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ORIGINAL ARTICLE

Mathematical modeling of drying of pretreated and untreated pumpkin

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Abstract In this study, drying characteristics of pretreated and untreated pumpkin were examined in a hot-air dryer at air temperatures within a range of 40–80 °C and a constant air velocity of 1.5 m/s. The drying was observed to be in the falling-rate drying period and thus liquid diffusion is the main mechanism of moisture movement from the internal regions to the product surface. The experimental drying data for the pumpkin fruits were used to fit Exponential, General exponential, Logarithmic, Page, Midilli-Kucuk and Parabolic model and the statistical validity of models tested were determined by non-linear regression analysis. The Parabolic model had the highest R^2 and lowest χ^2 and RMSE values. This indicates that the Parabolic model is appropriate to describe the dehydration behavior for the pumpkin.

Keywords Pumpkin fruits · Hot air drying · Effective diffusivity · Mathematical modelling

Nomenclature

a	Drying constant
b	Drying constant
c	Drying constant
DR	Drying rate (g water/g dry matter*h)
k	Drying constant, 1/min
M_e	Equilibrium moisture content (kg water/kg dry matter)
M_i	Initial moisture content (kg water/kg dry matter)
M_R	Dimensionless moisture ratio
$MR_{exp,i}$	Experimental dimensionless moisture ratio
$MR_{pre,i}$	Predicted dimensionless moisture ratio
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	Drying constant, positive integer
R^2	Coefficient of determination
t	Time (min)
W	Amount of evaporated water (g)
$W0$	Initial weight of sample (g)
$W1$	Sample dry matter mass (g)
z	Number of constants
χ^2	Reduced chi-square

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Introduction

Pumpkin (*cucurbita mixta*) is a fruit rich in Vitamin A, potassium, fiber and carbohydrates. It is a versatile fruit that can be used for either animal feed or for human consumption as a snack, or made into soups, pies and bread. The high moisture content of the fruit makes it susceptible to deterioration after harvest. The most common form of preservation being done locally is drying. It is a means of improving storability by increasing shelf-life of the food product. Dried products can be stored for months or even years without appreciable loss of nutrients. Drying also assist in reducing post harvest losses of fruits and vegetables especially which can be as high as 70% (Tunde-Akintunde and Akintunde 1996).

Sun drying is the common method of drying in the tropical region. However the process is weather dependent Also, the drying of food products with the use of sun-drying usually takes a long time thus resulting in products of low quality. There is a need for suitable alternatives in order to improve product quality. Hot air dryers give far more hygienic products and provide uniform and rapid drying which is more suitable for the food drying processes (Kingsly et al. 2007a; Doymaz 2004a).

Many types of hot-air dryers are being used for drying agricultural products. However the design of such driers for high-moisture foods constitutes a very complex problem owing to the characteristics of vegetable tissues. One of the most important factor that needs to be considered in the design of driers is the proper prediction of drying rate for shrinking particles and hence the appropriate drying time in the dryer needs to be investigated. This can be achieved by determination of the drying characteristics of the food material. Therefore the thin layer drying studies which normally form the basis of understanding the drying characteristics of food materials has to be carried out for each food material. Studies have been carried out on thin layer drying of some food materials (Gaston et al. 2004), fruits (Doymaz 2004a, c; Simal et al. 2005), leaves and grasses (Demir et al. 2004).

Though there has been some literature on drying of pumpkin (Alibas 2007; Doymaz 2007b; Sacilik 2007), the selection of appropriate model to describe the drying process for the variety common in the country and within the experimental conditions considered in this study is yet to be done. Thin layer drying models used in the analysis of drying characteristics are usually theoretical, semi-theoretical or purely empirical. A number of semi-theoretical drying models have been widely used by various researchers (Sharma and Prasad 2004; Simal et al. 2005; Sogi et al. 2003; Togrul and Pehlivan 2004).

