Research note

Determination of a suitable thin layer drying curve model for saffron (Crocus sativus L) stigmas in an infrared dryer

E. Akhondi, A. Kazemi, V. Maghsoodi *

Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, P.O. Box 11155-9465, Iran

Received 25 August 2010; revised 30 January 2011; accepted 24 April 2011

KEYWORDS
Saffron; Crocus sativus L; Infrared dryer; Thin layer.

Abstract The drying of saffron stigma was investigated in a laboratory infrared dryer. The effect of temperature on the drying rate of samples at various temperatures (60, 70 . . . 110 °C) was studied. The drying time decreased with an increase in drying air temperature. The constant-rate period is absent from the drying curve. The drying of saffron occurred in the falling rate period. Four, thin-layer drying models, namely, Lewis, Handerson and Pabis, Page, and Midilli and Kucuk, were fitted to drying data. The performance of these models was investigated by comparing the determination of coefficient (R²) and Root Mean Square Error (RMSE) between the observed and predicted moisture ratios. Among these models, in each of six drying temperatures, the Midilli and Kucuk model gave the best results and showed good agreement with the experimental data obtained from the experiments, including the thin layer drying process. In all drying temperatures, the amounts of R² were higher than 0.999, and the amounts of RMSE were less than 0.012. According to results, it can be said that the Midilli and Kucuk model adequately described the drying behavior of saffron stigmas at a controlled temperature range 60–110 °C in an infrared dryer.

© 2012 Sharif University of Technology. Production and hosting by Elsevier B.V. All rights reserved.

1. Introduction

Saffron is the dried stigmas of flowers scientifically identified as “Crocus sativus L”. It is the world's most expensive spice and, apart from its traditional value as a food additive, recent studies have indicated its potential as an anti-cancer agent [1,2].

A dehydration postharvesting treatment is necessary to convert Crocus sativus L stigmas into saffron spice. During the dehydration process, the stigmas lose about 80% of their weight. Drying brings about the physical, chemical and biochemical changes necessary to achieve the desired attributes of saffron. This process also plays an important role in preserving the spice. Lower moisture content, at least below the 12% value established by the International Standard ISO 3632, maintains the quality of the product for a longer time [3].

The drying of moist materials is a complicated process involving, simultaneously, coupled heat and mass transfer phenomena, which occur inside the material being dried. Thin layer drying means to dry as one layer of sample particles or slices [4].

For the past 60 years, the study of the drying behavior of different materials has been a subject of interest for various investigators on both theoretical and applicative grounds. Many studies, including drying processes, have been presented in the literature [5–9]. The most important aspect of drying technology is the mathematical modeling of drying processes and equipment. Its purpose is to allow design engineers to choose the most suitable operating conditions and then to size the drying equipment and drying chamber accordingly to meet desired operating conditions. The principle of modeling is based on having a set of mathematical equations that can adequately characterize the system. In particular, the solution of these equations must allow prediction of the process parameters as a function of time at any point in the dryer based only on initial conditions [10].

The main objective of this study is to determine and test the most appropriate thin layer drying model from between four thin-layer drying models, namely, Lewis [11,7], Handerson and Pabis [12], Page [13] and Midilli and Kucuk [14] for
understanding the drying behavior of saffron stigmas in an infrared dryer.

2. Materials and methods

2.1. Materials

Full-bloomed Crocus sativus L. flowers were handpicked from three different farms around Torbat Heydariya (Khorasan Province, Iran) at three different harvest dates of November 13, 18 and 22 in 2005. The flowers were transported and kept in cool conditions (4 °C) before treatment. Stigmas for the experiments were separated by hand from the flowers at 24 °C indoors. The initial moisture content of the stigmas was 426\% (d.b.).

