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Microwave-Conventional Drying Characteristics of Red Pepper: Modeling, Temperature Profile, Diffusivity and Activation Energy

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ABSTRACT

Microwave combined drying is an alternative technique that can be applied to dry foodstuffs, especially fruits and vegetables, due to shorter drying time and higher energy efficiency. In this regard, the effect of hybrid (microwave-conventional) drying conditions on drying kinetics, modeling, temperature profile, moisture and thermal diffusivities and activation energy of red pepper was investigated in a specially designed hybrid domestic oven. Three levels of microwave powers (120, 150, and 180W) and air temperatures (50, 60, and 70°C) were used. Both energy sources were applied simultaneously during the whole drying process. The drying process continued until the moisture content of the red pepper reached 10% on wet basis. Drying time decreased with increasing microwave power and air temperature. Temperature of red pepper slices sharply increased within the first 60 minutes, then reached equilibrium with drying medium and finally increased at the end of the drying process. Nine semi-theoretical models were applied to determine the drying behavior of the samples. Modified Logistic model was determined as the best model because it had the lowest RMSE and χ^2 and the highest R^2 values. Effective moisture and thermal diffusivity values increased with increasing microwave power and air temperature and ranged from 8.86×10^{-10} to 4.23×10^{-9} $m^2\ s^{-1}$ and 4.57×10^{-10} to 1.81×10^{-9} $m^2\ s^{-1}$, respectively. The activation energy of the dried red pepper slices was between 29.30 and 56.61 kJ mol^{-1}. The hybrid drying can be used as an alternative drying method for red pepper drying.

Keywords: Energy efficiency, Hybrid drying, Modified Logistic model, Thermal diffusivity.

INTRODUCTION

Pepper, specifically *Capsicum annuum*, is a general name for plants coming from Capsicum species of Solanaceae family (Luning *et al*., 1995). It can be consumed as raw, cooked, or used commonly in making paste, pickles, and sauce. It may be also used for preparing soups and stews. Peppers are a source of A and C vitamins, minerals, and energy in the human diet (Famurewa *et al*., 2006). Peppers show great genetic diversity in terms of color, size, shape and chemical composition and, therefore, vary greatly in their antioxidant properties, vitamins and other phytochemicals. In addition, peppers are rich in polyphenols, particularly the flavonoids, quercetin and luteolin (Chuah *et al*., 2008). However, red pepper is highly perishable foodstuff due to high moisture content. Therefore, it is susceptible to fungal diseases and encounters postharvest problems (Chitravathi *et al*., 2014). Thus, drying is an important technology for red pepper to reduce the moisture content for long-term storage and consumption (Charmongkolpradit *et al*., 2010). The increasing demand for high-quality shelf-stable dried vegetables requires the design, simulation and further optimization of the drying process with the purpose of accomplishing not only the efficiency of the

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process but also the final quality of the dry product (Arslan and Özcan, 2011).

Although the most commonly used technique for pepper drying is sun drying, the method is slow; therefore, drying needs too much time and the products are exposed to uncontrolled weather and unhygienic conditions. These situations lead to decreased product quality and safety. Hot air/conventional drying is the most common controlled technique for drying of fruits and vegetables due to relatively low-cost installation and simplicity compared to other controlled drying techniques such as microwave and heat pump drying. However, the hot air/conventional drying method has some disadvantages on product quality such as dark color, low rehydration capacity, hard texture due to long drying time, and less efficiency of heat and mass transfer (Askari *et al*., 2009). Microwave drying is an alternative technique that has been recommended as a fast and effective drying method over the hot air technique. However, it has also some drawbacks, especially when it is applied alone. These are non-uniform heating due to material shape causing overheating and charring, reduction of efficiency of microwave energy to heat at lower moisture content, possible textural damage and limited penetration of the microwaves through the samples (Zhang *et al*., 2006). Certain combined technique, for example microwave-hot air combined (hybrid) drying, can successfully overcome these drawbacks. In this combination, hot air facilitates to remove water in a free state from the surface of the product and microwave energy removes water from product interior (Sham *et al*., 2001). This type of hybrid drying also enhances drying rates, retains quality of the product, and reduces energy consumption (Sunkja *et al*., 2004). In literature, some microwave-hot air combined drying techniques for drying of red and green peppers have been reported (Soysal *et al*., 2009; Kowalski and Mierzwa, 2011; Szadzińska *et al*., 2017). However, the current study aimed to contribute to better understanding of the effect of the microwave-conventional drying with different microwave power and air temperature on drying characteristics such as drying rate, thin-layer modeling, temperature profile, effective moisture diffusivity, thermal diffusivity, and activation energy of red pepper.