A number of pre-treatments can be applied depending on the food to be dried, its end use, and availability (Doymaz 2010). Pretreatment of food materials which includes; blanching, osmotic dehydration, soaking in ascorbic acid before or on drying have been investigated to prevent the loss of colour by inactivating enzymes and relaxing tissue structure. This improves the effect of drying by reducing the drying time and gives the eventual dried products of good nutritional quality (Kingsly et al. 2007b; Doymaz 2010). Various commercially used pretreatments include potassium and sodium hydroxide, potassium meta bisulphate, potassium carbonate, methyl and ethyl ester emulsions, ascorbic and citric acids, (Kingsly et al. 2007a, b; Doymaz 2004a, b; El-Beltagy et al. 2007). However non-chemical forms of pretreatment are generally preferred especially among small-scale processors in the tropics. Blanching as a pre-treatment is used to arrest some physiological processes before drying vegetables and fruits. It is a heat pre-treatment that inactivates the enzymes responsible for commercially unacceptable darkening and off-flavours. Blanching of fruits and vegetables is generally carried out by heating them with steam or hot water (Tembo et al. 2008). However other forms of blanching i.e. oil-water blanching have been used by Akanbi et al. (2006) in a previous study for pretreating chilli. These forms of blanching were observed to have an effect on the drying rate and quality of the dried chili. However oil-water blanching pretreatments have not been studied for pumpkin. The aim of this study was: (a) to study the effect of the different blanching pre-treatments on the drying times and rate, and (b) to fit the experimental data to seven mathematical models available in the literature.

Materials and methods

Experimental procedure

Fresh pumpkin fruit were purchased from Arada, a local market in Ogbomoso, Nigeria. The initial average moisture content of fresh pumpkin samples was determined by oven drying method (AOAC 1990), and it was found to be 91.7% (wet basis) or 10.90 (g water/g dry matter). The samples were washed and peeled after which the seeds were removed. The pumpkin was then sliced into pieces of 5 mm×5 mm dimensions. The blanching pre-treatments for inactivation of enzymes are as indicated below while untreated samples (UT) were used as the control.

i) Samples submerged in boiling water for 3 minutes and cooling immediately in tap water - (WB)
ii) Samples steamed over boiling water in a water bath (WBH 14/F2, England) for 3minutes and cooled immediately in tap water - (SB)
iii) Samples dipped for 3 minutes in a homogenized mixture of oil and water of ratio 1:20 (v/v) with 0.1 g of butylated hydroxyl anisole (BHA) heated to 95 °C - (O/W B)

In all the pretreatments the excess water was removed by blotting the pretreated pumpkin samples with tissue paper. The moisture contents after pretreatment were 12.69 (g water/g dry matter) for water and oil-water blanching and 11.5 (g water/g dry matter) for steam blanching.

Drying procedure

The drying experiments of pumpkin samples were carried out in a hot-air dryer (Gallenkamp, UK) having three tiers of trays. Perforated trays having an area of approximately 0.2 m^2 were

Table 1 Mathematical models fitted to pretreated pumpkin drying curves

Model name	Model	References
Exponential model	$MR = \exp(-kt)$	El-Beltagy et al. (2007)
Generalized exponential model	$MR = A\exp(-kt)$	Shittu and Raji (2008)
Logarithmic model	$MR = a\exp(-kt) + c$	Akpinar and Bicer (2008)
(Page's model)	$MR = \exp(-kt^n)$	Singh et al. (2008)
Midilli–Kucuk model	$MR = a\exp(-kt^n) + bt$	Midilli and Kucuk (2003)
Parabolic model	$MR = a + bt + ct^2$	Sharma and Prasad (2004), Doymaz (2010)

placed on each tier and the trays were filled with a single layer of the pumpkin samples. The air passes from the heating unit and is heated to the desired temperature and channeled to the drying chamber. The hot air passes from across the surface and perforated bottom of the drying material and the direction of air flow was parallel to the samples. The samples utilised for each experimental condition weighed 200±2 g. Drying of the pumpkin was carried out at drying temperatures of 40 to 80^0C with 20 °C increment, and a constant air velocity of 1.5 m/s for all circumstances. The dryer was adjusted to be selected temperature for about half an hour before the start of experiment to achieve the steady state conditions. Weight loss of samples was measured at various time intervals, ranging from 30 min at the beginning of the drying to 120 min during the last stages of the drying process by means of a digital balance (PH Mettler) with an accuracy of ±0.01 g. The samples were taken out of the dryer and weighed during each of the time intervals. Drying was stopped when constant weight was reached with three consecutive readings. The experiments were repeated twice and the average of the moisture ratio at each value was used for drawing the drying curves.

