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Mathematical Modeling of Green Pepper Drying in Microwave-convective Dryer

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ABSTRACT

In this study, green pepper was dried by a laboratory scale microwave-convective dryer. The effects of microwave power on drying rate, effective moisture diffusivity, and energy consumption of green pepper were studied at four different microwave powers of 180, 360, 540, and 720W. The drying data were fitted to the four thin-layer drying models. The moisture reduction of the green pepper samples, from 2.894 to 0.1 kg water kg^{-1} dry matter, lasted 120 and 495 seconds at microwave power of 720 and 180W, respectively. The drying model assessment revealed that the Midilli model exhibited the best performance in fitting the experimental data, providing the highest R^2 (0.927), and the lowest *RMSE* (0.2065) and χ^2 (0.0555). With increase in microwave (drying) power from 180 to 720W, moisture diffusivity increased from 6.249×10^{-9} to 3.445×10^{-8} m^2 s^{-1}. Results also indicated that drying rate increased by increasing the microwave power and decreased continuously with passing of drying time and decreasing moisture content. The least specific energy consumption (7.2 MJ kg^{-1} water) was at microwave power of 360 W and the highest (9.26 MJ kg^{-1} water) was at 540W.

Keywords: Drying rate, Energy consumption, Microwave power, Moisture diffusivity.

INTRODUCTION

Pepper has been dried for many centuries. The major dried pepper producers and exporter countries are India, Iran, Turkey, Australia, Hungary, Morocco, Tunisia and Israel. For optimum conduction of effective storing, marketing, and processing, peppers have to be dried from an initial moisture content of about 3–4.8 to final 0.1 kg water kg^{-1} dry mater at a temperature range between 50 and 80°C (Nogueira *et al.*, 2005).

Major disadvantages of hot air drying of foods are low energy efficiency and lengthy drying time during the falling rate period, which may cause serious damage to the flavour, colour, nutrients, and rehydration capacity of the dried product. Microwave drying of vegetables have several advantages including the shortening of drying time and formation of suitable dry product characteristics due to the increase in temperature in the center of the material.

Because of the concentrated energy of a microwave drying system, only 20-35% of the floor space is required, as compared to conventional heating and drying equipment (Vadivambal and Jayas, 2007; Maskan, 2000). In microwave drying, operational cost is lower than other methods, because energy is not consumed in heating the walls of the apparatus or the environment (Mullin, 1995; Thuery, 1992).

Passamia and Saravia (1997a; 1997b) developed a phenomenological drying model of red pepper variety ‘‘Morron’’.

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Kooli *et al.* (2007) studied the drying of red pepper in open sun and greenhouse conditions at 32, 42 and 49ºC drying air temperatures, 0.5, 1 and 1.5 m s^{-1} drying air velocities, and zero, 380, 520, and 800 W m^{-2} incident radiations. Soysal *et al.* (2009) investigated mathematical modeling of microwave–convective drying of red pepper. They showed that the convective air drying treatments were about 10.4–19.6 times and 2.5–11.8 times longer than the continuous microwave–convective drying and the intermittent microwave–convective treatment, respectively. Akpinar *et al.* (2003) developed a mathematical model of convective drying of red pepper slices at inlet drying air temperatures of 55, 60, and 70°C at an air velocity of 1.5 m s^{-1}. They concluded that the diffusion drying model could adequately describe the one layer convective drying behavior of red pepper slices.

Most of the previous studies on drying of pepper have focused on solar or convective hot-air drying, and the effects of drying on drying kinetics, moisture sorption isotherms and mathematical modeling of the drying process (Akpinar *et al*., 2003; Kooli *et al*., 2007; Doymaz and Pala, 2002; Vega *et al*., 2007; Scala and Crapiste, 2008). There is no available report regarding the effectiveness of microwave-convective drying of green pepper. Therefore, the objective of this study was to investigate the drying behavior of green pepper in microwave-convective dryer and develop suitable mathematical drying model.