MATERIALS AND METHODS

Red peppers (*Capsicum annuum* L. Cv. Kapija) were obtained from a local market in Gaziantep/Turkey. The samples were stored at refrigerator. Red peppers were cut into 2 longitudinal slices by using a sharp knife (the thickness of red pepper slices was 17.37±2.51 mm). The initial moisture content of red pepper was determined by the oven method at 105°C until constant weigh was obtained (AOAC, Method no: 935.29, 1995). The final moisture content of the red pepper was selected as 10% on wet basis according to the dried pepper samples that were commercially sold in the markets. The drying operation was finished when the weight of samples corresponded to the final moisture content.

Drying Equipment and Procedure

A programmable air-circulating hybrid domestic microwave oven (Arçelik KMF 833 l, Turkey) was used for drying of pepper slices (Figure 1). Microwave and conventional energies were utilized at the same time in the oven. The oven had a maximum output of 900W at 2,465 MHz frequency. Microwaves were emitted from top of the oven. The oven could supply hot air from 40 to 280°C. It contained a fan for circulating air and perforated polyamide platforms and trays holding the samples. Four holes were opened from bottom of the oven for connecting the platforms to digital balance placed at the bottom of drying cabinet. A 0.01 g precision analytical balance (Radwag, PS3500/C/1, Radom, Poland) with capacity 3.5 kg was placed at

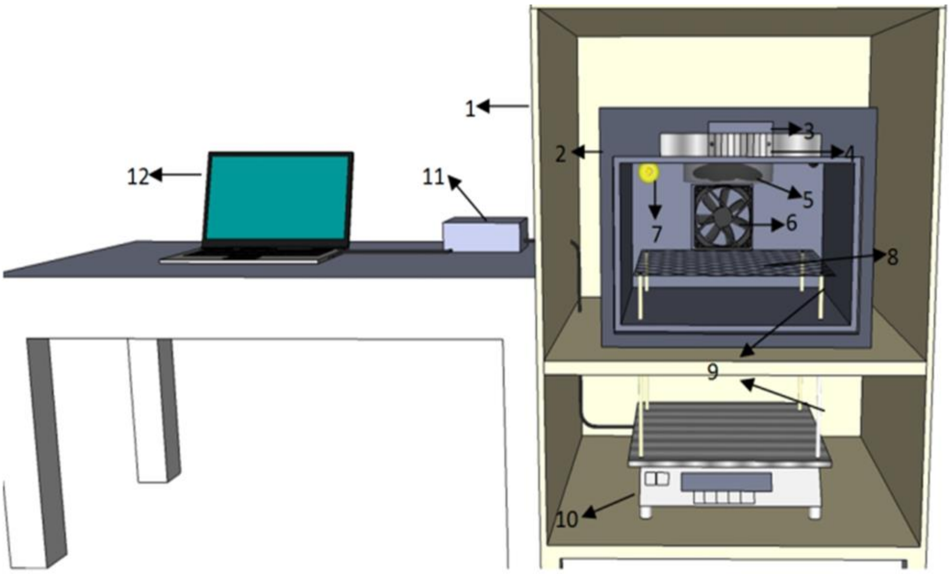

Figure 1. Schematic representation of microwave-convntional hybrid oven: (1) Drying cabinet; (2) Hybrid oven; (3) Display; (4) Control buttons; (5) Microwave emitter; (6) Fan; (7) Light; (8) Polyamide tray; (9) Polyamide legs; (10) Analytical balance; (11) Data logger, (12) PC.

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the bottom of drying cabinet. Drying operations were performed at three microwave power and air temperature levels, which were 120, 150, 180W and 50, 60, 70°C with 0.5 m s^{-1} velocity, respectively. The 3-level factorial experimental design for two independent variables was created by use of Design Expert (Version 6, Minneapolis, USA). According to the experimental design, the number of total drying experiments was 13 and 5 drying experiments were done at center point (150W+60°C) whose results were expressed in average. About 690.68±7.78 g of samples was put into the drying tray for every run. The moisture loss of the pepper slices was recorded automatically in 10 minutes intervals for the first 2 hours and then in 120 minutes intervals by the digital balance connected to a computer. The temperature of pepper slices was also recorded in 60 minutes intervals for the first 2 hours and then 120 minutes intervals during drying operation by fiber optic thermometer (ReFlexTM, Neoptix, Canada), which was mounted directly and inextricably to the pepper sample. Drying operations were carried out until the moisture content of samples decreased from 91.45±0.20 to 10±0.01% (wb).