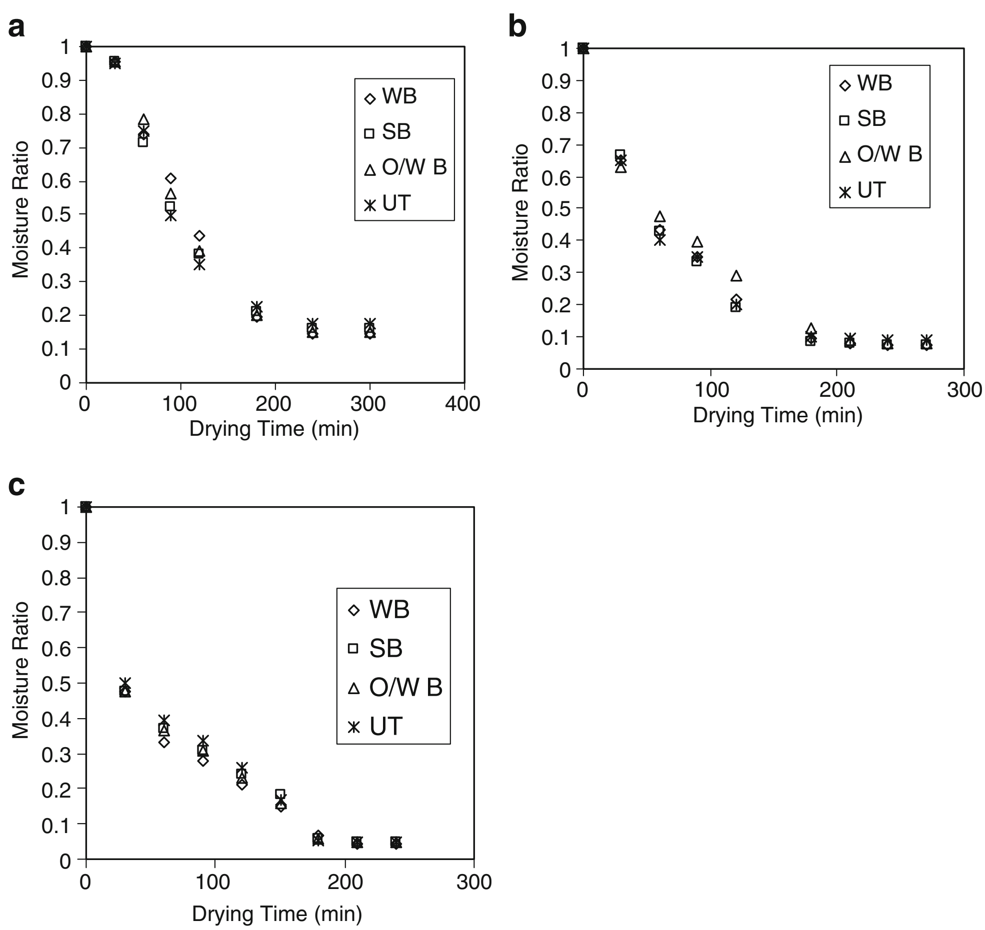

Fig. 1 Drying curve of pumpkin slices dried at (**a**) 40, (**b**) 60 and (**c**) 80 °C (WB-water blanched, SB-steam blanched, O/W B- oil water blanched, UT-untreated). Each observation is a mean of two replicate experiments (n=2)

Mathematical modeling

The moisture content at any time of drying (kg water/kg dry matter), M_t was calculated as follows:

$$M_t = \frac{(W_o - W) - W_1}{W_1} \quad (1)$$

Where W_0 is the initial weight of sample, W is the amount of evaporated water and W_1 is the sample dry matter mass.

