes values were measured via ImageJ (1.42e, USA) software.

Another color parameter that was calculated is color changes index (ΔE) which was calculated by total color difference as follow:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{13}$$

Where ΔL is L_2-L_1, Δa is a_2-a_1 and Δb is b_2-b_1.

Statistical analysis

The experimental data were subjected to an analysis of variance (ANOVA) for a completely random design using a statistical analysis system (SAS 9.1, 2003, Institute, Inc.). Significant difference between data means was determined using Duncan's multiple range test at P-value<0.05 and it was performed to establish the impact of IR radiation power (150, 250, and 375 W), the distance of the sample from lamp (4, 8 and, 12 cm), mucilage thickness (0.5, 1 and 1.5 cm) on drying time of WSSM (P-value<0.05). All measurements were conducted in triplicate.

Results and Discussion

Drying time

Statistical analysis of experimental results (data) demonstrated that the IR power, samples distance and mucilage thickness have a significant effect on the evolution of drying time of WSSM (p<0.01) (Table 1). In conclusion, experimental results showed that the infrared power, mucilage distance, mucilage thickness, infrared power × mucilage distance, infrared power × thickness, and mucilage distance × mucilage thickness, have significant effects on the drying time of WSSM. The interaction effects of IR lamp power, and mucilage distance, IR lamp power, and mucilage thickness, and mucilage distance and mucilage thickness on the drying time of WSSM are shown in Figure 2.

Table 1- Results of analysis of variance for drying time parameters of wild sage seed mucilage drying

Sources of changes	Degrees of freedom	Sum of squares	Mean square	P
Power	2	174988	87494	0.000
Distance	2	109956	54978	0.000
Thickness	2	189562	94781	0.000
Power × Distance	4	6611	1653	0.006
Power × Thickness	4	24752	6188	0.000
Distance × Thickness	4	24980	6245	0.000
Power × Distance × Thickness	8	3031	379	0.490
Error	54	21698	402	
Total	80			