Modeling of Thin-Layer Drying

In order to determine the best model for describing the drying behavior of red pepper slices, 8 known thin-layer drying models and Modified Logistic model were used (Table 1). The moisture ratio was calculated from Equation (1).

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

Where, MR is the Moisture Ratio, M_t, M_e and M_0 are Moisture content at any time during drying, equilibrium Moisture content and initial Moisture content in g water g^{-1} dry matter, respectively. The value of M_e are relatively small compared to M_t or M_0, thereby the error involved in the simplification is negligible. In this regard, MR was simplified to M_t/M_0 (Zomorodian and Moradi, 2010; Mortezapour *et al*., 2014). The value of M_0 was 10.6959 g water g^{-1} dry matter.

Table 1. Thin-layer drying models used in the study.

Model name	Model	Reference
Newton	MR= exp(-kt)	Darvishi *et al*. (2013)
Page	MR= exp(-kt^n)	Mazandarani *et al*. (2017)
Modified Page (Mod Page)	MR= exp(-(kt^n))	Esmaeili Adabi *et al*. (2013)
Logaritmic (Logar)	MR= aexp(-kt)+c	Darvishi *et al*. (2014)
Henderson and Pabis (H and P)	MR= aexp(-kt)	Zarein *et al*. (2015)
Two-Term Exponential (TTE)	MR= aexp(-kt)+(1-a) exp(-kat)	Motavali *et al*. (2016)
Verma	MR= aexp(-kt)+(1-a) exp(-gt)	Mortezapour *et al*. (2014)
Diffusion Approach (Dif Appr)	MR= aexp(-kt)+(1-a) exp(-kbt)	Zomorodian and Moradi (2010)
Modified Logistic (Mod Log)	MR= a/[1+exp(-4k(l-t)/a+2)]	Horuz *et al*. (2017)

Drying Rate (DR) of red pepper slices, in g water g^{-1} dry matter min^{-1}, was calculated from Equation (2).

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

Where, $M_{t+\Delta t}$ is the Moisture content at t+Δt in g water g^{-1} dry matter, M_t is the Moisture content at t in g water g^{-1} dry matter, and t is time in minute.

Drying models were fitted to the drying data by nonlinear regression analysis procedure using Sigma Plot software (Version 11, Erkrath, Germany). The terms used to evaluate the goodness of fit were the correlation coefficient (R^2), reduced Chi-square (χ^2), and Root Mean Square Error (RMSE). The highest R^2 and the lowest χ^2 (Equation 3) and RMSE (Equation 4) values indicate the best model (Darvishi *et al*., 2014).

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \quad (4)$$

Where, $MR_{exp,i}$ is the experimental Moisture Ratio found in any measurement, $MR_{pre,i}$ is the predicted Moisture Ratio, N is the Number of experimental data and z is the number of parameters in the model.

Effective Moisture and Thermal Diffusivities

Fick's second law of diffusion was used to calculate the effective moisture and thermal diffusivities with the assumptions of moisture migration being by diffusion, negligible shrinkage, constant diffusion coefficients, and infinite slab (Crank, 1975).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{4L^2}\right) \quad (5)$$

$$TR = \left(\frac{T - T_s}{T_0 - T_s}\right) = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(-(2n+1)\pi^2\frac{\alpha t}{4L^2}\right) \quad (6)$$

Where, D_{eff} and α are the effective moisture and thermal Diffusivity, respectively (m^2 s^{-1}), and L is the half thickness of samples (m), TR is the dimensionless Temperature Ratio, T is Temperature of slab at any time (°C), T_s is Temperature of drying chamber (°C), T_0 is initial Temperature of red pepper slab (°C). For long drying times, n= 1 and the equation could be simplified to straight-line equations.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}D_{eff}t\right) \quad (7)$$

$$\ln(TR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}\alpha t\right) \quad (8)$$

The effective moisture diffusivity and thermal diffusivity were typically determined by plotting experimental drying data in terms of ln(MR) and ln(TR) versus drying time (t) separately. A linear regression was performed to calculate the diffusion coefficients from the slopes of the straight lines of Equations (7) and (8). The plots give straight lines with slopes given in Equations (9) and (10).