The reduction of moisture ratio with drying time was used to analyse the experimental drying data. The moisture ratio, M_R, was calculated as follows:

$$M_R = \frac{M_t - M_e}{M_i - M_e} = \exp(-Kt) \quad (2)$$

Where M_t, M_i and M_e are moisture content at any time of drying (kg water/kg dry matter), initial moisture content (kg water/kg dry matter) and equilibrium moisture content (kg water/kg dry matter), respectively.

The equilibrium moisture contents (EMCs) were determined by drying until no further change in weight was observed for the pumpkin samples in each treatment and drying condition (Hii et al. 2009)

The drying constant, K, is determined by plotting experimental drying data for each pretreatment and drying temperature in terms of Ln M_R against time (t) where M_R is moisture ratio. The slope, k, is obtained from the straight line graphs above.

The drying rate for the pumpkin slices was calculated as follows:

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (3)$$

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

The moisture ratio curves obtained were fitted with six semi-theoretical thin layer-drying models, Exponential, Generalized exponential, Page, Logarithmic, Midilli -Kucuk and Parabolic models (Table 1) in order to describe the drying characteristics of pretreated pumpkin.

These linear forms of these models were fitted in the experimental data using regression technique. To evaluate the models, a nonlinear regression procedure was performed for six models using SPSS (Statistical Package for

