Infrared drying of sweet potato (*Ipomoea batatas* L.) slices

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Abstract The effect of different infrared power levels (104, 125, 146 and 167 W) on drying kinetics and rehydration ratio of sweet potato slices was investigated. It was observed that the power levels affected the drying time and rehydration ratio. The increase in infrared power level decreased the drying time. The experimental data obtained from drying study were fitted with Newton, Henderson and Pabis and Logarithmic models to evaluate the drying kinetics of the sweet potato slices. The fit quality of the proposed models was evaluated by using the determination of coefficient (R^2), mean relative percent error (P), reduced chi-square (χ^2) and root means square error ($RMSE$). Among the three drying models, the Logarithmic model gave a better fit over the other two models. Effective diffusivity varied from 1.31×10^{-10} to 3.66×10^{-10} m²/s and was significantly influenced by infrared power.

Keywords Sweet potato · Infrared drying · Rehydration ratio · Effective diffusivity

Nomenclature

a, c	Drying coefficients
D_{eff}	Effective diffusivity (m ² /s)
d	Slice thickness (mm)
k	Drying rate constant (1/min)
L	Half-thickness of the slab in samples (m)
$MR_{\text{exp},i}$	Experimental dimensionless moisture ratio
$MR_{\text{pre},i}$	Experimental dimensionless moisture ratio

M_e	Equilibrium moisture content (kg water/kg dry matter)
M_0	Initial moisture content (kg water/kg dry matter)
M_t	Moisture content at any time of drying (kg water/kg dry matter)
M_{t+dt}	Moisture content at $t+dt$ (kg water/kg dry matter)
N	Number of observations
n	Constant positive integer
P	Mean relative percent error
R^2	Determination of coefficient
$RMSE$	Root means square error
T	Temperature (°C)
t	Drying time (min)
z	Number of coefficients and constants
χ^2	Reduced chi-square

Introduction

Sweet potato (*Ipomoea batatas* L.) represent the sixth most important food crop in the world. World-wide production of sweet potato is 107,6 million tonnes in 2009 and the major producers include China, Uganda, Indonesia, India and Japan (FAO 2010). The sweet potato is used widely as ready-to-eat foods such as noodles, Chinese style French fries, canned foods, etc. (Antonio et al. 2008). Sweet potato is excellent source of vitamin A and C, and the starch content of the fresh roots varies from 6.9 to 30.7%. Besides, they are high in energy and dietary fibre, low in fat, and are important sources of beta-carotene (Aina et al. 2010). Fresh sweet potatoes having relatively high moisture contents are very sensitive to microbial spoilage, even at refrigerated conditions (Xiao et al.

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2009). Hence, they must be consumed within a few weeks after harvest or be processed into various products such as flour. The sweet potatoes are peeled, sometimes sliced, blanched in hot water and then sun-dried. The dried sweet potato is milled into flour (Akişsoé et al. 2003).

Drying is the most common form of food preservation. This process improves the food stability, since it reduces considerably the water and microbiological activity of the material and minimizes physical and chemical changes during its storage (Hatamipour et al. 2007). Drying is the most energy intensive process in food industry. Therefore, new drying techniques and dryers must be designed and studied to minimize the energy cost in drying process (Kocabiyik and Tezer 2009).

In recent years, infrared drying has gained popularity as an alternative drying method for a variety of agricultural products. The use of infrared radiation technology in drying agricultural products has several advantages. These may include decreased drying time, high energy efficiency, high quality finished products, and uniform temperature in the product (Nowak and Lewicki 2004; Sharma et al. 2005; Shi et al. 2008; Kocabiyik and Tezer 2009). Several agricultural products have been successfully dried by the infrared application and/or by a combined infrared-assisted convection process such as Nowak and Lewicki (2004) for apple, Sharma et al. (2005) and Kumar et al. (2006) for onion, Shi et al. (2008) for blueberry, Ruiz-Celma et al. (2009) for grape by-products, Caglar et al. (2009) for seedless grapes, and Kocabiyik and Tezer (2009) for carrot. However, I found no report on infrared drying of sweet potatoes in the literature. The aim of this study was: (a) to study the effect of infrared power levels on the drying time and rehydration ratio, (b) to fit the experimental data to their mathematical models, and (c) to compute effective diffusivity of sweet potato slices.