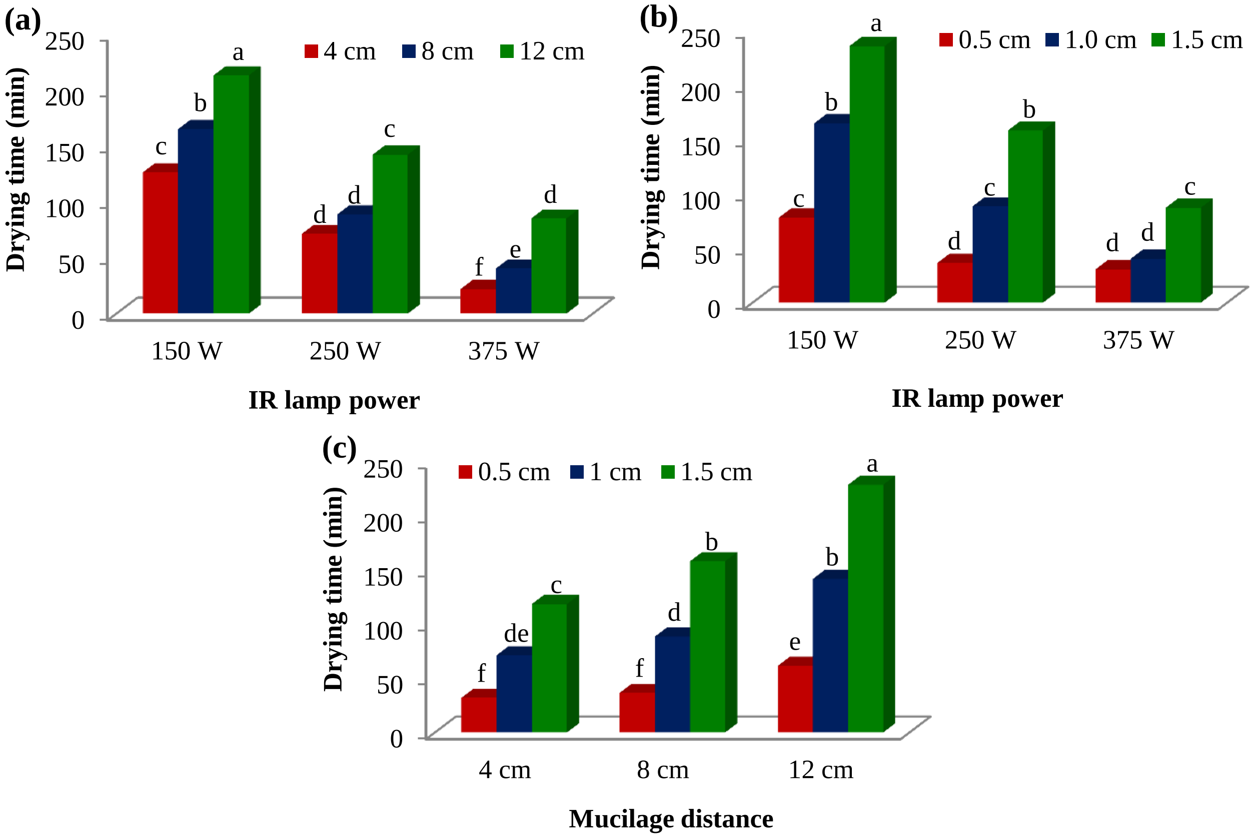

Fig.2. The interaction effects of IR lamp power and mucilage distance (a), IR lamp power and mucilage thickness (b), and mucilage distance and mucilage thickness (c) on the drying time of wild sage seed mucilage. Means with different superscripts differ significantly (P<0.05).

As expected, drying time was decreased by increasing the power because of increased temperature and heat transfer gradient between air and samples. The average drying times of WSSM were 172.04, 104.26, and 58.93 min at 150, 250 and 375 W, respectively. In addition, the drying time of WSSM was increased by increasing the distance of mucilage from the lamp surface and mucilage thickness. The average drying time reduced from 160.81 min to 72.03 min and from 173.67 min to 55.59 min when the mucilage distance and mucilage thickness were decreased from 12 to 4 cm, and from 1.5 to 0.5 cm, respectively.

The effects of IR power, samples distance and mucilage thickness on the MC of WSSM are shown in Figure 3. MC of WSSM was decreased with increasing the power because of the increasing temperature and heat transfer gradient between the air and samples. With increasing IR intensity, due to the increase in mucilage temperature and increasing evaporation rate and the decrease in drying time, the specific energy for drying of WSSM decreases.