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

$$Slope = \frac{\pi^2\alpha}{4L^2} \quad (10)$$

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Activation Energy

The activation energy values of dried red pepper slices were calculated by plotting ln (D_{eff}), ln (α) and ln (k) vs the reciprocal of the absolute temperature (Kelvin, K), respectively, as presented in Equations (11), (12) and (13). The slope of the straight line is –*Ea*/*R* assuming that the Arrhenius equation applies.

$$D_{eff} = D_0 \exp(-\frac{E_a}{RT}) \quad (11)$$

$$\alpha = \alpha_0 \exp(-\frac{E_a}{RT}) \quad (12)$$

$$k = k_0 \exp(-\frac{E_a}{RT}) \quad (13)$$

Where, D_0 and α_0 are the pre-exponential constants of the Arrhenius equation (m^2 s^{-1}), k is the drying rate constant obtained from the best fitted model (1/min), k_0 is the pre-exponential constant of the Arrhenius equation (1/min), E_a is the activation Energy in kJ mol^{-1}, R is the ideal gas constant (8.314x10^{-3} kJ mol^{-1} K^{-1}), and T is the temperature in (K).

RESULTS AND DISCUSSIONS

Drying Rate

Drying rate values were calculated by using the Equation (2) and plotted against average moisture content of peppers (Figure 2). High drying rates and moisture diffusion were observed at the initial stage of the drying processes due to the high initial moisture content of the pepper slices. Also, drying rate increased with increasing air temperature and microwave power. At these process variables, the heat generated within the sample cause a larger vapor pressure differential between the center and the surface of products. It is obviously seen in the Figure 2 that drying rates increased at initial part of the drying due to adaptation of the food materials to the drying medium and ease of removal of free water from the food material. Then, the evaporation of free water could cause cooling of the sample and, hence, decreasing the drying rate. Towards the end of drying process, removing of water molecules from the materials is more difficult because water molecules bound to high molecular substances like protein and starch (Tunde-Akintunde *et al*., 2005; Arslan and Özcan, 2011).

The short constant rate period was observed especially at low microwave power and temperature indicating that water evaporation at the product-air interface occurs at nearly the same rate as water diffusion from the sample interior. Water evaporation inside the product due to volumetric heating causes a partial pressure gradient (Constant *et al*., 1996). This gradient acts as an extra driving force to

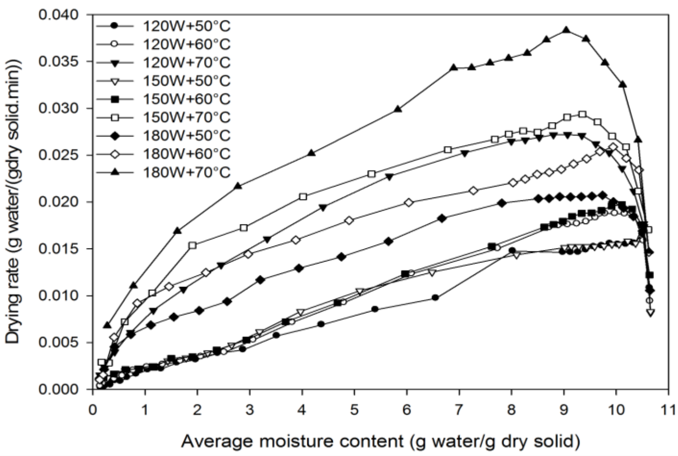

Figure 2. Drying rate curves of red pepper slices.

enhance the water diffusion rate to reach rates similar to those of surface evaporation (Igual *et al*., 2012). As the drying carries on, the portability of water molecules decreases and lowers microwave absorption (Contreras *et al*., 2008). Therefore, the falling rate period was observed.

Temperature Profile of Dried Red Pepper Slices

The temperature profile of pepper slices is shown in Figure 3. At the beginning of the drying, pepper slices were heated by both conventional and microwave energy from outside and inside, respectively. This contributed to a fast increase in sample temperature. When the surface temperature of the samples exceeded the air temperature, the air started to cool the pepper slice. Although a balance was established between the energy supplied by the microwave and the heat loss due to surface conventional cooling and evaporative heat loss, the center temperature continued to increase as a result of microwave heating. Finally, the sample temperature reached a plateau. Although the absorbed microwave energy decreased at the end of drying due to reduction in dielectric properties and moisture diffusivity, the temperature of products increased toward the end of hybrid drying process. This could be because of inadequate surface cooling due to a decrease in evaporation when moisture content was relatively low. However, it was still able to couple microwave energy to generate heat and the absorption of microwave energy still exceeded the energy losses caused by evaporative and conventional cooling. This heating could lead to excessive increase in temperature of sample (Lu *et al*., 1999).