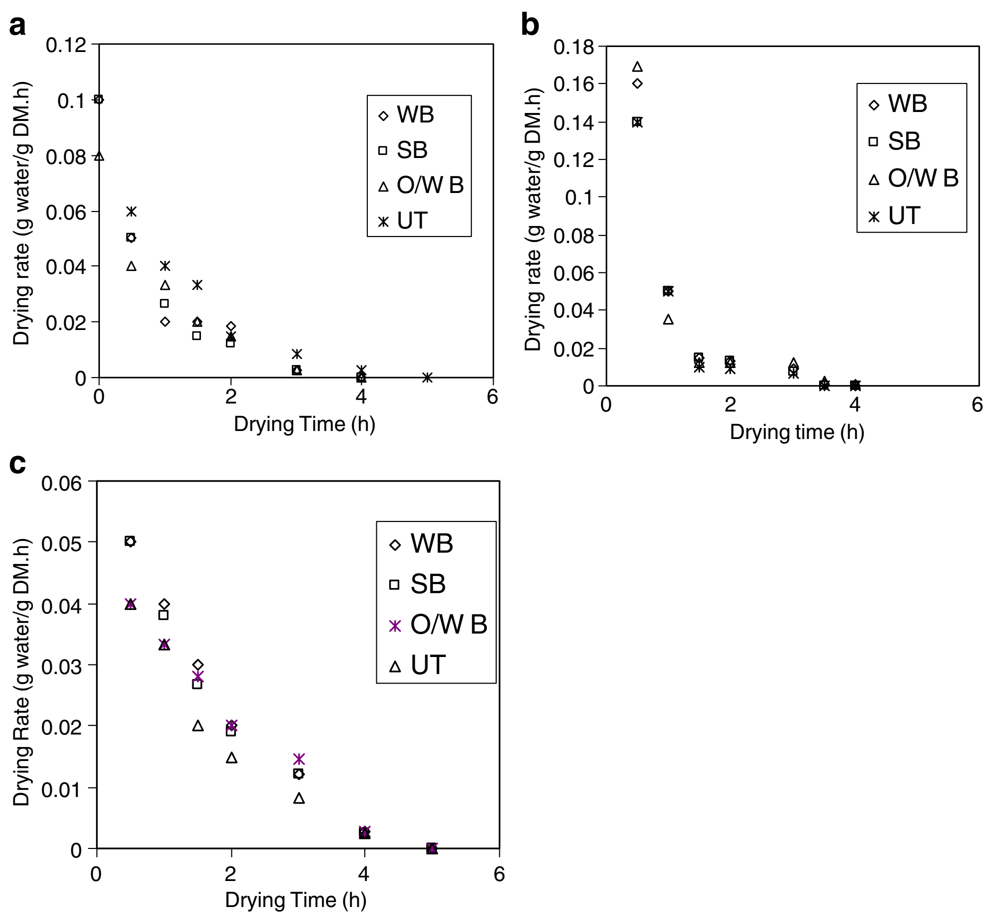

Fig. 2 Drying rate curve of pretreated pumpkin dried at (**a**) 40, (**b**) 60 and (**c**) 80 °C (WB-water blanched, SB-steam blanched, O/W B- oil water blanched, UT-untreated). Each observation is a mean of two replicate experiments (n=2)

Table 2 Drying constant (K) values for pretreatment methods and drying temperatures

Drying Temperature (°C)	Pretreatment method			
	Steam Blanching	Water Blanching	Oil-Water Blanching	Untreated
40	0.4529	0.4458	0.4226	0.4029
60	0.6223	0.6163	0.6015	0.5637
80	0.7884	0.7871	0.7837	0.7803

social scientists) 11.5.1 software package. The correlation coefficient (R^2) was one of the primary criteria to select the best equation to account for variation in the drying curves of dried samples. In addition to R^2, other statistical parameters such as reduced mean square of the deviation (χ^2) and root mean square error (RMSE) were used to determine the quality of the fit. The higher the value of R^2 and the lower the values of χ^2 and RMSE were chosen as the criteria for goodness of fit. (Togrul and Pehlivan 2002; Demir et al. 2004; Doymaz 2004b; Goyal et al. 2006). The above parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{(\exp,i)} - MR_{(pred,i)}\right)^2}{N - z} \quad (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pred,i} - MR_{\exp,i}\right)^2\right]^{\frac{1}{2}} \quad (5)$$

Where $MR_{exp,i}$ and $MR_{pre,i}$ are experimental and predicted dimensionless moisture ratios, respectively; N is number of observations; z is number of constants

Results and discussion

Drying characteristics

The characteristics drying curves showing the changes in moisture ratio of pretreated pumpkin with time at drying temperatures of 40, 60 and 80 °C are given in Fig. 1. Figure 2 show the changes in drying rate as a function of drying time at the same temperatures. It is apparent that moisture ratio decreases continuously with drying time. According to the results in Fig. 1, the drying air temperature and pre-treatments had a significant effect on the moisture ratio of the pumpkin samples as expected. This is in agreement with the observations of Doymaz (2010) for apple slices. The figures show that the drying time decreased with increase in drying air temperature. Similar results were also reported for food products by earlier

Table 3 Curve fitting criteria for the various mathematical models and parameters for pumpkin pretreated with water blanching and dried at temperatures of 40, 60 and 80 °C

Model name	Coefficient of determination (R^2)	Reduced chi-square (χ)	Root mean square error (RMSE)
40 °C			
Generalized Exponential Model	0.9518	0.005824	0.071384
Exponential Model	0.9655	0.005196	0.062424
Logarithmic Model	0.9684	0.005621	0.059272
Page Model	0.97375	0.003279	0.048397
Midilli–Kucuk model	0.86398	0.027752	0.109059
Parabolic model	0.9963	0.000473	0.01644
60 °C			
Generalized Exponential Model	0.9874	0.001382	0.035049
Exponential Model	0.9882	0.001346	0.032351
Logarithmic Model	0.9942	0.000785	0.022878
Page Model	0.98039	0.00111	0.028847
Midilli–Kucuk model	0.81857	0.014514	0.085189
Parabolic model	0.9941	0.000448	0.016726
80 °C			
Generalized Exponential Model	0.9564	0.003862	0.058588
Exponential Model	0.9622	0.003861	0.054796
Logarithmic Model	0.9725	0.010795	0.082138
Page Model	0.9595	0.008616	0.080386
Midilli–Kucuk model	0.93702	0.02237	0.105759
Parabolic model	0.9865	0.003292	0.04685