Materials and methods

Sample preparation

Fresh sweet potatoes (*Ipomoea batatas* L.) were purchased from a local market in Istanbul, Turkey. The samples were stored in a refrigerator at 4 °C until used. The samples were washed with tap water, peeled and sliced manually by different thickness (slice thickness (d): 3, 5 and 8 mm). The average moisture content of the sweet potatoes was $81.8 \pm 0.2\%$ (w.b.), as determined by vacuum drying at 70 °C for 24 h (AOAC 1990).

Experimental procedure

Drying experiments were carried out in a moisture analyzer with one 250 W halogen lamp (Snijders Moisture Balance,

Snijders b.v., Tilburg, Holland). The infrared drying process, the sample should be separated evenly and homogeneously over the entire pan. Otherwise, a large portion of the incident infrared radiation will be reflected at the exposed pan bottom not covered by the sample (Caglar et al. 2009). The experiments were performed at infrared power levels varying from 104 to 167 W. The power level was set in control unit of equipment. The samples were distributed uniformly as a thin-layer into a metal screen of 11 cm diameter located 40 mm from the upper emitter (near infrared). Each sample utilized in the experiment weighed 25 ± 1 g. The weight loss was recorded at 15 min by using a digital balance (Mettler-Toledo AG, Grefensee, Switzerland, model BB3000) with an accuracy of 0.1 g. Drying process was stopped when the moisture content of the samples was about $15\% \pm 0.5$ (w.b.). The dried product was cooled and packed in low-density polyethylene bags that were heat-sealed. All experiments were conducted in triplicate and the average of the moisture content at each value was used for drawing the drying curves.

Mathematical modeling of drying curves

It has been accepted that the drying characteristics of biological products in falling rate period can be described by using Fick's second law of diffusion (Falade and Solademi 2010). The solution of Fick's second law in slab geometry given by Crank (1975), assuming moisture migration being only by diffusion, constant effective diffusivity and temperature, and negligible shrinkage, is:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff}}{4L^2} t\right) \quad (2)$$

where MR is the moisture ratio, M_t , M_0 and M_e are the moisture content at any time, initial and equilibrium moisture contents (kg water/kg dry matter), respectively, D_{eff} is the effective diffusivity m^2/s , L is the half-thickness of the slab in samples in m, and n is positive integer. The value of M_e is relatively small compared with M_t or M_0 , especially for infrared drying (Diamante and Munro 1993; Shi et al. 2008). For long drying period, Eq. 2 can be further simplified to only term of series (Madamba 2003; Aghbashlo et al. 2009). Thus, Eq. 2 is written in a logarithmic form as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (3)$$

Equation 3 can also be written in more simplified form as:

$$MR = a \exp(-kt) \quad (4)$$

where a is the drying coefficient and k is a drying rate constant (1/min). Equation 4 is known to be the Henderson and Pabis model. This model was used to model drying of corn and black tea (Henderson and Pabis 1961; Erbay and Icier 2010).

The Newton model is a special case of the Henderson and Pabis model where the intercept is unity. This model has been used commonly by El-Beltagy et al. (2007) for strawberry.

$$MR = \exp(-kt) \quad (5)$$

Another model, which is widely used for thin-layer drying studies, is the logarithmic model. The logarithmic model has produced good fits in predicting drying of laurel leaves and organic tomato (Sacilik and Elicin 2006; Akpinar 2008):

$$MR = a \exp(-kt) + c \quad (6)$$

where c is the drying coefficient.

The drying rate (DR) of sweet potato slices was calculated using Eq. 7:

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (7)$$

where M_{t+dt} is moisture content at $t+dt$ (kg water/kg dry matter), t is time (min).

Statistical tests

The fitting quality of the experimental data to all models was evaluated using the determination of coefficient (R^2), mean relative percent error (P), reduced chi-square (χ^2) and root mean square error (RMSE). These parameters can be calculated using Eqs. 8, 9 and 10:

$$P = \frac{100}{N} \sum_{i=1}^N \frac{|M_{R,exp,i} - M_{R,pre,i}|}{M_{R,exp,i}} \quad (8)$$

$$\chi^2 = \frac{\sum_{i=1}^N (M_{R,exp,i} - M_{R,pre,i})^2}{N - z} \quad (9)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (M_{R,pre,i} - M_{R,exp,i})^2 \right]^{1/2} \quad (10)$$

where $M_{R,exp,i}$ and $M_{R,pre,i}$ are experimental and predicted dimensionless moisture ratios, respectively; N is number of observations; z is number of coefficients and constants. The best model describing the drying characteristics of samples was chosen as the one with the highest coefficient of determination, the least mean relative percent error, reduced chi-square, and root mean square error (Sacilik and Elicin

2006; Ruiz Celma et al. 2009; Caglar et al. 2009; Aghbashlo et al. 2009). Analysis of variance (ANOVA) of fitness parameters among the different models was conducted using the Duncan method at $p < 0.05$.