2.2. Saffron dehydration process

The drying process was carried out with infrared waves, using a Shimadzu Electronic Moisture Balancer Model LIBBROREB-340MOC (Figure 1). The specifications of the Shimadzu Electronic Moisture Balancer Model LIBBROREB-340MOC are: Uniform heating with precise temperature control brings accurate result quickly. Ceramic Heater Far infrared radiation is applied onto the surface of the sample to heat it evenly. The ceramic plate heater is practically free from the failure of the element. Accurate Temperature Control the PID controller of the heater temperature ensures accurate measurement. Dry-end Point Detection microcomputer automatically detects the absolute drying point by finding the loss equilibrium point. Completion of the measurement is signaled by a buzzer. The water content ratio is automatically displayed. Results can be printed automatically using an optional printer. Time Course Measurement with an optional electronic printer EP-50 provides the water content ratio during measurement by continuous recording (Figure 2).

Five grams of the sample (fresh stigmas) were placed in the instrument pan in each experiment, and drying temperatures were fixed at 60, 70, . . . , 110 °C to investigate the effects of drying temperature on drying rate. The tray load was the same in all experiments and stigmas were distributed uniformly in a thin layer with about 0.7 mm height. Moisture loss was recorded at 2 min intervals during drying for determination of drying curves by the instrument. All experiments were repeated three times and then mean values were used.

2.3. Mathematical modeling

Four thin layer drying models (Table 1) were investigated to find the most suitable. Sun drying conditions were assumed in these models, therefore, the Moisture Ratio (MR) was simplified to \( \frac{M}{M_0} \) instead of \( \frac{M(t) - M_e}{M_0 - M_e} \), as the value of \( M_e \) is relatively small compared to \( M \) or \( M_0 \). The Page model expressed as:

\[
MR = \exp(-kt^b)
\]

was applied to air-drying data of high sugar containing products such as plums, figs, grapes and currants, and a linear relationship was found to fit the experimental results. The Exponential model is expressed as:

\[
MR = a \exp(-ct)
\]

is the first term of a general series solution of Fick’s second law. In this model, the moisture ratio (MR) may be taken instead of MR = \( \frac{M(t) - M_e}{M_0 - M_e} \) for mathematical modeling of the sun drying curves, because of the continuous fluctuation of the relative humidity of the drying air during the sun drying process [15].

Regression analysis was performed using MATLAB computer software. Correlation coefficient \( R^2 \) was one of the primary criteria to select the best model.

Another statistical parameter, i.e. Root Mean Square Error (RMSE), was used to determine the quality of the fit. These parameters can be calculated as given below:

\[
MR = \frac{M - M_e}{M_0 - M_e},
\]

\[
\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt},
\]

\[
R^2 = \frac{\sum_{i=1}^{N} (MR_i - MR_{\text{pre}})^2 + \sum_{i=1}^{N} (MR_i - MR_{\exp})^2}{\sum_{i=1}^{N} (MR_i - MR_{\text{pre}})^2 + \sum_{i=1}^{N} (MR_i - MR_{\exp})^2},
\]

Nomenclature

\[
\begin{align*}
k, a, b, n & \quad \text{drying constants} \\
N & \quad \text{number of observations} \\
M & \quad \text{moisture content} \\
M_0 & \quad \text{initial moisture content} \\
M_t & \quad \text{moisture content at} \ t \\
M_{t+dt} & \quad \text{moisture content at} \ t + dt \ (\% \text{ dry basis}) \\
M_e & \quad \text{equilibrium moisture content} \\
MR & \quad \text{dimensionless moisture ratio} \\
t & \quad \text{drying time (min)} \\
d.b. & \quad \text{dry basis subscripts} \\
exp & \quad \text{experimental data} \\
pre & \quad \text{predicted data} \\
R^2 & \quad \text{correlation coefficient} \\
RMSE & \quad \text{root mean square error}
\end{align*}
\]
Table 1: Mathematical models applied to moisture ratio values.

| Model no. | Model name          | Model equation |
|-----------|---------------------|-----------------|
| 1         | Lewis               | \( MR = \exp(-kt) \) |
| 2         | Handerson and Pabis | \( MR = a\exp(-kt) \) |
| 3         | Page                | \( MR = b\exp(-kt) \) |
| 4         | Midilli and Kucuk   | \( MR = a\exp(-kt^n) + bt \) |

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

where \( \text{MR}_{\text{exp},i} \) and \( \text{MR}_{\text{pre},i} \) are experimental and predicted dimensionless moisture ratios, respectively, and \( N \) is the number of observations. For the analysis, it was assumed that the equilibrium moisture content \( (M_e) \) was equal to zero [9]. The model is said to be good if the \( R^2 \) value is high and the RMSE value is low [5].

