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Microwave assisted hot air drying of papaya (*Carica papaya* L.) pretreated in osmotic solution

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In this study, mathematical modeling of microwave (MW) assisting hot air drying of thin-layer papaya (*Carica papaya* L.) slices with 5 ± 1 mm thickness in an experimental drying process is presented. The osmosis solution comprised 50% sucrose + 2% NaCl solutions. The osmosis dehydration characteristics obtained by solid gain (SG), water loss (WL) and weight reduce (WR) parameters. The drying air velocity (0.9 ± 0.1 m/s) and temperatures (40, 50 and 60°C) were examined in drying papaya slices from initial moisture content of 700 ± 2% (d.b) to moisture content of 20 ± 1% (d.b). The slices were subjected to 10 s 540 W MW power at each 15 min interval as an auxiliary drying method. Ten thin-layer drying models were fitted to drying experimental data of papayas, implementing non-linear regression analysis techniques. The statistical analysis using correlation coefficient (R^2), chi-square (χ^2) and root mean square error (RMSE) concluded that, the best model in terms of fitting performance for MW assisted hot air drying of papaya pretreated in osmosis solution at 40 and 50°C was page model while that at 60°C was two-term model.

Key words: Papaya, mathematical modeling, microwave (MW), cabinet drier.

INTRODUCTION

Drying is a technique of conservation that consists of the elimination of large amount of water present in a food by the application of heat under controlled conditions, with the objective to diminish the chemical, enzymatic and microbiological activities that are responsible for the deterioration of foods (Barnabas et al., 2010). Air-drying is one of the traditional method which used for food dehydration by means of some kinds of driers such as cabinet drier, fluidized-bed drier, but recent studies pointed out the efficiency in water removal when air drying is combined with microwaves (MW) heating (Momenzadeh et al., 2010; Funebo and Ohlsson, 1998; Drouzas et al., 1999). Fruit dehydration by immersion in osmotic solutions has been of rising interest during the last decades since it can improve food quality when combined with other type of dehydration method (Mauro and Menegalli, 2003). To carry out osmotic dehydration, fruit pieces were immersed in a concentrated solution containing one or more solutes.

In the osmotic dehydration, because of high concentration in solutes (sugar and salt), promoting two simultaneous flows in counter current, a water outflow from the food, and an inflow of solutes from the solution to the food, due to the establishment of gradients of chemical potential of water and solutes (Petchi and Manivasagan, 2009). In the process, more water than solute is usually transfers due to the deferential permeability of cellular membranes (Mauro and Menegalli, 2003). MW drying is a rapid dehydration technique that can be applied to specific foods. Compared to conventional hot air drying, MW drying is rapid, more uniform and energy efficient and includes

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space savings and energy drying. In MW, processing the energy is transferred directly to the sample producing a volumetric heating (Abbasi and Mowla, 2008; Oliveira and Franca, 2002). Momenzadeh et al. (2010) studied drying characteristics of shelled corn (*Zea mays* L*)* in a fluidized bed dryer assisted by MW heating. Their results showed that, increasing the drying air temperature resulted in up to 5% decrease in drying time while in the MW -assisted fluidized bed system, the drying time decreased dramatically up to 50% at a given and corresponding drying air temperature at each MW energy level.

The drying kinetics of food is a complex phenomenon and requires dependable models to predict drying behavior (Sharma et al., 2003). Kingsly and Sing (2007) studied thin-layer drying of pomegranate arils in a cabinet drier at drying temperatures of 50, 55, and 60°C. They reported that, the page model satisfactorily represented the drying characteristics of pomegranate arils than other models. This present article focuses on mathematical modeling of papaya during drying using MW assisted hot air drying pretreated in osmotic solution (osmosis-cabinet- MW) process as a new kind of combined drying method in different hot air drying temperatures (40, 50 and 60°C). The MR (moisture ratio) for each drying temperature was obtained and a suitable thin-layer drying model to describe the drying process was developed.