Rehydration

Dried sweet potato slices (d: 5 mm) were rehydrated in water at 20 °C (± 1 °C). About 3 g of the dried products were added to 300 ml distilled water, in a 400 ml beaker. Weight of the sample was measured after 4 h. Subsequently, the samples were drained, blotted with tissue paper, and weighed. The rehydration ratio (RR) was calculated as follows:

$$RR = \frac{\text{Weight after rehydration}}{\text{Weight before rehydration}} \quad (11)$$

Results and discussions

Drying characteristics

Changes in the moisture content with drying time and drying rate versus drying time during infrared drying of sweet potato sliced to 5 mm thickness at different infrared power levels are shown in Fig. 1. It is clear that the moisture content and drying rate decrease continuously with drying time. Results show that drying of sweet potato slices occurs entirely in the falling-rate period. This shows that diffusion is dominant physical mechanism governing moisture movement in the samples. The results were generally in agreement with some of the literature on the drying of various food products (Akpinar et al. 2003; Singh et al. 2006; Falade et al. 2007; Sobukola et al. 2008; Shi et al. 2008; Basavaraj et al. 2008).

According to the results in Fig. 1, the infrared power level had a significant effect on the moisture content of the sweet potato slices as expected. The results showed that drying time decreased greatly when the infrared power level increased. The drying time required to reach the final moisture content of samples were 270, 195, 150 and 105 min at the infrared power levels of 104, 125, 146 and 167 W, respectively. The average drying rates increased 2.57 times as infrared power level increased from 104 W to 167 W. The decrease in drying time with an increase in the infrared power level has been reported by Sharma et al. (2005) for onion slices and Kocabiyik and Tezer (2009) for carrot slices.

Effect of thickness

Efforts were made to study the effect of the slice thickness (3, 5 and 8 mm) on drying at constant infrared

Fig. 1 Variation of drying characteristics of sweet potato slices of 5 mm thickness at various infrared power levels (a: moisture content—drying time, b: drying rate—moisture ratio)

power level (146 W) and mass load 25 g (Fig. 2). As expected for these drying curves, the slice thickness had much more effect on the moisture content of sweet potato slices. In other words, the decrease in slice thickness resulted in decrease in drying time. The drying time to reach the final moisture content for the sweet potato slices of 3, 5 and 8 mm were 120, 150 and 255 min at the infrared power level of 146 W, respectively. In comparison with slice thickness of 3 mm, that of 8 mm caused an increase in drying time by about 108.3%. This increase in the drying time with increasing slice thickness was due to the effect the exposed surface area resulting in increased diffusion path of moisture out of the sweet potato slices during infrared drying. Therefore, slice thickness had a significant effect on the drying time, as found in previous studies for fruits and vegetables (Sacilik and Elicin 2006; Falade et al. 2007).

Fitting of drying curves

The drying experimental data were used to predict the drying characteristics of sweet potato slices using the Lewis, Henderson and Pabis, and Logarithmic models. The statistical results from models are summarised in Table 1. The best model selected based on the highest R^2 and the lowest P , χ^2 and RMSE values. The R^2 values for Lewis, Henderson and Pabis and Logarithmic models were all above 0.97, and that for Lewis model was lower. The statistical parameter estimations showed that R^2 , χ^2 , RMSE and P values were ranged from 0.9746 to 0.9996, 3.5995–37.9316, 0.00005 to 0.00260, and 0.01594 to 0.16305, respectively. Among the three models, the Logarithmic model fitted the best with experimental drying data for sweet potato slices, with the highest R^2 for all temperatures. P , χ^2 and RMSE also showed best results with the smaller values. Figure 3 compares experimental data with those predicted with the Lewis, Henderson and Pabis, and Logarithmic models for sweet potato slices. The prediction using the Logarithmic model showed MR values banded along the straight line, which showed the suitability of this model in describing drying characteristics of sweet potato slices.