3. Results and discussion

3.1. Drying behavior of saffron stigmas

Saffron stigmas with 4.26 g water/g dry matter average initial moisture content were dried to 0.10 g water/g dry matter in an infrared dryer at different temperatures (60, 70, . . . , 110 °C).

Figures 3–5 show the drying curves of saffron stigmas at different temperatures in an infrared dryer. The moisture ratio and drying rate of the samples were calculated using Eqs. (1) and (2). The drying rate decreased continuously throughout the drying period. It is obvious from Figures 3–5 that the constant rate period was absent and the complete drying process of the saffron stigmas took place during the falling rate period. These results are in good agreement as compared to the earlier studies of various vegetables [4,8,10].

![Figure 3: Variations of drying rate with drying time at different temperatures for saffron stigmas.](image)

![Figure 4: Variations of drying rate with moisture ratio at different temperatures for saffron stigmas.](image)
Experiment and predicted moisture ratios by the Midilli and Kucuk model with drying time at different temperatures for saffron stigmas. Several authors reported similar temperature increase, other drying conditions being the same, effective parameter for the drying of saffron stigmas. As the temperature increased, other drying conditions being the same, moisture removal increased, thus resulting in a substantial decrease in drying time. Several authors reported similar findings for various vegetables [7,8,10].

3.2. Mathematical modeling of drying curves

Figure 5 presents variations of the moisture ratio versus drying time for saffron stigmas dried at different drying temperatures. Additionally, Figure 5 shows the comparison of experimental and predicted moisture ratios by the Midilli and Kucuk model. The moisture content data at the different drying temperatures were converted to the more useful moisture ratio expression, and then curve fitting computations with the drying time were carried out on the four drying models evaluated by previous workers (Table 1). The statistical analyses results were applied to these models at the drying process at different drying temperatures. The best model describing the thin layer-drying characteristic was chosen as the one with the highest $R^2$ value and the lowest RMSE value. The results of statistical analyses undertaken on these models are given in Table 2. From Table 2, it was noticed that the Midilli and Kucuk model gave the highest $R^2$ and the lowest RMSE for all drying temperatures for saffron stigmas. The various methods for drying saffron were reported by different researchers, such as near-infrared spectroscopy [16]. The validation procedures, with the results obtained by UV-visible and HPLC-DAD (Diode Array Detectors) measurements, demonstrated that this technique is appropriate to determine the following parameters: moisture and volatile content, and coloring strength. The results reveal that NIRS spectroscopy has an enormous potential for its application to saffron quality control. The mild temperature and air flow dehydration [17,18] showed that a brief (20 min) initial period at a relatively high temperature (between 80 and 92 °C) followed by continued drying at a lower temperature (43 °C), produced saffron with quality color and fragrance [19]. Drying saffron with cabinet driers and atmosphere pressure is favorable for the colour, flavour and fragrance of saffron [20]. A batch type vibration aided infrared dryer was developed and studied for drying characteristics of three varieties of high moisture paddy, and the Page model adequately fitted the experimental drying data [21]. The values of thermal diffusivity, moisture diffusivity and drying rate under different drying temperatures and moisture content were determined using data obtained from the infrared drying of seedless grapes. Nine non-linear equations, including the effect of initial moisture content and temperature,
were derived for obtaining equations that can be used in the calculation of thermal diffusivity, moisture diffusivity and drying rate [22]. Carrot slices were dried from an initial moisture content of 8.52 kg water kg⁻¹ dry matter to 0.11 kg water kg⁻¹ dry matter using an infrared dryer. The drying rate increased with increasing infrared power [23]. No result has been found related to the infrared drying method for saffron.