MATERIALS AND METHODS

Sample preparation

Papayas (*Carica papaya L.*) were provided by a producer in Sistan and Blouchestan province- Iran. Papayas were stored at 4°C prior to use in the drying experiment. After one-day storage in a refrigerator, it was taken and reached to room temperature (24 ± 1°C) 1 h before the start of the experiment. For all experiments papayas were peeled and sliced (5 ± 1 mm thickness) with a stainless steel knife in approximately 5 × 2 cm^2. The initial moisture content of papaya was 700 ± 2 % (d.b.). The pH and Brix of fresh papaya was 5.1 and 11.4, respectively.

Preparation of osmosis solution

Osmotic solution was prepared with sucrose 50 and 2% NaCl, which were obtained from Merck Company, Germany. The product to solution ratio was prepared 1:10 (weight basis) (Antonio et al., 2004). Temperature controlled mixing tank was used for osmotic operation.

Cabinet dryer and microwave setup

Cabinet dryer with controllable airflow and temperature system and air humidity monitoring system utilized for hot air drying process. The absolute humidity and the hot air velocity for all of drying temperatures were 0.6 ± 0.02 g/kg dry air and 0.9 ± 0.1 m/s, respectively.

Combination oven MW system (LG, Korea) with power control dial (power output 180 to 900 W) was used in combination with hot air drying method.

Microstructure analysis

SEM imaging of papaya was carried out to exhibit the surface properties of the samples. The thin layers prepared from the untreated and dried papaya coated with gold using an ion sputter (Fisons Instruments, UK). The coated samples were viewed and photographed using the scanning electron microscope (model 5526, Cambridge, UK) at 20 kV.

Experimental procedure

Osmosis treatment

Papaya slices were weighed and placed into an osmotic solution in a dynamic conditions provided by agitation (150 rpm) at room temperature (24 ± 1°C) for 4 h. The product to solution ratio was 1:10 (w/w). The samples were then removed from the solution and were blotted in order to remove excess solution and then dried with filter paper for almost 5 min (Antonio et al., 2004). It was weighed prior to placing in the cabinet drier. For each treatment, water loss (WL), solid gain (SG) and weight reduction (WR) were evaluated based on following equations and the results were expressed in g/100g of initial fresh fruit weight:

$$WL = \frac{(ww_0)-(w_t-ws_t)}{(ws_0+ww_0)} \tag{1}$$

$$SG = \frac{(ws_t-ws_0)}{(ws_0+ww_0)} \tag{2}$$

$$WR = WL - SG \tag{3}$$

Where, ww_0 is the weight of water in initial sample, ws_0 is the weight of solids initially present in the fruit (g); w_t and ws_t are the weight of the fruit (g) and the weight of solids at the end of treatment (g), respectively (Petchi and Manivasagan, 2009; Mujica-Paz et al., 2003; Lazarides et al., 1995). The changes in SG as well as WL determined consecutively each 30 min after the process for 4 h. All the experiments were done in triplicate.

Microwave assisted hot air drying

One layer of samples after 4 h osmosis dehydration placed in the cabinet dryer at 3 temperature of 40, 50, and 60°C for hot air drying process and weight – time data were recorded consecutively using a digital weighter (….) until 20 ± 1% (d.b) moisture content was achieved from initial moisture content of 700 ± 2% (d.b). In connection with using MW energy as an accessory drying method which combined with hot air drying, selected samples were exposed to MW energy following convection hot air drying. The MW power output was set to 540W. Fruits were subjected to 10 seconds micro power at each 15 min interval. A sample for each treatment was placed in an oven set to 105°C to obtain the solid content (total moisture content). The MR vs. drying time curve was obtained for each treatment.

Mathematical modeling

Ten models of thin layer drying described in Table 1 were investigated to find the most suitable drying model for the drying process of papaya. In these models, the moisture ratio was simplified to M/M_0 instead of $(M - M_e)/(M_0 - M_e)$ as the value of M_e is relatively small compare to M or M_0 (Doymaz, 2004). Correlation coefficient (R^2) was one of the primary criteria to select the best

Table 1. Mathematical models for thin-layer drying.