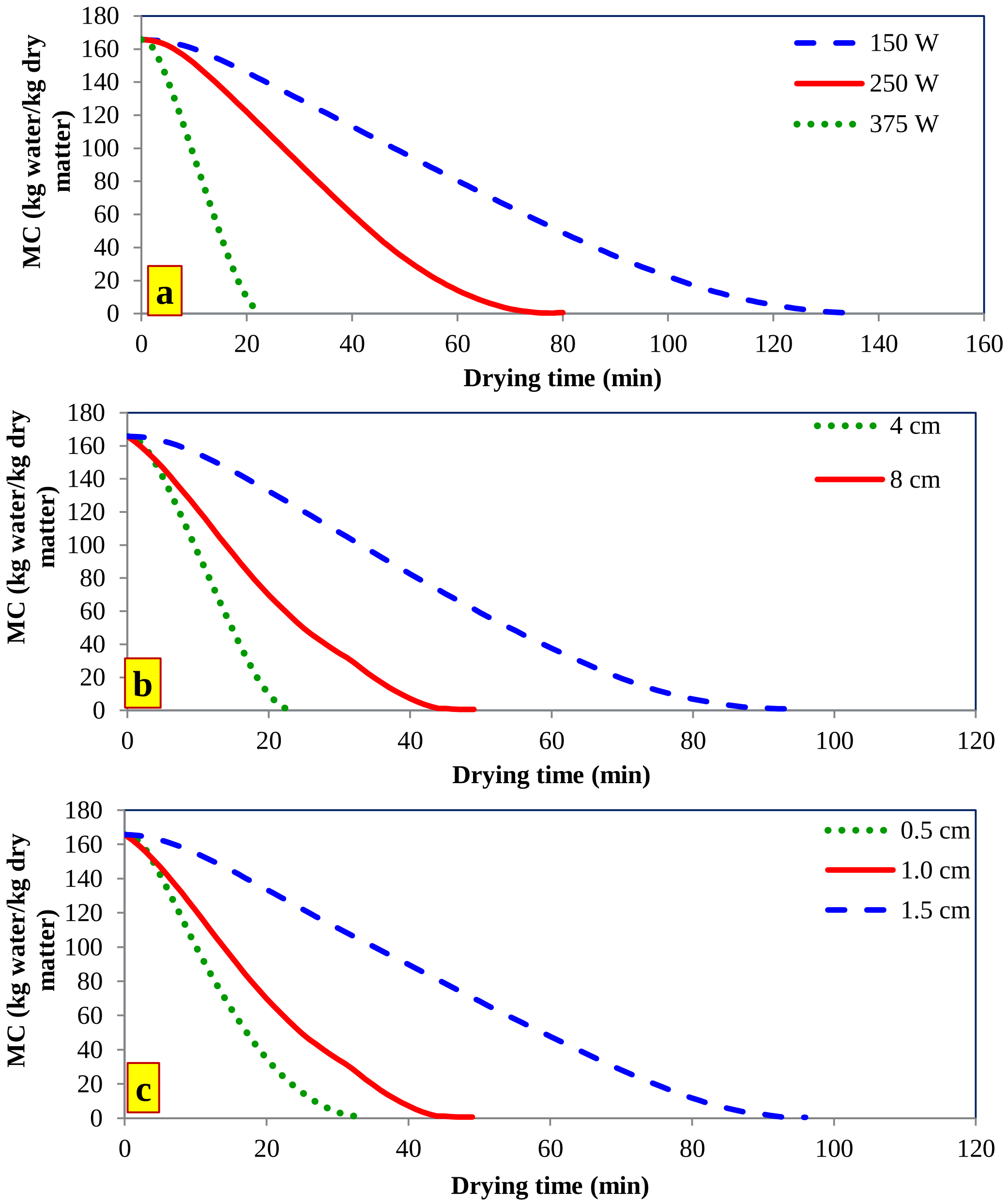

Fig.3. Variations of moisture content (MC) with drying time of wild sage seed mucilage at different: a) IR power (4 cm distance and 1.0 cm thickness); b) Sample distance (375W and 1.0 cm thickness); c) Sample thickness (375W and 8 cm distance).

Fitting of the Drying Curves

To estimate the drying kinetics of food products, numerous empirical models have been used by researchers. In this study, 7 thin-layer equations were selected and fitted to experimental data to choose the best and most suitable equation. The model with the highest r value and the lowest MSE, RMSE, MAE, and SE values was selected as the best suitable model describing the IR drying processes of WSSM. The model that satisfied these features was the Page model (Eq. 14):

$$MR= exp\ (-kt^{n}) \quad (14)$$

Where MR and t are moisture ratio and drying time, respectively. The estimated parameters (fitting data) of the Page model including drying constants, k, and n, are tabulated in Table 2 along with corresponding statistical data (MSE, RMSE, MAE, SE and r) for all experiments conditions. The values of MSE, RMSE and MAE for all experiments were in the ranges of 0.1×10^{-3}-1.1×10^{-3}, 1.04×10^{-2}-3.25×10^{-2} and 8.7×10^{-3}-27.1×10^{-3}, respectively. Also, the values of r and SE for all experiments were in the ranges of 0.995-0.999 and 0.010-0.031, respectively.

Figure 4 shows the comparison of fitted MR data by Page model with experimental results (375 W, 4 cm distance, and 1.0 cm thickness). These results indicate that Page model is appropriate in describing the drying characteristics of WSSM under the various IR drying conditions.