MATERIALS AND METHODS

Fresh green peppers were harvested from a green house in the Ilam province of Iran, in September 2009 and were stored in the refrigerator at temperature of 4°C until the experiments were carried out. Before the experiments, the samples were removed from the refrigerator and allowed to reach room temperature (about 18°C). The green peppers (average dimensions of 0.7±0.1 cm diameter and 6±1 cm length) were washed and halved. After removing the seed samples, they were cut to the length of 2 cm (Figure 1). The green pepper had an initial moisture content of 73.33% (wet basis), which was determined by drying in a convective oven at 103±1°C until the weight did not change any more (Kashani Nejad *et al*., 2002).

Drying Equipment and Method

The drying was performed in a microwave dryer which was developed for this purpose (Figure 2). The dryer consisted of a microwave oven (model MG-607 900W, LG, Korea) and a variable speed fan which passed ambient air (about 18ºC) through the oven. Air velocity was kept at a constant value of 1.0±0.1 m s^{-1} measured with a vane

Figure 1. Preparation of green pepper sample.

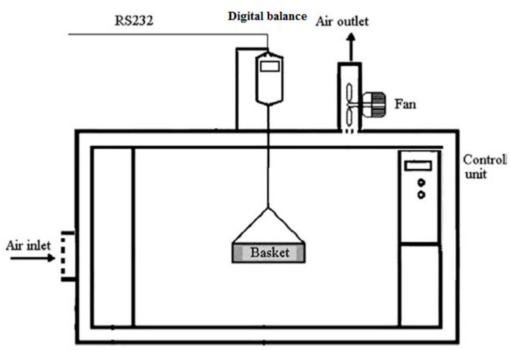

Figure 2. Diagram of microwave drying system.

probe anemometer (model AM- 4202, Lutron, Korea) flowed perpendicular to the bed.

The microwave power was regulated by a control terminal which could control both microwave power level and emission time. Drying trial was carried out at four different microwave generation powers: 180, 360, 540, and 720W. About 15 g of the samples were suspended beneath a digital balance (with accuracy of ±0.01 g) into the microwave oven by using a mesh basket (Figure 2). The digital balance was interfaced to a computer by a RS-232 cable, and the drying weight loss of the green pepper layer was recorded on-line every 15 seconds until the weight did not change any more. Three replications of each experiment were performed according to a preset microwave output power.

Mathematical Modeling

The moisture ratio (MR) was calculated using the following equation:

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

Where, MR is moisture ratio (dimensionless); M_t is moisture content at time t (kg water kg^{-1} dry matter); M_e is equilibrium moisture content (kg water kg^{-1} dry matter); and M_0 is initial moisture content (kg water kg^{-1} dry matter). The value of M_e is relatively small compared to M_t or M_0 for long drying times. Thus, the moisture ratio can be simplified to the following equation (Wang *et al.*, 2007; Maskan, 2000; Soysal, 2004):

$$MR = \frac{M_t}{M_0} \tag{2}$$

Numerous mathematical models have been proposed to describe the drying characteristics of agricultural products. Drying curves were simulated using five empirical models, listed in the Table 1. The models were evaluated based on coefficient of determination (R^2), root mean square error (RMSE), and Chi-squared (χ^2). The best model describing the thin layer drying characteristics of green pepper was chosen as the one with the lowest Chi-squared (χ^2) and *RMSE*, and the highest R^2. The statistical values are defined as follows (McMinn, 2006; Ozbek and Dadali, 2007):

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - Z} \tag{4}$$

Where, MR_{exp} is experimental moisture ratio (dimensionless); MR_{per} is predicted moisture ratio (dimensionless); Z and N are number of constants and observations, respectively; χ^2 is Chi-squared (dimensionless).

Effective Moisture Diffusivity

Fick's second law of the unsteady state diffusion was selected to determine the moisture diffusivity of green pepper as described in the following equation:

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \tag{5}$$

Where, D_{eff} is the effective moisture

Table 1. Thin-layer drying models that were fitted to the experimental data.