As shown in Figure 3, final temperature of samples was found as 55.5, 56.5, and 60°C for 120, 150, and 180W coupled with 50°C; 57.5, 59.8, and 65.0 °C for 120, 150 and 180W coupled with 60°C; and 73.0, 76.0 and 79.0°C for 120, 150, and 180W coupled with 70°C hot-air treatment, respectively. This showed that there was no distinct difference between the sample temperatures at 120 and 150W microwave powers. However, the final product temperature obtained by 180W microwave power was much higher than those of the other two microwave powers. The results also showed that the temperature of the sample exceeded the air temperature during drying due to insufficient surface cooling. Varith *et al*. (2007) dried peeled longan fruit (500 g) by use of microwave-hot air-drying technique with 100, 180, 350, and 400W and 40, 50 and 60°C and measured the temperature of the dried sample during drying. They found that treatments with low microwave power (100 and 180W) increased sample temperature up to the hot-air temperature and concluded that hot air treatments dominated sample temperature rather than the microwave treatment at low microwave powers. However, at microwave applications at 300 and 450W, the maximum temperature of the sample was 9 and 15°C above the temperature of the hot air, respectively.

Evaluation of Drying Models

The drying data obtained from the experiments were fitted into nine semi-theoretical models. Non-linear regression was used to obtain each parameter value of every model. The statistical outputs of all the models, including the drying rate constant of the models and comparison criteria used to evaluate goodness of fit coefficient of determination (R^2), Chi square (χ^2) and Root Mean Square Error (RMSE) are summarized in Table 2. In all cases, the statistical parameter estimations showed that R^2, RMSE, and χ^2 values ranged from 0.9627 to 0.9999, 0.0031 to 0.0679, and 1.07×10^{-5} to 4.15×10^{-3}, respectively. The best model to describe the drying behavior of pepper slices was selected based on the highest R^2, and the lowest χ^2 and RMSE values. According to this concept, Modified Logistic model was the best model in order

Table 2. Results of statistical analysis on the modeling of red pepper slice drying. [a]

Drying condition		Model name								
		Newton	Page	Mod Page	Logar	H and P	TTE	Verma	Diff Appr	Mod Log
120W+50°C	R^2	0.9996	0.9998	0.9998	0.9998	0.9998	0.9998	**0.9999**	**0.9999**	0.9999
	RMSE	0.0079	0.0040	0.0040	0.0041	0.0045	0.0052	**0.0031**	**0.0031**	0.0038
	$\chi^2\times10^5$	6.38	1.74	1.74	1.84	2.15	2.97	**1.07**	**1.07**	1.61
	$k\times10^3$	1.66	1.28	1.28	1.67	1.69	1.71	1.80	1.80	1.90
120W+60°C	R^2	0.9993	0.9996	0.9996	0.9997	0.9997	0.9995	**0.9997**	**0.9997**	0.9997
	RMSE	0.0099	0.0077	0.0077	0.0063	0.0068	0.0086	**0.0062**	**0.0062**	0.0068
	$\chi^2\times10^5$	10.20	6.38	6.38	4.47	4.97	8.00	**4.23**	**4.23**	5.14
	$k\times10^3$	1.87	1.50	1.50	1.87	1.91	1.92	2.15	2.15	2.11
120W+70°C	R^2	0.9731	0.9996	0.9996	0.9966	0.9867	0.9988	0.9992	0.9992	**0.9996**
	RMSE	0.0604	0.0077	0.0077	0.0214	0.0425	0.0126	0.0104	0.0104	**0.0075**
	$\chi^2\times10^5$	381	6.42	6.42	52.16	196.76	17.40	12.27	12.27	**6.35**
	$k\times10^3$	3.35	0.42	0.42	2.50	3.79	6.94	3.34	3.34	5.37
150W+50°C	R^2	0.9981	0.9994	0.9994	0.9994	0.9992	0.9993	**0.9996**	**0.9996**	0.9994
	RMSE	0.0166	0.0088	0.0088	0.0091	0.0110	0.0103	**0.0079**	**0.0079**	0.0091
	$\chi^2\times10^5$	28.50	8.35	8.35	9.21	13.02	11.36	**6.90**	**6.90**	9.22
	$k\times10^3$	1.76	1.05	1.05	1.72	1.82	1.89	2.40	2.40	2.19
150W+60°C	R^2	0.9993	0.9996	0.9996	**0.9997**	0.9996	0.9996	0.9996	0.9997	0.9997
	RMSE	0.0097	0.0072	0.0072	**0.0054**	0.0072	0.0077	0.0077	0.0058	0.0069
	$\chi^2\times10^5$	9.77	5.59	5.59	**3.33**	5.64	6.51	6.78	3.82	5.44
	$k\times10^3$	1.96	1.57	1.57	1.91	1.99	2.50	2.59	2.59	2.23
150W+70°C	R^2	0.9702	0.9982	0.9982	0.9971	0.9826	0.9970	0.9976	0.9976	**0.9990**
	RMSE	0.0608	0.0151	0.0151	0.0189	0.0464	0.0195	0.0171	0.0171	**0.0113**
	$\chi^2\times10^5$	388.24	25.01	25.01	41.15	237.27	41.68	33.97	33.97	**14.81**
	$k\times10^3$	3.67	0.51	0.51	2.60	4.12	7.56	5.56	5.56	5.86
180W+50°C	R^2	0.9817	0.9985	0.9985	0.9990	0.9895	0.9979	0.9983	0.9983	**0.9990**
	RMSE	0.0493	0.0143	0.0143	0.0118	0.0372	0.0166	0.0148	0.0148	**0.0114**
	$\chi^2\times10^5$	252.34	22.02	22.02	15.59	149.39	29.92	24.74	24.74	**14.67**
	$k\times10^3$	2.64	0.48	0.48	1.90	2.89	5.00	2.73	2.73	3.93
180W+60°C	R^2	0.9767	0.9967	0.9967	0.9981	0.9850	0.9959	0.9965	0.9965	**0.9984**
	RMSE	0.0545	0.0203	0.0203	0.0154	0.0436	0.0229	0.0209	0.0209	**0.0142**
	$\chi^2\times10^5$	309.45	45.15	45.15	27.10	207.05	57.13	49.89	49.89	**22.92**
	$k\times10^3$	3.19	0.57	0.57	2.12	3.50	6.15	3.30	3.30	4.82
180W+70°C	R^2	0.9627	0.9982	0.9982	0.9979	0.9789	0.9968	0.9974	0.9974	**0.9984**
	RMSE	0.0679	0.0139	0.0139	0.0150	0.0472	0.0184	0.0164	0.0164	**0.0128**
	$\chi^2\times10^5$	415.36	21.67	21.67	26.68	248.58	37.99	31.94	31.94	**19.48**
	$k\times10^3$	4.42	0.61	0.61	2.76	5.04	9.62	7.89	7.89	7.41