Table 2- Model constants of Page model for all experiments

Power (W)	Distance (cm)	Thickness (cm)	k	n	MSE	RMSE	MAE	SE	r
150	4	0.5	0.00097	1.918	0.00074	0.0272	0.0234	0.027	0.996
150	4	1.0	0.00047	1.805	0.00044	0.0210	0.0177	0.021	0.997
150	4	1.5	0.00031	1.784	0.00039	0.0197	0.0159	0.019	0.998
150	8	0.5	0.00099	1.829	0.00055	0.0235	0.0206	0.023	0.997
150	8	1.0	0.00031	1.765	0.00094	0.0307	0.0250	0.029	0.995
150	8	1.5	0.00025	1.702	0.00059	0.0243	0.0207	0.024	0.997
150	12	0.5	0.00048	1.788	0.00051	0.0226	0.0198	0.022	0.997
150	12	1.0	0.00028	1.701	0.00106	0.0325	0.0271	0.031	0.995
150	12	1.5	0.00024	1.592	0.00057	0.0239	0.0214	0.023	0.997
250	4	0.5	0.00446	1.898	0.00026	0.0162	0.0143	0.016	0.998
250	4	1.0	0.00099	1.890	0.00027	0.0165	0.0140	0.015	0.998
250	4	1.5	0.00068	1.727	0.00057	0.0239	0.0189	0.021	0.998
250	8	0.5	0.00286	1.937	0.00047	0.0217	0.0191	0.023	0.998
250	8	1.0	0.00052	1.922	0.00054	0.0233	0.0199	0.023	0.997
250	8	1.5	0.00068	1.641	0.00040	0.0201	0.0148	0.017	0.998
250	12	0.5	0.00185	1.782	0.00050	0.0224	0.0199	0.022	0.997
250	12	1.0	0.00042	1.798	0.00045	0.0211	0.0187	0.020	0.998
250	12	1.5	0.00038	1.644	0.00025	0.0158	0.0109	0.013	0.999
375	4	0.5	0.01189	2.109	0.00018	0.0134	0.0105	0.015	0.999
375	4	1.0	0.00479	2.073	0.00043	0.0208	0.0172	0.022	0.998
375	4	1.5	0.00185	2.051	0.00061	0.0247	0.0205	0.025	0.997
375	8	0.5	0.00932	1.718	0.00011	0.0104	0.0087	0.010	0.999
375	8	1.0	0.00836	1.555	0.00038	0.0195	0.0158	0.018	0.998
375	8	1.5	0.00081	1.809	0.00070	0.0264	0.0226	0.025	0.996
375	12	0.5	0.00247	1.799	0.00024	0.0156	0.0140	0.015	0.999
375	12	1.0	0.00073	1.872	0.00034	0.0186	0.0163	0.018	0.998
375	12	1.5	0.00059	1.662	0.00035	0.0187	0.0138	0.015	0.999

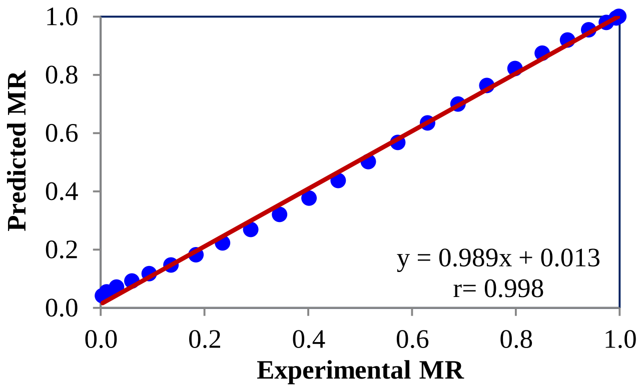

Fig.4. Comparison of fitted data by Page model with experimental results (375 W, 4 cm distance and 1.0 cm thickness).