Model name	Model [a]	Reference
Henderson –Pabis	$MR= a\exp(-kt)$	Motevali *et al.* (2012)
Logarithmic	$MR= a\exp(-kt)+b$	Yaldiz and Ertekin (2001)
Page	$MR = \exp(-kt^{n})$	Wang *et al.* (2007)
Midilli	$MR= a\exp(-kt^n)+bt$	Midilli *et al.* (2002)
Wang -Singh	$MR= 1+bt+at^2$	Tahmasebi *et al.* (2011)

[a] Where, *a, b, k* (1 min^{-1}) and n are drying constants in the models.

diffusivity (m^2 s^{-1}) and M is the material moisture content (kg water kg^{-1} dry matter).

Fick's second law in thin layer was solved with the assumptions of mass transfer being only by diffusion and constant diffusion coefficient being described with the following equation (Ozbek and Dadali, 2007):

$$MR = \frac{8}{\pi^2}\sum_{0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{eff}}{H^2}t\right) \quad (6)$$

Where, t is drying time (s) and H is thickness of the layer (m). When the mass transfer Fourier number is greater than 0.2, Equation (6) can be simplified to Equation (7):

$$t = \left(\frac{H^2}{\pi^2 D_{eff}}\right)\ln\left(\frac{8}{\pi^2}\frac{M_t}{M_0}\right) \quad (7)$$

The effective moisture diffusivity can be determined from the slope of the normalized plot of $ln(M_t/M_0)$ versus drying time.

Drying Rate

Drying rate (DR) is expressed as the amount of the evaporated moisture over time. The DR (kg water kg^{-1} dry matter.min) of the green pepper during drying process can be determined using the following equation:

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (8)$$

2.6. Specific Energy Consumption

The specific energy consumption for drying of green pepper was calculated from the following equation (Ozkan *et al.*, 2007):

$$E_s = \frac{P.t\times10^{-6}}{m_w} \quad (9)$$

Where, E_s is the specific energy consumption to evaporate a unit mass of water from the product (MJ kg^{-1} water), P is the microwave output power (W), t is drying time (s), and m_w is the mass of evaporated water (kg).

RESULTS AND DISCUSSION

Drying Kinetic Models

Figure 3 shows how moisture ratio of green pepper decreased with increasing drying time under various microwave output powers. The moisture ratio dropped rapidly at the beginning and then decreased slowly as drying continued. Falling rate periods decreased by increasing drying power. The drying time until the moisture ratio of 0.5 was 185, 97, 70 and 53 seconds for the samples dried at 180, 360, 540 and 720W, respectively. Compared to hot air drying reported by Akpinar *et al.* (2003), Doymaz and Pala (2002), Vega *et al,* (2007), and Scala and Crapiste (2008), microwave-convective dryer technique used in this study could greatly reduce the drying time of green pepper.

Soysal *et al.* (2009) dried 300 g red pepper

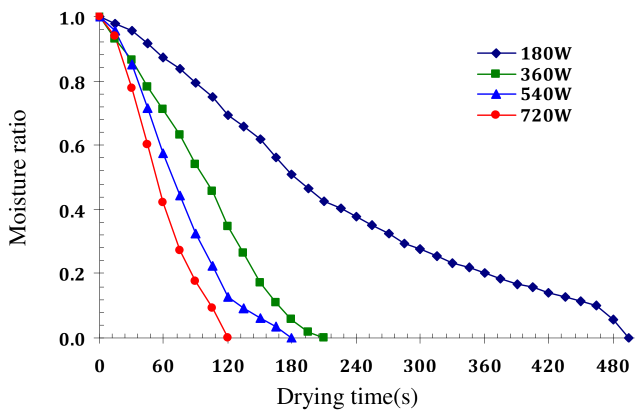

Figure 3. Moisture ratio vs. drying time for green pepper under different drying powers.

by microwave-convective drying under microwave power of 597.20 to 697.87W and convective air at 33ºC and 1.5 m s^{-1} in longer time (about 10-14 times) compared to this study (15 g green pepper, under microwave power of 540 to 720W and convective air at 18ºC and 1 m s^{-1}). This was because the increase in air velocity (1.5 times) and mass of samples (20 times) resulted in low energy absorption and cooling of drying product, i.e. reducing its temperature and thus increasing the drying time. Several other researchers (Ozbek and Dadali, 2007; Sharma and Prasad, 2006) have also reported similar findings.