[a] Bold figures indicate the highest R^2 and the lowest χ^2 and *RMSE*.

to explain the experimental data of hybrid-dried pepper slices. This was an important result of the study because the model has not been reported for describing the drying behavior of red pepper according to our best knowledge. The model is generally used for describing the sigmoidal behavior such as microbial growth curve, biomass, and biovolume production (Zwietering *et al*., 1990). However, a typical drying curve is also sigmoidal. Therefore, the model can be used for modeling of the drying behavior of foodstuffs. Darvishi *et al*. (2014) reported that the Midilli model was the most appropriate model for microwave drying behavior of thin layer pepper samples. Horuz *et al*. (2017) indicated that the best model of hybrid

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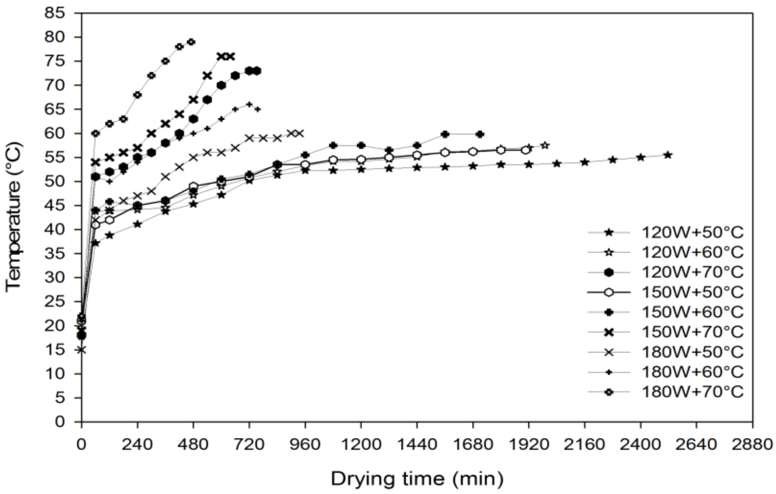

Figure 3. Temperature profile of red pepper slices during drying.

(microwave-conventional) dried apricot halves was Modified Logistic model.