Table 4 Curve fitting criteria for the various mathematical models and parameters for pumpkin pre-treated with steam blanching and dried at temperatures of 40, 60 and 80 °C

Model name	Coefficient of determination (R^2)	Reduced chi-square (χ)	Root mean square error (RMSE)
40 °C			
Generalized Exponential Model	0.9593	0.004843	0.065095
Exponential Model	0.9689	0.004274	0.056615
Logarithmic Model	0.96896	0.005065	0.056262
Page Model	0.9599	0.004587	0.057237
Midilli–Kucuk model	0.81847	0.034238	0.121134
Parabolic model	0.9949	0.000649	0.019252
60 °C			
Generalized Exponential Model	0.98737	0.001354	0.034688
Exponential Model	0.9876	0.001448	0.033563
Logarithmic Model	0.99081	0.000864	0.023994
Page Model	0.9749	0.001287	0.031073
Midilli–Kucuk model	0.98227	0.016922	0.091982
Parabolic model	0.9941	0.000598	0.019336
80 °C			
Generalized Exponential Model	0.9436	0.005484	0.069818
Exponential Model	0.95187	0.010844	0.060609
Logarithmic Model	0.95819	0.005201	0.082325
Page Model	0.92237	0.006567	0.070179
Midilli–Kucuk model	0.95502	0.021093	0.102696
Parabolic model	0.97959	0.004723	0.058882

Table 5 Curve fitting criteria for the various mathematical models and parameters for pumpkin pre-treated with oil-water blanching and dried at temperatures of 40, 60 and 80 °C

Model name	Coefficient of determination (R^2)	Reduced chi-square (χ)	Root mean square error (RMSE)
40 °C			
Generalized Exponential Model	0.9454	0.006729	0.076734
Exponential Model	0.9603	0.005953	0.066819
Logarithmic Model	0.96175	0.006953	0.065922
Page Model	0.9645	0.004596	0.057295
Midilli–Kucuk model	0.83801	0.032813	0.118587
Parabolic model	0.9956	0.000822	0.021672
60 °C			
Generalized Exponential Model	0.97665	0.001791	0.039903
Exponential Model	0.98271	0.00202	0.039642
Logarithmic Model	0.98695	0.001662	0.033287
Page Model	0.97469	0.001258	0.03072
Midilli–Kucuk model	0.8884	0.008374	0.064708
Parabolic model	0.9928	0.000453	0.016822
80 °C			
Generalized Exponential Model	0.94785	0.004794	0.065279
Exponential Model	0.9554	0.0048	0.061101
Logarithmic Model	0.9625	0.012026	0.086696
Page Model	0.93223	0.010644	0.089346
Midilli–Kucuk model	0.9494	0.020094	0.100234
Parabolic model	0.98357	0.004354	0.053874

Table 6 Curve fitting criteria for the various mathematical models and parameters for untreated pumpkin and dried at temperatures of 40, 60 and 80 °C

Model name	Coefficient of determination (R^2)	Reduced chi-square (χ)	Root mean square error (RMSE)
40 °C			
Generalized Exponential Model	0.94876	0.005896	0.071829
Exponential Model	0.9585	0.005679	0.065264
Logarithmic Model	0.95911	0.006735	0.06488
Page Model	0.9412	0.006475	0.068007
Midilli–Kucuk model	0.7898	0.039925	0.130808
Parabolic model	0.98595	0.001869	0.032678
60 °C			
Generalized Exponential Model	0.9735	0.002436	0.046534
Exponential Model	0.9749	0.002884	0.047363
Logarithmic Model	0.98107	0.001185	0.028035
Page Model	0.9584	0.002147	0.040127
Midilli–Kucuk model	0.7669	0.016307	0.090296
Parabolic model	0.99039	0.001179	0.02722
80 °C			
Generalized Exponential Model	0.94998	0.004584	0.063836
Exponential Model	0.9572	0.004768	0.060896
Logarithmic Model	0.95985	0.005046	0.057999
Page Model	0.92016	0.007738	0.069542
Midilli–Kucuk model	0.9507	0.017959	0.09476
Parabolic model	0.9775	0.004285	0.056692