In order to find the most suitable form of drying model, different mathematical models were selected using the experimental data to determine the pertinent coefficients for each model by applying the non-linear regression analysis technique. The models are described in Table 2. For all models, the R^2, χ^2, and *RMSE* were higher than 0.927 and lower than 0.0555 and 0.2065, respectively. Midilli Model provided the highest R^2 and lowest χ^2 and *RMSE*, thus, it was selected for predicting the moisture ratio of green pepper.

Validation of the selected model was confirmed by comparing the predicted moisture contents with the measured values at different microwave (drying) powers. The plot of experimental versus predicted moisture ratios by Midilli model are shown in Figure 4. The data points are closely banding around 1:1 line, which indicates very good agreement between the calculated and the experimental data. Therefore, Midilli model could adequately describe the drying behavior of green pepper.

Effective Diffusivity

The effective moisture diffusivities at different microwave powers are shown in Table 3. With increase in microwave (drying) power from 180 to 720W, moisture diffusivity increased from 6.249×10^{-9} to 3.445×10^{-8} m^2 s^{-1}. The increase in

Table 2. Coefficients of the fitting statistics of various thin layer models at different drying powers.

Model name	P (W)	Constants	R^2	χ^2	*RMSE*
Henderson-Pabis	180	*a*= 1.114, *k*= 0.315	0.934	0.0031	0.0529
	360	*a*= 1.125, *k*= 0.614	0.927	0.0105	0.0916
	540	*a*= 1.142, *k*= 0.859	0.946	0.0087	0.0819
	720	*a*= 1.112, *k*= 1.049	0.978	0.0122	0.0901
Logarithmic	180	*a*= 1.362, *b*= -0.302, *k*= 0.167	0.994	0.0018	0.0400
	360	*a*= 3.654, *b*= -2.622, *k*= 0.101	0.991	0.0151	0.1098
	540	*a*= 1.617, *b*= -0.537, *k*= 0.398	0.984	0.0034	0.0513
	720	*a*= 2.674, *b*= -1.619, *k*= 0.259	0.989	0.0044	0.0544
Page	180	*n*= 1.384, *k*= 0.139	0.997	0.0003	0.0177
	360	*n*= 1.839, *k*= 0.319	0.990	0.0013	0.0333
	540	*n*= 1.812, *k*= 0.552	0.999	0.0001	0.0075
	720	*n*= 1.845, *k*= 0.872	0.998	0.0004	0.0159
Midilli	180	*a*= 1.009, *b*= -0.002, *k*= 0.147, *n*= 1.337	0.997	0.0003	0.0171
	360	*a*= 1.003, *b*= -0.053, *k*= 0.278, *n*= 1.523	0.998	0.0004	0.0180
	540	*a*= 1.003, *b*= -0.004, *k*= 0.547, *n*= 1.760	1	0.0001	0.0071
	720	*a*= 1.008, *b*= -0.031, *k*= 0.788, *n*= 1.703	0.999	0.0002	0.0104
Wang - Singh	180	*a*= 0.0079, *b*= -0.181	0.991	0.0009	0.0281
	360	*a*= 0.0085, *b*= -0.333	0.992	0.0011	0.0308
	540	*a*= 0.0553, *b*= -0.513	0.979	0.0030	0.0500
	720	*a*= 0.0349, *b*= -0.585	0.985	0.0023	0.0426