Effective Moisture and Thermal Diffusivities of Pepper Slice

Moisture diffusivity is a significant transport property required for the design, optimization, and modeling of mass transfer processes that involve internal moisture movement like drying, adsorption, and desorption of moisture during storage (Zogzas *et al*., 1996). Effective moisture diffusivity describes all possible mechanisms of moisture movement within the foods, such as liquid diffusion, vapor diffusion, surface diffusion, capillary flow, and hydrodynamic flow (Kim and Bhowmik, 1995). Generally, effective moisture diffusivity is used due to limited information on the mechanism of moisture movement during drying and the complexity of the process (Madamba *et al*., 1995). In order to calculate the effective moisture and thermal diffusivities of pepper slices, Equations (7) and (8) were used. ln(MR) and ln(TR) versus time graphs were plotted by use of experimental data, respectively. The diffusivities were calculated by using the slopes of the graphs and are given in Table 3. The D_{eff} and α values increased with increasing microwave power and air temperature. According to the experimental results, a strong positive and negative relationship existed between D_{eff}/α and drying rate and D_{eff}/α and drying time, respectively. The effective moisture diffusivity values of dried pepper slices ranged from 8.86×10^{-10} to 4.23×10^{-9} m^2 s^{-1}. D_{eff} values obtained from the drying technique was within the general range of 10^{-12} to 10^{-8} m^2 s^{-1} for food materials (Zogzas *et al*., 1996). The values of D_{eff} are comparable with the reported values such as those of Arslan and Özcan (2011) for red bell pepper dried by use of sun, oven, and microwave drying techniques. They found that the D_{eff} values of pepper slices for the sun, oven at 50 and 70°C, microwave 210 and 700W drying process were 0.31×10^{-9}, 0.40×10^{-9}, 1.31×10^{-9}, 55.97×10^{-9} and 87.39×10^{-9} m^2 s^{-1}, respectively. Darvishi *et al*. (2014) dried green peppers by microwave at 180, 240, 300, 360, 420, 480, and 540W. They found the D_{eff} values of the microwave dried peppers to vary from 8.32×10^{-8} to 2.36×10^{-7} m^2 s^{-1}. Deng *et al*. (2018) dried red pepper by use of infrared-assisted air-drying technique. They found that the effective moisture diffusivity of the sample was between 1.75×10^{-10} and 8.97×10^{-10} m^2 s^{-1}.

Thermal diffusivity is a substantial transport feature that is used for explanation of modeling and computations of transient heat and mass transfer in basic food processes, such as drying, thermal processing, and cooling/freezing (Kostaropoulos and Saravacos, 1997). However, limited data have been published on the thermal diffusivity properties of dried and semidried foods. Thermal diffusivity values of hybrid dried pepper slices ranged from 4.57×10^{-10} to 1.81×10^{-9} m^2 s^{-1}. They found that the thermal diffusivities ranged from 9.47×10^{-11} to 1.88×10^{-7} m^2 s^{-1}. Çağlar *et al*. (2009) dried seedless grape at 50, 60, 70, and 80°C by use of infrared drying technique. They reported that thermal diffusivity of the sample increased with increase in drying temperature and decreased with increase in moisture content. Horuz *et al*. (2017) applied hybrid (microwave-hot air) drying technique for entire drying process to dry apricot halves. They found that thermal diffusivity of dried apricots ranged from 3.64×10^{-10} to 1.34×10^{-9} and increased with increase in microwave power and air temperature.

Activation Energy Estimation of Pepper Slice

The activation Energy values (Ea) of dried pepper slices were calculated by using effective moisture diffusivity, thermal diffusivity, and drying rate constant obtained from the best fitting thin layer drying model (Modified Logistic). Therefore, the ln D_{eff}, ln α and ln k versus the reciprocal of the absolute Temperature (1/T) graphs were plotted, respectively. The Ea values were obtained from the slopes of the graphs. The calculated Ea values are shown in Table 4. According to the results, Ea values obtained from effective moisture diffusivity, thermal diffusivity, and drying rate constant were close to each other. This was an important finding because, in literature, calculation of Ea values have been generally done by use of D_{eff} values. However, the results obtained from the current study revealed that activation energy values can be calculated by using thermal diffusivity and drying rate constant as well as effective moisture diffusivity. The Ea values obtained from the current study were in the range reported in literature. Zogzas *et al*. (1996) reported that *Ea* values of various food and agricultural products ranged from 12.7 to 110 kJ mol^{-1}. Doymaz and Kocayiğit (2012) reported that the Ea values of conventional dried Charleston variety of red pepper at 55, 60, 65, and 70°C air temperature and 2.1 m s^{-1} air velocity were 50.27, 49.21 and 48.45 kJ mol^{-1} for the control, pretreated with citric acid, and ethyl oleate, respectively. Deng *et al*. (2018) found the activation energy of infrared-assisted hot air-dried red pepper as 50.90 kJ mol^{-1}.