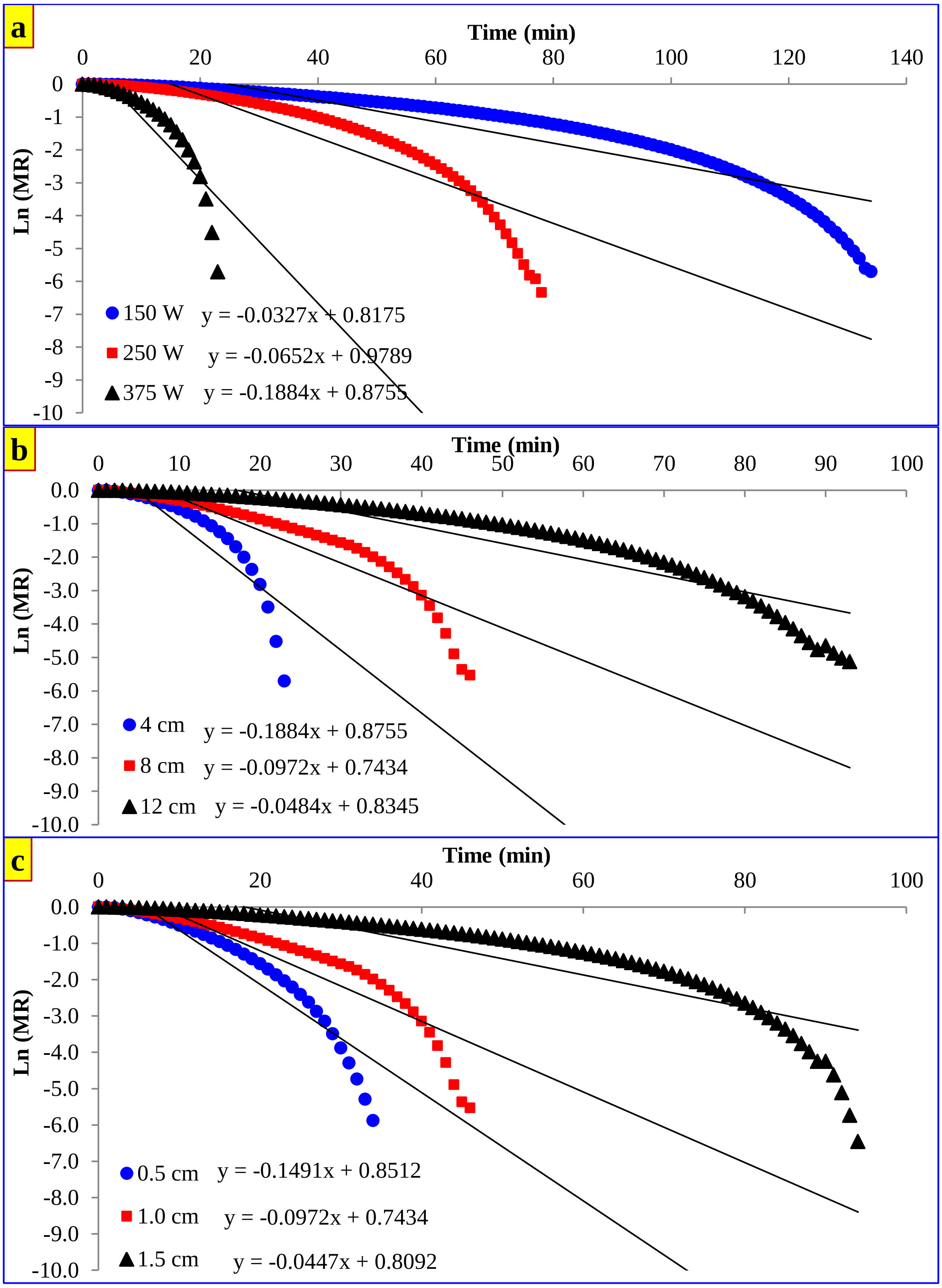

Fig.5. Variations of the Ln (MR) with drying time of wild sage seed mucilage at different: a) IR power (4 cm distance and 1.0 cm thickness); b) Sample distance (375W and 1.0 cm thickness); c) Sample thickness (375W and 8 cm distance).