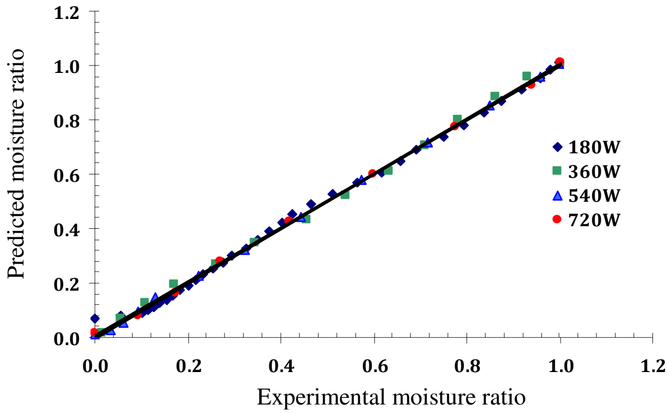

Figure 4. Experimental and predicted (from Midilli model) moisture ratio values at different microwave powers.

microwave power resulted in rapid heating of the product, thus increasing the vapor pressure inside the product, thereby accelerating the diffusion of moisture towards the surface. The observed values of D_{eff} lie within the general range of 10^{-11} to 10^{-9} m^2 s^{-1} for food materials (Doymaz, 2005) and are comparable with the reported moisture diffusivity of red pepper (2.75×10^{-8} m^2 s^{-1}), which was dried with hot air at 60°C (Doymaz and Pala, 2002)

The relationship between microwave power and moisture diffusivity can be represented as:

$$D_{eff} = 7.289 \times 10^{-8} \exp\left(-\frac{427.3}{P}\right), \quad R^2 = 0.95 \qquad (10)$$

Where, D_{eff} is the effective moisture diffusivity (m^2 s^{-1}) and P is the microwave power (W).

Table 3. Effective diffusion coefficient at different microwave powers.

P (W)	D_{eff} (m^2 s^{-1})
180	6.249×10^{-9}
360	2.863×10^{-8}
540	3.258×10^{-8}
720	3.445×10^{-8}

Drying Rate

The variation of drying rate with drying time is shown in Figure 5. Drying rate increased initially until about 60 seconds and, then, decreased continuously with time. The moisture content of the green pepper was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. This shows that diffusion is the dominant physical mechanism governing moisture movement in the green pepper. These results are in good agreement with previous studies on various vegetables (Soysal *et al*., 2009; Figiel, 2009; Doymaz, 2005; Sumnu *et al*., 2005; Togrul and Pehlivan, 2003).

The higher drying rate at high microwave power could be due to higher heating energy, which speeds up the movement of water molecules and results in higher moisture diffusivity. This result is in agreement with the earlier observations made by Ozbek and Dadali

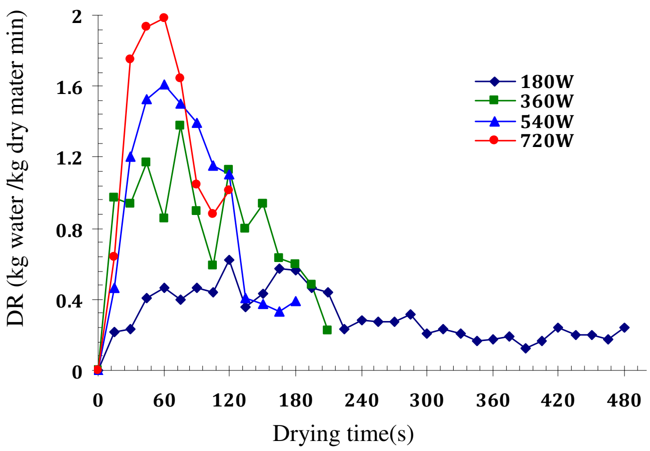

Figure 5. Variation of drying rate (DR) with drying time for pepper under different drying powers.

(2007), Ozkan *et al.* (2007), and Wang *et al.* (2007).

Specific Energy Consumption

Figure 6 shows the values of specific energy consumption for drying of green pepper at different microwave powers. The specific energy consumption values varied between 7.20 and 9.26 MJ kg^{-1} water at microwave powers of 360 and 720 W, respectively. There was no clear trend for changes in specific energy consumption. This phenomenon agreed with the drying characteristics of many bioproducts under thin layer drying (Motevali *et al.*, 2011). Drying at 720W instead of 360W, the drying time decreased about 74%, while the energy consumption increased about 5%. The microwave energy consumption values for green pepper were relatively high as compared to spinach (Ozkan *et al.*, 2007) and parsley (Soysal *et al.*, 2006).