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	Westerman et al. (1973)
Page	$MR = \exp(-kt^n)$	Guarte (1996)
Modified Page	$MR = \exp(-kt)^n$	Yaldiz et al. (2001)
Henderson and Pabis	$MR = a.\exp(-kt)$	Yagcioglu et al. (1999)
Logarithmic	$MR = a.\exp(-kt) + c$	Yaldiz et al. (2001)
Two-term	$MR = a.\exp(-k_0 t) + b.\exp(-k_1 t)$	Rahman et al. (1997)
Exponential two-term	$MR = a.\exp(-kt) + (1-a)\exp(-kat)$	Yaldiz et al. (2001)
Wang and Sing	$MR = 1 + at + bt^2$	Ozdemir and Devres (1999)
Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Yaldiz and Ertkin (2001)
Midilli et al.	$MR = a\exp(-kt^n) + bt$	Sacilik et al. (2006)

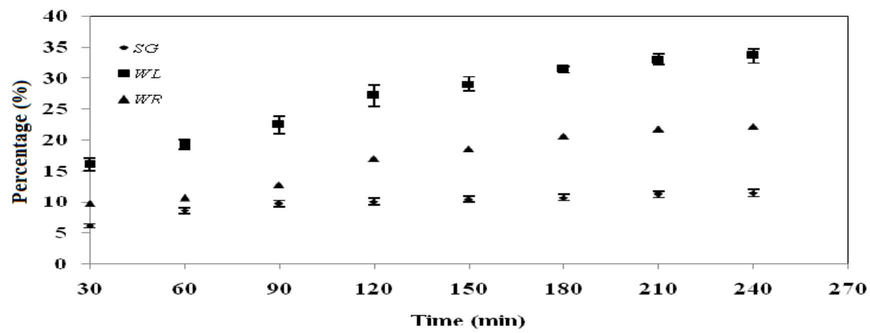

Figure 1. The changes in SG, WL and WR during osmosis dehydration.

model. Other statistical parameters such as chi-square (χ^2) and root mean square error (RMSE) were used to determine the quality of the fit. These parameters can be calculated as given equations: (Singh and Sodhi, 2000; Togrul and Pehlivan, 2002).

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})^2 (MR_{pre,i} - \overline{MR}_{pre})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})^2 \sum_{i=1}^{N}(MR_{pre,i} - \overline{MR}_{pre})^2} \quad (4)$$

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

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{per,i})^2}{N - z} \quad (6)$$

The model is said to be good if R^2 value is high, χ^2 and RMSE values are low (Sarsavadia et al., 1999; Togrul and Pehlivan, 2002).

RESULTS AND DISCUSSION

Osmosis treatment

The moisture content of the fresh papaya was 700 ± 2% (d.b). The effect of osmosis treatment on dehydration of the samples pointed through the changes in parameters of the process (SG, WL, and WR) during dehydration that are shown in Figure 1. The results showed that, the WL, SG and WR of papaya increased with increasing immersion time in the osmotic solution. These results were in agreement with that of Petchi and Manivasagan (2009) and Heng et al. (1990).

In the most intense processing condition (after 4 h immersion), water loss and weight loss attained to 33.64 and 22.19 g/100 g of initial fresh fruit, respectively. Figures 1 shows that, at the end of the osmosis treatment especially at 210 and 240 min after immersion, the changes in WL were very low that the slope of the changes was near to zero. This is to say that, the rate of mass transfer by increasing the immersion time will be lower because of the decreasing in driving force between the solution and the product that hinders the mass transfer. It means that, the system comes to equilibrium.