Moisture Diffusivity

The effect of IR drying systems on the D_{eff} of some fruits and vegetables was studied by Salehi (2020a). The D_{eff} values lie within in range of 10^{-8} to 10^{-10} m^2s^{-1} for fruits and vegetables. The D_{eff} values are determined by plotting experimental drying data in terms of lnMR versus time. The effects of IR radiation power, samples distance, and mucilage thickness on the lnMR are shown in Figure 5.

The values of D_{eff} at different conditions drying of WSSM obtained by using Eq. (19) and estimated values are shown in Table 3. The D_{eff} values of WSSM were ranged from 1.31×10^{-9} and 41.5×10^{-9} m^2s^{-1}. D_{eff} values increased with increasing IR radiation power because of the rapid movement of water at high temperatures (Doymaz, 2011).

Table 3- Effective moisture diffusivity values (D_{eff}) of wild sage seed mucilage at different IR drying conditions

Power (W)	Distance (cm)	Thickness (cm)	Effective diffusivity (m^2s^{-1})	r
150	4	0.5	2.57×10^{-9}	0.902
150	4	1.0	5.56×10^{-9}	0.909
150	4	1.5	9.5×10^{-9}	0.911
150	8	0.5	2.32×10^{-9}	0.923
150	8	1.0	4.52×10^{-9}	0.899
150	8	1.5	6.86×10^{-9}	0.900
150	12	0.5	1.31×10^{-9}	0.937
150	12	1.0	4.06×10^{-9}	0.882
150	12	1.5	4.82×10^{-9}	0.944
250	4	0.5	5.49×10^{-9}	0.951
250	4	1.0	1.09×10^{-8}	0.909
250	4	1.5	1.35×10^{-8}	0.866
250	8	0.5	5.52×10^{-9}	0.917
250	8	1.0	8.59×10^{-9}	0.882
250	8	1.5	9.83×10^{-9}	0.878
250	12	0.5	2.62×10^{-9}	0.925
250	12	1.0	5.81×10^{-9}	0.913
250	12	1.5	6.58×10^{-9}	0.917
375	4	0.5	9.32×10^{-9}	0.931
375	4	1.0	3.14×10^{-8}	0.877
375	4	1.5	4.15×10^{-8}	0.880
375	8	0.5	6.21×10^{-9}	0.937
375	8	1.0	1.59×10^{-8}	0.920
375	8	1.5	1.66×10^{-8}	0.889
375	12	0.5	3.4×10^{-9}	0.942
375	12	1.0	8.07×10^{-9}	0.924
375	12	1.5	9.74×10^{-9}	0.913

The average D_{eff} values increased with increasing mucilage thickness and they were equal to 4.31×10^{-9}, 10.5×10^{-9} and 13.2×10^{-9} m^2s^{-1} for 0.5, 1.0 and 1.5 cm thickness of mucilage, respectively. In addition, the average D_{eff} values decreased from 14.4×10^{-9} to 5.16×10^{-9} m^2s^{-1} with increasing distance of mucilage from 4 to 12 cm.

The values of D_{eff} are comparable with the reported values of 1.00×10^{-8} to 3.72×10^{-8} m^2s^{-1} for dried quince in the IR system (Mehrnia *et al.*, 2017) and 0.87×10^{-9} to 2.64×10^{-9} m^2s^{-1} for dried pomegranate arils in the IR system (Briki *et al.*, 2019). These values are consistent with the present estimated D_{eff} values for WSSM. The results of such fitting gave an average regression coefficient of 0.91 indicating that the quality of such fitting was satisfactory.