Effective diffusivity

From Eq. 3, a plot of $\ln MR$ versus drying time gave a straight line with a slope (K) of:

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

Fig. 2 Effect of slice thickness on moisture content of samples during air drying at 146 W

Table 1 Statistical analysis of models at various infrared power levels

Infrared power level (W)	Model name	R^2	P	χ^2	RMSE
104	Newton	0.9856	24.6721	0.00133	0.13690
	Henderson and Pabis	0.9898	20.5996	0.00100	0.11546
	Logarithmic	0.9992	4.6118	0.00008	0.03047
125	Newton	0.9746	37.9316	0.00260	0.16305
	Henderson and Pabis	0.9803	33.0402	0.00218	0.14443
	Logarithmic	0.9985	8.7829	0.00017	0.03778
146	Newton	0.9937	16.6193	0.00065	0.06917
	Henderson and Pabis	0.9951	14.3250	0.00055	0.06350
	Logarithmic	0.9992	5.4998	0.00010	0.02639
167	Newton	0.9872	29.8383	0.00143	0.08541
	Henderson and Pabis	0.9884	28.2003	0.00152	0.08567
	Logarithmic	0.9996	3.5995	0.00005	0.01594

The effective diffusivity was calculated using Eq. 12 and is shown in Fig. 4. The D_{eff} values of dried samples at infrared power level of 104–167 W were varied in the range of 1.31×10^{-10} to 3.66×10^{-10} m²/s. It can be seen that D_{eff} values increased greatly with increasing infrared power level. The higher power level caused an increase of effective moisture diffusivity because of higher mass transfer. The obtained values of D_{eff} from this study lie within in general range 10^{-12} to 10^{-8} m²/s for drying of

food materials (Zogzas et al. 1996). The values of D_{eff} are comparable with the reported values of $0.62\text{--}3.50 \times 10^{-10}$ m²/s mentioned for onion slices infrared drying (Sharma et al. 2005), 2.24 to 16.4×10^{-10} m²/s for blueberry infrared drying at 60–90 °C (Shi et al. 2008), 6.36×10^{-11} to 9.75×10^{-9} m²/s for sweet potato hot air drying at 50–80 °C (Falade and Solademi 2010), 2.72 to 6.81×10^{-10} m²/s for tea leaves hot air drying at 45–55 °C (Sinija and Mishra 2009), and 3.55 to 19.20×10^{-10} m²/s for potato slices hot air drying at

Fig. 3 Comparison between experimental and predicted moisture ratios using different models at infrared power levels (a: 104 W, b: 125 W, c: 146 W, and d: 167 W) for sample thickness of 5 mm

Fig. 4 Variation of effective diffusivity (a) and rehydration ratio (b) for sweet potato slices with different infrared power levels

40–85 °C (Hassini et al. 2007). These values are consistent with the present estimated D_{eff} values for sweet potato.

Rehydration ratio

Rehydration ratio is widely used as a quality index after drying of fruit and vegetables. It indicates the physical and chemical changes during drying as influenced by processing conditions, sample pretreatment and composition (Feng and Tang 1998). Rehydration curves of sweet potato slices at different infrared power levels, calculated from Eq. 11, are shown in Fig. 4. The rehydration ratio (except of 167 W infrared power) increased with the increase in infrared power level. The highest rehydration ratio values were obtained in infrared power of 146 W. An increase in power level above 146 W had an adverse effect on the final

rehydration ratio value, which decreased with increasing power level (increasing product temperature). This may be indicative of a change in the product induced by power level and perhaps a loss of solids during rehydration. Similar results have been reported by Cunningham et al. (2008) and Kocabiyik and Tezer (2009).

Conclusions

In this study, infrared drying characteristics of sweet potato slices were investigated. The infrared drying of sweet potato slices occurred in falling rate period. The drying rate was significantly influenced by infrared power. The drying time decreased with the increase in infrared power level. In order to explain the drying characteristics of sweet potato slices, three thin-layer drying models were compared with R^2 , P , χ^2 and RMSE. The logarithmic model gave the best representation of drying data under all experimental conditions. The effective diffusivity was computed from Fick's second law, the values of which varied between 1.31×10^{-10} and $3.66 \times 10^{-10} m^2/s$, over the infrared power level range. The effective diffusivity increases as infrared power level increases. The rehydration ratio confused that the highest rehydration ratio values were obtained in infrared power of 146 W.

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