Microwave assisted hot air drying

Figure 2 shows the drying curves (moisture ratio versus time) obtained under specific process conditions. As

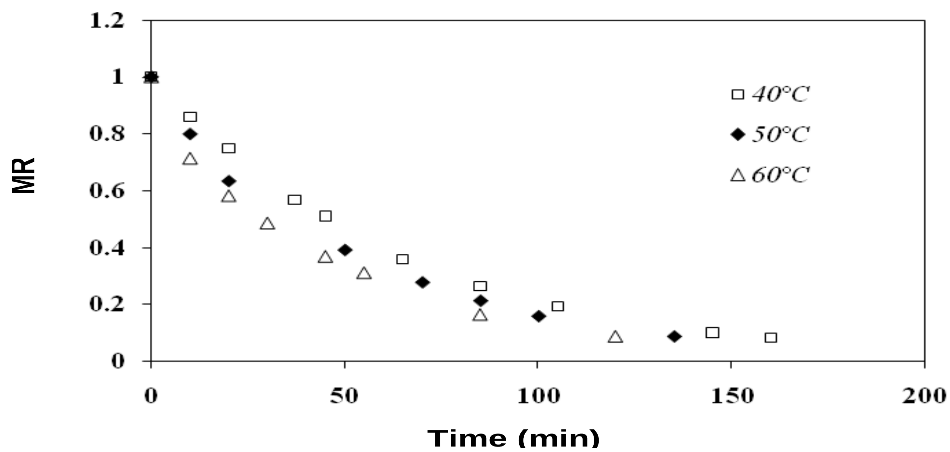

Figure 2. Effect of osmosis-cabinet- MW drying time on moisture ratio at 40, 50 and 60°C.

Table 2. Regression analysis coefficients of mathematical drying models for osmosis-cabinet-microwave drying process at 40°C

Model name	Model coefficients	R^2	RMSE	χ^2
Newton	K = 0.015	0.999	0.007	5.05E-05
Page	K = 0.013 n =1 .030	0.999	0.004	2.38E-05
Modified page	K = 0.015 n =1.027	0.999	0.007	5.68E-05
Henderson and pabis	K = 0.015 a =1.007	0.999	0.006	4.52E-05
Logarimetric	K = 0.015 a =1.015 c = -0.011	0.999	0.005	4.28E-05
Two-term	K_0 = 1.015 K_1 = 0.015 a = -0.015 b = 1.015	0.999	0.005	4.24E-05
Exponential two-term	K = 0.017 a = 1.392	0.999	0.005	2.71E-05
Approximation of diffusion	K = 0.307 a = -0.016 b = 0.051	0.999	0.005	3.49E-05
Wang and Sing	A = -0.012 b = 4.36E-05	0.997	0.019	0.000
Midilli et al.	K = 0.029 n = 0.810 a = 1.021 b = -0.000	0.995	0.021	0.001

expected, increasing air temperature reduced the drying time. At higher temperature due to the quick removal of moisture, the drying process was shorter. The decrease in drying time with increase in drying temperature may be due to increase in water vapor pressure within the papaya pieces, which increased the migration of moisture especially as the drying occurs only in falling rate period. Similar observation was reported for apple purees (Vergara et al., 1997).

The moisture ratio of papaya reduced exponentially as the drying time increased. Continuous decrease in moisture ratio indicates that, diffusion governed the internal mass transfer (Haghi and Amanifard, 2008).

Mathematical modeling

Figure 2 shows drying curves of osmosis-cabinet- MW process which exhibits the effect of drying time on moisture ratio. The MR values were fitted against the drying time for each temperature by applying the non-linear regression analysis technique. The best model for each treatment obtained using comparison of statistical parameters of R^2, RMSE and χ^2. The characteristics of the curves fitting attributed to 40, 50 and 60°C of osmosis-cabinet- MW drying process are shown in Tables 2 to 4, respectively.

As the results show, Page model demonstrated the best curve fitting results (highest R^2, lowest RMSE and χ^2) at 40 and 50°C while Two-term model represented the best characteristics for the thin-layer drying of papaya at 60°C. These models can be used as the best ones to predict the drying behavior. Figure 3 shows the coincidence between experimental MR and predicted MR obtained from the best model related to each drying condition, which banded around the straight line *(X = Y)*; that proved the feasibility of the selected models in describing the drying behavior of *Carica papaya*.

Microstructure analysis

Figure 4 shows the scanning electron microscopy images of fresh papaya. Papaya at the end of osmosis

Table 3. Regression analysis coefficients of mathematical drying models for osmosis-cabinet-microwave drying process at 60°C.