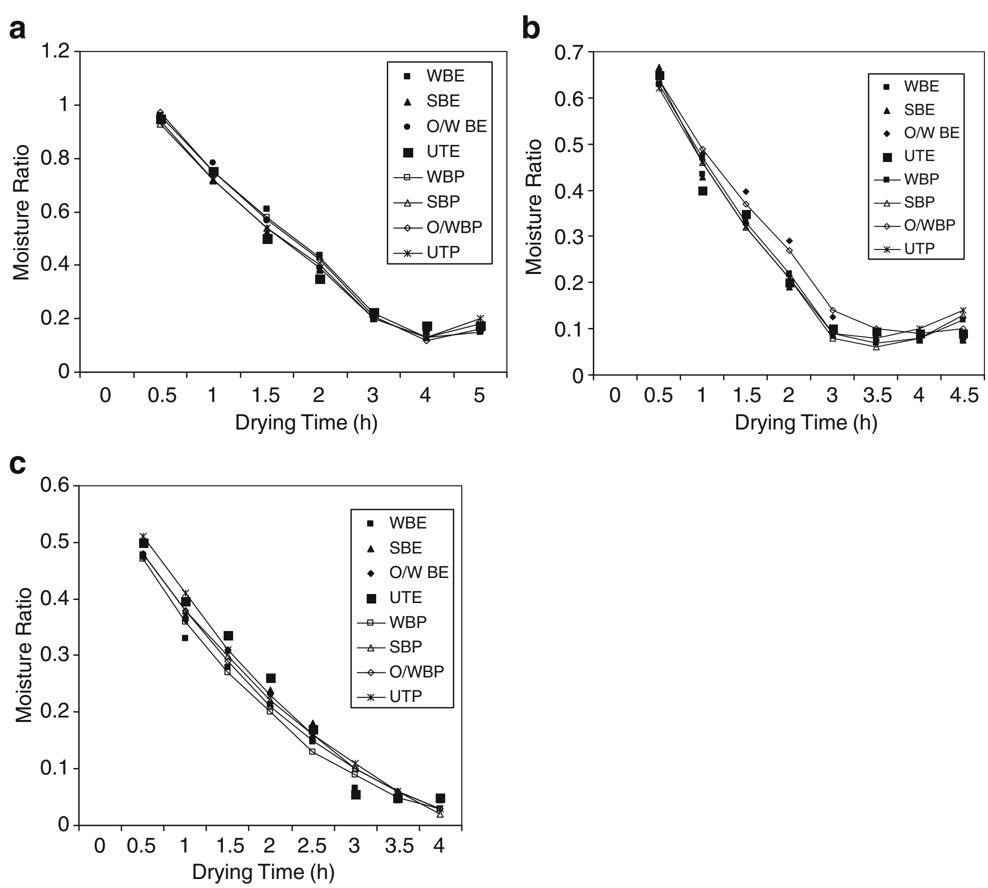

Fig. 3 Comparison of experimental and predicted moisture ratio values using Parabolic model for pretreated pumpkin dried at (**a**) 40, (**b**) 60 and (**c**) 80 °C (WBE-water blanched experimental, SBE-steam blanched experimental, O/W BE-oil water blanched experimental, UTE-untreated experimental, WBP-water blanched predicted, SBP-steam blanched predicted, O/W BP-oil water blanched predicted, UTP-untreated predicted). Each observation is a mean of two replicate experiments (n=2)

researchers (Sacilik and Elicin 2006; Lee and Kim 2009; Kumar et al. 2010). The drying time required to lower the moisture ratio of water blanched samples to 0.034 when using an air temperature of 40 °C (5 h) was approximately twice that required at a drying air temperature of 80 °C (2.5 h). This same trend occurred for both untreated and other pretreatment methods. The drying time required to reach moisture ratio of 0.018 for drying temperature of 60 °C for samples pretreated with steam blanching was 3 h while the corresponding values for water blanched, oil-water blanched and control samples were 3.5, 3.9 and 4 h respectively. The difference in drying times of pre-treated samples with steam blanching was 16.7%, 30% and 33.3% shorter than water blanched, oil-water blanched and control samples, respectively. Similar trends were observed at drying temperatures of 40 and 80 °C.