Color measurement

The quality attributes of WSSM during IR drying at various conditions as measured by the changes in color parameters of L*, a*, b* and, ΔE are shown in Table 4. The fresh WSSM exhibited a light color, with L_1*, a_1*

and, b_1* equal to 87.69, -0.11 and, -0.90, respectively. The IR radiation power was found to have a significant effect on the color of WSSM. The rise in power has a negative effect on the ΔE and with increasing in IR radiation power from 150 to 375 W, it was increased from 16.05 to 17.59. As shown in Table 4, the L^* values varied from 85.82 to 87.01 at various drying conditions. The rise in power has a positive effect on the b^* index and with increasing in IR power from 150 to 375 W, it was increased from 13.65 to 16.35. Onwude *et al.* (2018) reported similar changes in the color values of sweet potatoes undergoing IR drying.

Table 4- Color parameters results of IR dried wild sage seed mucilage.

Power (W)	Distance (cm)	Thickness (cm)	L^*	a^*	b^*	ΔE
150	4	0.5	96.67±0.69	-1.28±0.14	7.33±0.66	12.24
150	4	1.0	83.13±0.86	1.38±0.16	19.63±0.91	21.08
150	4	1.5	80.25±0.75	1.68±0.08	18.70±0.27	21.04
150	8	0.5	94.98±0.31	-0.47±0.06	4.71±0.52	9.20
150	8	1.0	85.67±0.33	1.24±0.10	12.98±0.33	14.09
150	8	1.5	80.63±0.26	1.78±0.10	16.90±0.19	19.24
150	12	0.5	92.98±0.79	-0.34±0.13	9.75±0.13	11.89
150	12	1.0	87.88±0.22	0.14±0.06	9.81±0.64	10.72
150	12	1.5	80.93±0.14	1.58±0.16	23.03±0.59	24.92
250	4	0.5	89.82±1.34	-0.60±0.16	15.69±2.11	16.73
250	4	1.0	85.92±0.89	0.61±0.13	18.63±1.38	19.62
250	4	1.5	81.25±0.37	1.29±0.11	23.68±0.25	25.45
250	8	0.5	95.88±0.28	-0.70±0.06	6.00±0.69	10.72
250	8	1.0	86.02±0.70	0.41±0.08	15.70±0.44	16.69
250	8	1.5	82.20±0.30	1.69±0.04	18.84±0.35	20.57
250	12	0.5	94.47±0.19	-0.49±0.06	9.16±0.72	12.14
250	12	1.0	85.57±0.17	1.24±0.07	14.86±0.03	15.96
250	12	1.5	82.53±0.35	1.88±0.03	17.55±0.49	19.26
375	4	0.5	80.45±1.36	3.37±0.39	21.04±0.89	23.36
375	4	1.0	83.87±0.54	1.37±0.14	23.30±0.52	24.54
375	4	1.5	87.26±0.89	0.76±0.25	24.95±0.97	25.86
375	8	0.5	86.26±1.52	-0.12±0.12	10.47±0.21	11.46
375	8	1.0	86.77±1.97	-0.19±0.25	13.12±0.32	14.05
375	8	1.5	88.81±1.44	0.34±0.15	11.69±0.55	12.65
375	12	0.5	90.21±0.44	-0.21±0.09	7.21±0.39	8.50
375	12	1.0	84.89±0.85	0.41±0.05	18.34±0.22	19.45
375	12	1.5	83.85±1.00	2.07±0.18	16.99±0.41	18.42

L^* (darkness/lightness, 0 to 100), a^*(greenness/redness, -120 to 120) and b^* (blueness/yellowness, -120 to 120).

Conclusion

The IR lamp power, the distance of mucilage from lamp and, mucilage thickness influenced the drying time of WSSM. The average drying time of WSSM samples was 172.04, 104.26 and 58.93 min at 150, 250 and, 375 W, respectively. The drying characteristics were satisfactorily described by the Page model with the highest r value (greater than 0.99) and the lowest MSE, RMSE, MAE and SE values (a good fit). Values for the D_{eff} of WSSM samples were obtained in the range of 1.31×10^{-9} and, 41.5×10^{-9} m^2s^{-1} and, they were increased with increasing lamp power while decreased with increasing distance of mucilage from lamp and mucilage thickness. Color parameters were estimated in terms of L*, a* and, b* indexes and total color difference (ΔE) measurements. The increases in IR radiation power have a negative influence on ΔE and with rising in IR power from 150 to 375 W, it was increased from 16.05 to 17.59.