Model name	Model coefficient	R^2	RMSE	χ^2
Newton	k = 0.023	0.990	0.033	0.001
Page	k = 0.048 n=0.800	0.998	0.011	0.000
Modified page	k = 0.027 n = 0.851	0.990	0.033	0.001
Henderson and pabis	k = 0.021 a = 0.949	0.988	0.027	0.002
Logarithmic	k = 0.025 a = 0.899 c = 0.066	0.991	0.023	0.002
Two-term	K_0 = 0.018 K_1 = 0.896 a = 0.859 b = 0.140	0.999	0.003	3.96E-05
Exponential two-term	k = 0.128 a = 0.148	0.998	0.011	0.000
Approximation of diffusion	k = 0.025 a = 0.152 b = 0.863	0.990	0.033	0.002
Wang and Sing	a = -0.018 b = 9.36E-05	0.971	0.053	0.004
Midilli et al.	k = 0.0617 n = 0.711 a = 0.998 b = -0.0006	0.999	0.006	9.14E-05

Table 4. Regression analysis coefficients of mathematical drying models for osmosis-cabinet-microwave drying process at 50°C

Model name	Model coefficient	R^2	RMSE	χ^2
Newton	k = 0.018	0.999	0.007	8.11E-05
Page	k = 0.022 n = 0.952	0.999	0.002	6.4E-06
Modified Page	k = 0.019 n = 0.955	0.999	0.007	9.46E-05
Henderson and Pabis	k = 0.018 a = 0.989	0.999	0.006	6.34E-05
Logarithmic	k = 0.019 a = 0.097 c = 0.022	0.999	0.004	3.91E-05
Two-term	K_0 = 0.017 K_1 = 0.967 a = 0.974 b = 0.025	0.999	0.003	2.71E-05
Exponential two-term	k = 0.025 a = 0.530	0.999	0.003	1.97E-05
Approximation of diffusion	k = 0.017 a = 0.933 b = 4.004	0.999	0.003	2.56E-05
Wang and Sing	a = - 0.014 b = 6.030	0.993	0.027	0.001
Midilli et al.	k = 0.036 n = 0.808 a =1.017 b =-0.0005	0.998	0.012	0.000

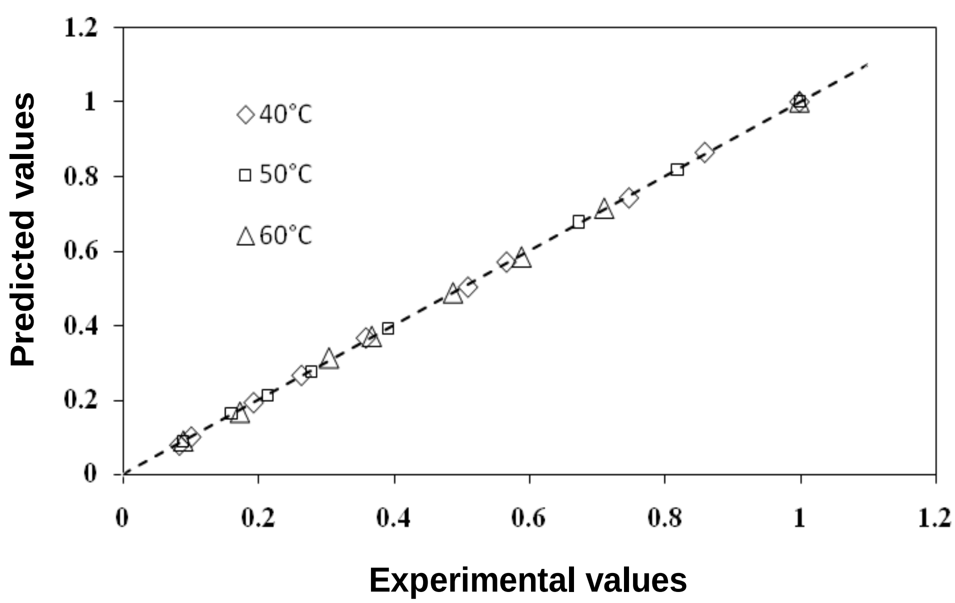

Figure 3. Comparison of the experimental and predicted MR (by the best resulting model).