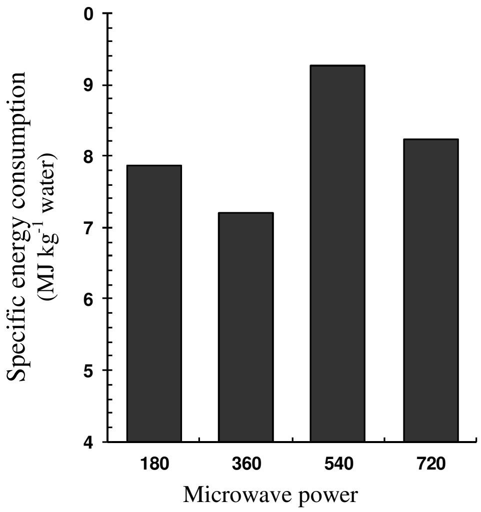

Figure 6. Specific energy consumption during the drying of green pepper at different microwave powers.

CONCLUSIONS

In the microwave drying process of green pepper, drying took place mainly in the falling rate period after a very short accelerating period at the beginning in drying processes of samples, and no constant rate period was observed. Drying time decreased considerably by increasing microwave output power. Therefore, microwave output power had a crucial effect on the drying rate. Average drying rates of green pepper changed from 0.308 to 1.210 kg water kg^{-1} dry matter.min for the output power between 180 and 720W, respectively. Also, the results showed that green pepper drying kinetics were best fitted by Midilli model. The effective diffusivity varied from 6.249×10^{-9} to 3.445×10^{-8} m^2 s^{-1}, by increasing microwave power. Specific energy consumption values ranged from 7.20 to 9.26 MJ ka^{-1} water.

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مدل ریاضی خشک کردن فلفل سبز در خشک کن میکروویو–همرفتی

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چکیده

در این تحقیق، فلفل سبز در یک خشک‌کن میکروویو– همرفتی در مقیاس آزمایشگاهی خشک گردید. تاثیر انرژی میکروویو بر روی نرخ خشک شدن، نفوذ رطوبتی موثر و انرژی مصرفی خشک کردن فلفل سبز در چهار سطح توانی ۱۸۰، ۳۶۰، ۵۴۰ و W ۷۲۰ مورد بررسی قرار گرفت. داده‌های خشک شدن با چهار مدل خشک شدن لایه نازک تطبیق داده شد. در فرآیند خشک کردن میکروویو، میزان کاهش رطوبت فلفل سبز از ۲/۸۹۴ تا kg water/kg dry mater ۰/۱، در قدرت مایکروویو ۷۲۰ و ۱۸۰ وات به ترتیب مدت زمان ۱۲۰ و s ۴۹۵ طول کشید. ازریابی مدلهای خشک کردن نشان داد که مدل میدلی بهترین مدل برای تطبیق داده‌های آزمایش می‌باشد (بیشترین R^2، ۰/۹۲۴ و کمترین RMSE، ۰/۲۰۶۵ و χ^2، ۰/۰۵۵۵). با افزایش توان میکروویو از ۱۸۰ تا W ۷۲۰ نفوذ رطوبتی موثر از $۶/۲۴۹\times۱۰^{-۹}$ تا m^2/s $۳/۴۴۵\times۱۰^{-۸}$ افزایش یافت. نتایج حاکی از آن است که نرخ خشک شدن با افزایش قدرت مایکروویو، افزایش و با گذشت زمان و کاهش میزان رطوبت، کاهش می‌یابد. افزایش توان میکروویو باعث افزایش نرخ خشک شدن و کاهش انرژی مصرفی می‌گردد. کمترین (MJ/kg water ۷/۲)انرژی مصرفی ویژه در سطح توانی W ۳۶۰ و بیشترین آن (MJ/kg water ۹/۲۶) در سطح توانW ۵۴۰ به دست آمد.