Conflict of Interests: Authors declare that there no conflict of interest exists.

List of symbols

ΔE	Color changes index
D_0	Pre-exponential factor (m^2s^{-1})
D_{eff}	Effective moisture diffusivity (m^2s^{-1})
k	Drying rate constants in models (s^{-1})
K	Slope

L	Half slab thickness of the samples (m)
M_0	Initial MC (kg water/kg dry matter)
Me	Equilibrium MC (kg water/kg dry matter)
M_t	MC at time t (kg water/kg dry matter)
MR	Moisture ratio
n	Number of constants
N	Number of observations
r	Correlation coefficient
t	Drying time (min)

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مقاله پژوهشی

جلد ۱۲، شماره ۱، بهار ۱۴۰۱، ص ۷۹-۶۷

تأثیر خشک‌کردن فروسرخ بر سینتیک خشک شدن و تغییرات رنگ موسیلاژ دانه مرو

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چکیده

در این مطالعه، تأثیر پارامترهای سیستم خشک‌کن فروسرخ شامل توان فروسرخ، فاصله موسیلاژ از سطح لامپ، ضخامت موسیلاژ بر روی سینتیک خشک شدن و شاخص‌های رنگ (L*، a*، b* و ΔE) موسیلاژ دانه مرو در سیستم خشک‌کن فروسرخ بررسی شد. داده‌های آزمایشگاهی نسبت رطوبت با ۷ مدل تجربی لایه‌نازک مختلف برازش داده شد. مشخص شد که مدل پیج بهترین تناسب را برای نشان دادن رفتار سینتیکی دارد و به‌طور قابل قبولی رفتار خشک‌کردن فروسرخ موسیلاژ دانه مرو را با کمترین مقادیر میانگین خطای مربع (MSE)، جذر میانگین مربعات خطا (RMSE)، میانگین خطای مطلق (MAE) و خطای استاندارد (SE) و بیشترین مقدار ضریب همبستگی (r). مقادیر MSE، RMSE و MAE برای همه آزمایش‌ها به‌ترتیب در محدوده ۰/۰۰۰۱-۰/۰۰۱۱، ۰/۰۱۰۴-۰/۰۳۲۵ و ۰/۰۰۸۷-۰/۰۲۷۱ بود. متوسط نفوذ مؤثر رطوبت (D_{eff}) با افزایش توان لامپ از ۱۵۰ به ۳۷۵ وات از $۴/۶۱\times۱۰^{-۹}$ به $۱۵/۸\times۱۰^{-۹}$ مترمربع بر ثانیه افزایش یافت، اما با افزایش فاصله موسیلاژ از ۴ به ۱۲ سانتی‌متر و کاهش ضخامت موسیلاژ از ۱/۵ به ۰/۵ سانتی‌متر، این ضریب به‌ترتیب از $۱۴/۴\times۱۰^{-۹}$ به $۵/۱۶\times۱۰^{-۹}$ مترمربع بر ثانیه و از $۱۳/۲\times۱۰^{-۹}$ به $۴/۳۱\times۱۰^{-۹}$ مترمربع بر ثانیه کاهش یافت. افزایش توان تابش فروسرخ تأثیر مثبتی بر شاخص زردی (افزایش ۱۹/۷۸ درصدی در شاخص b*) موسیلاژ دانه مرو خشک‌شده داشت. همچنین، شاخص تغییرات رنگ (ΔE) را از ۱۶/۰۵ به ۱۷/۵۹ افزایش داد.

واژه‌های کلیدی: شاخص‌های رنگی، صمغ، مدل پیج، نسبت رطوبت، نفوذ مؤثر رطوبت

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