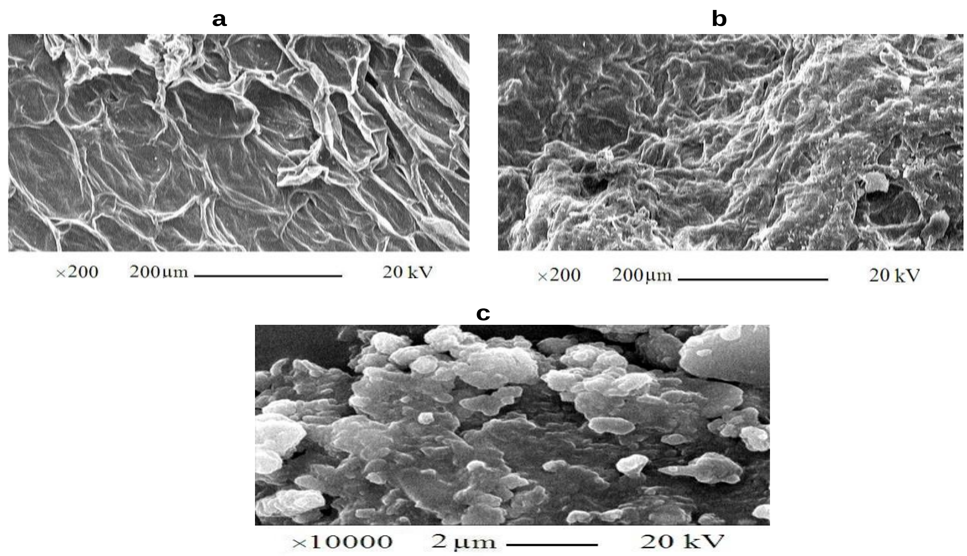

Figure 4. SEM images of a: fresh papaya, b: dried papaya at 50°C using osmosis-cabinet- MW process, c:osmosis treated papaya for 4 h.

dehydration (after 4 h) and papaya sample at the end of osmosis-cabinet- MW drying process at 50°C. Figures 4b and 4c clearly exhibit the sucrose particles that migrated to sample's surface. These particles are responsible for increasing the SG during 4 h immersion in the 50% sucrose + 2% NaCl solution. Comparsion of Figures 4a with 4b obviously shows that, the external porosity of the samples obtained from osmosis-cabinet- MW drying process was less than that of the fresh sample. The similar results reported for garlic and carrot slices (Lozano et al., 1980).

Conclusion

As the results, Page model showed the best curve fitting results for the experimental moisture ratio values for osmosis-cabinet- MW drying process at two temperatures of 40 and 50°C. In addition, Two-term model represented the best fitting traits to predict the drying characteristics of papaya slices during the drying process at 60°C. So, the introduced models can be used to predict moisture content of papaya fruit slices during drying at each mentioned temperature. The less porosity obtained for dried papayas using osmosis-cabinet- MW drying process which observed from scanning electron microscopy pictures causes more easily transportation of their slices because of lesser bulk volume.

Nomenclature: a, b, c, n, Empirical coefficients in drying models; **k,** k_0, k_1, empirical constants in drying models; **M,** moisture content at any time of drying; M_e, **MR,** equilibrium moisture content; M_0, initial moisture content; moisture ratio; $MR_{pre,i}$, ith predicted M.R; $MR_{\exp,i}$, ith experimentally observed M.R; **N,** number of observations; **z,** number of constants in models; **R^2,** coefficient of determination; **RMSE,** root of mean square error; χ^2, reduced chi-square; **ww_0,** Weight of water in initial sample; **ws_0,** Weight of solids initially present in the fruit; **ws_t,** weight of solids at the end of osmosis treatment; **w_t,** weight of the fruit.

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