All the pretreated samples had higher drying curves than the untreated samples generally (Fig. 1). This is an indication of the fact that various forms of blanching pretreatments increase the drying rate for pumpkin samples. This is similar to the observations of Goyal et al. (2008), Doymaz (2007a), Kingsly et al. (2007a), Doymaz (2004b) for apples, tomato, peach slices and mulberry fruits. The difference in drying is more pronounced at the initial stages of drying when the major quantity of water is evaporated while at the latter stages of drying the difference in the amount of water evaporated is not as pronounced as the early drying stages. The difference in the drying of the different pretreatments experienced in the initial stages becomes less pronounced with increase in drying temperature. This may be because at higher temperatures the driving force due to diffusion from the internal regions to the surface is higher thus overcoming hindrances to drying more effectively resulting in more uniform drying. The K values for pretreated samples were higher than that of untreated samples for all the drying temperatures (Table 2). This confirms the fact that the various forms of blanching pretreatments increased the rate at which drying took place.

Analysis of the drying rate curves (Fig. 2) showed no constant-rate period indicating that drying occurred during the falling-rate period. Therefore, it can be considered a diffusion-controlled process in which the rate of moisture removal is limited by diffusion of moisture from inside to surface of the product. This is similar to the results reported for various agricultural products such Amasya red apples (Doymaz 2010), peach (Kingsly et al. 2007a), yam (Sobukola et al. 2008), and tumeric (Singh et al. 2010).

Fitting of drying curve

SPSS statistical software package for non-linear regression analysis was used to fit moisture ratio against drying time to determine the constants of the four selected drying models. The R^2, χ^2 and RMSE used to determine the goodness of fit of the models are shown in Tables 3, 4, 5 and 6. The Parabolic model gave the highest R^2 value which varied from 0.9963 to 0.9775 for experimental conditions considered in this study. The values of χ^2 and RMSE for the Parabolic model which varied from 0.000448 to 0.004723 and 0.01644 to 0.058882 respectively were the lowest for all the models considered. From the tables, it is obvious that the Parabolic model therefore represents the drying characteristics of pretreated pumpkin (for individual drying runs) better than the other models (Generalized exponential, Exponential, Logarithmic, Page or Midilli–Kucuk) considered in this study. The comparison between experimental moisture ratios and predicted moisture ratios obtained from the Parabolic model at drying air temperature of 40 °C, 60 °C and 80 °C for pumpkin samples are shown in Fig. 3. The suitability of the Parabolic model for describing the pumpkin drying behaviour is further shown by a good conformity between experimental and predicted moisture ratios as seen in Fig. 3. This is similar to the observations of Doymaz (2010) for drying of red apple slices at 55, 65 and 75 °C.

Conclusion

The effect of temperature and pre-treatments on thin layer drying of pumpkin in a hot-air dryer was investigated. Increase in drying temperature from 40 to 80 °C decreased the drying time from 5 hours to 4 hours for all the samples considered. The pretreated samples dried faster than the untreated samples. Samples pretreated with steam blanching had shorter drying times (hence higher drying rates) compared to water blanched, oil-water blanched and control samples The entire drying process occurred in falling rate period and constant rate period was not observed. The suitability of four thin-layer equations to describe the drying behaviour of pumpkin was investigated. The model that had the best fit with highest values of R^2 and lowest values of χ^2, MBE and RMSE was the Parabolic model. Thus this model was selected as being suitable to describe the pumpkin drying process for the experimental conditions considered.

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