4. Conclusions

In this study, the drying behavior of saffron stigmas was investigated in an infrared dryer at different temperatures. The drying of saffron stigmas at each temperature occurred in the falling rate period; no constant-rate period of drying was observed. To explain the drying behavior of saffron stigmas, four thin layer drying models were applied. Among these models, at each of six drying temperatures, the Midilli and Kucuk model gave the best results, and showed good agreement with experimental data obtained from the experiments, including the thin layer drying process. At all drying temperatures, the amounts of $R^2$ were higher than 0.999, and the amounts of RMSE were less than 0.012. According to results, it can be said that the Midilli and Kucuk model adequately described the drying behavior of saffron stigmas at a controlled temperature range of 60–110 °C in an infrared dryer. Further study should be undertaken to evaluate the quality of dried saffron produced by this method.

References

[1] Dufresne, C., Cormier, F. and Dorion, S. “In vitro formation of crocetin glucosyl esters by Crocus sativus callus extract”, Planta Medica, 63, pp. 150–153 (1997).
[2] Tarantilis, P.A., Polissiou, M. and Manfait, M. “Separation of picrocrocin, cistens-crocin and safranal of saffron using high performance liquid photodiode-array detection”, Journal of Chromatography A, 684, pp. 53–61 (1994).
[3] Carmona, M., Zalacain, A., Pardo, J.E., Lopez, E., Alvarruz, A. and Alonso, G.L. “Influence of different drying and aging conditions on saffron constituents”, Journal of Agriculture and Food Chemistry, 53, pp. 3974–3979 (2005).
[4] Akpinar, E.K. “Determination of suitable thin layer drying curve model for some vegetables and fruits”, Journal of Food Engineering, 73, pp. 75–84 (2006).
[5] Sarsavadia, P.N., Sawhney, R.L., Pangavhane, D.R. and Singh, S P “Drying behaviour of brined onion slices”, Journal of Food Engineering, 40, pp. 219–226 (1999).
[6] Midilli, A. “Determination of pistachio drying behavior and conditions in a solar drying system”, International Journal of Energy Research, 25, pp. 715–725 (2001).
[7] Yaldiz, O. and Ertekin, C. “Thin layer solar drying of some vegetables”, Drying Technology, 19, pp. 583–596 (2001).
[8] Ibrahim, D., Tugrul, N. and Pala, M. “Drying characteristics of dill and parsley leaves”, Journal of Food Engineering, 77, pp. 559–565 (2006).
[9] Midilli, A., Olgun, H. and Ayhan, T. “Experimental studies of mushroom and pollen drying”, International Journal of Energy Research, 23, pp. 1143–1152 (1999).
[10] Akpinar, E.K., Bicer, Y. and Cetinkaya, F. “Modelling of thin layer drying of parsley leaves in a convective dryer and under open sun”, Journal of Food Engineering, 75, pp. 308–315 (2006).
[11] Bruce, D.M. “Exposed-layer barley drying, three models fitted to new data up to 150 °C”, Journal of Agricultural Engineering Research, 32, pp. 337–347 (1985).

Ebrahim Akhondi

His/her biography was not available at the time of publication.

Akhatar Kazemi received B.S. and M.S. Degrees from Tehran University, Iran. She has been a member of the academic staff of Sharif University of Technology (SUT) in the Biochemical and Biorenvironmental Research Center (BBRC) since 1978, and Vice Education and Vice Research President of the BBRC from 1979 to 1991. Since 1982, she has been Assistant Professor in the Chemical and Petroleum Engineering Department of SUT, and in 2010, she obtained Dr Hedayat, a distinguished Professor in Food Engineering, Award.

Vida Maghsoudi received a B.S. Degree in Chemistry from Ferdowsi University in 1978 and an M.S. Degree in Food Technology from Leeds University (England) in 1981. Since 1981, she has been an assistant professor in the Chemical and Petroleum Engineering Department.