CONCLUSIONS

Drying behavior, modeling, temperature

Table 3. Effective moisture and thermal diffusivities of dried pepper slices.

Drying condition	Effective moisture diffusivity (m^2 s^{-1})	Thermal Diffusivity (m^2 s^{-1})
120W+50°C	8.86×10^{-10}	4.57×10^{-10}
120W+60°C	1.06×10^{-9}	5.59×10^{-10}
120W+70°C	2.87×10^{-9}	1.40×10^{-9}
150W+50°C	1.06×10^{-9}	5.87×10^{-10}
150W+60°C	1.16×10^{-9}	6.96×10^{-10}
150W+70°C	3.29×10^{-9}	1.69×10^{-9}
180W+50°C	2.17×10^{-9}	9.41×10^{-10}
180W+60°C	2.83×10^{-9}	1.23×10^{-9}
180W+70°C	4.23×10^{-9}	1.81×10^{-9}

Table 4. Activation energy values of pepper slice drying.

Drying condition	Ea-calculated from drying rate constant (kJ mol^{-1})	Ea-calculated from moisture diffusivity (kJ mol^{-1})	Ea-calculated from thermal diff (kJ mol^{-1})
120W+50°C 120W+60°C 120W+70°C	47.55	53.79	51.32
150W+50°C 150W+60°C 150W+70°C	45.01	51.82	48.40
180W+50°C 180W+60°C 180W+70°C	29.15	30.68	29.98

profile, effective moisture, and thermal diffusivities and activation energy of pepper slices dried in a hybrid oven were investigated. Drying rate increased with increasing microwave power and air temperature. The temperature of pepper slices increased in the first 60 minutes, then, reached a plateau and finally increased at the end of the drying process. This profile consistent with drying behavior. The short constant rate period was observed especially at low microwave power and temperature. The Modified Logistic Model was the best model because it fitted our experimental data better compared to the other models. The model can be accepted as an alternative model to describe drying behavior of pepper slices according to the statistical analysis. The effective moisture and thermal diffusivities varied from 8.86×10-10 to 4.23×10-9 and 4.57×10-10 to 1.81×10-9 m^2 s^{-1}, respectively, at various drying conditions. The diffusivities increased with increase in microwave power and hot air temperature. Ea values were calculated by using thermal diffusivity and the best-model drying rate constant as well as effective moisture diffusivity.

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REFERENCES

1. AOAC. 1995. *Official Method of Analysis*. Association of Official Analytical Chemists, Washington, DC.
2. Arslan, D. and Özcan, M. M. 2011. Dehydration of Red Bell-Pepper (*Capsicum annuum* L.): Change in Drying Behavior, Color and Antioxidant Content. *Food Bioprod. Process.*, **89:** 504–513.
3. Askari, G. R., Emam-Djomeh, Z. and Mousavi, S. M. 2009. An Investigation of the Effects of Drying Methods and Conditions on Drying Characteristics and Quality Attributes of Agricultural Products during Hot Air and Hot Air/Microwave-Assisted Dehydration. *Dry. Technol.*, **27**: 831-841.
4. Charmongkolpradit, S., Triratanasirichai, K. and Srihajong, N. 2010. Drying Characteristics of Chili Using Continuous Fluidized-Bed Dryer. *Am. J. Appl. Sci.*, **7**: 1300–1304.
5. Chitravathi, K., Chauhan, O. P. and Raju, P. S. 2014. Postharvest Shelf-Life Extension of Green Chillies (*Capsicum annuum*L.) Using Shellac-Based Edible Surface Coatings. *Postharv. Biol. Technol.*, **92:** 146–148.
6. Chuah, A. M., Lee, Y. C., Yamaguchi, T., Takamura, H., Yin, L. J. and Matoba, T. 2008. Effect of Cooking on the Antioxidant Properties of Colored Pepper. *Food Chem.*, **111:** 20-28.
7. Constant, T., Moyne, C. and Perré, P. 1996. Drying with Internal Heat Generation: Theoretical Aspects and Application to

Microwave Heating. *AIChE J*., **42(2):** 359-368.

8. Contreras, C., Martín-Esperza, M. E., Chiralt, A. and Martínez-Navarrete, N. 2008. Influence of Microwave Application on Convective Drying: Effects on Drying Kinetics, and Optical and Mechanical Properties of Apple and Strawberry. *J. Food. Eng*., **88:** 55–64.
9. Crank, J. 1975. *The Mathematics of Diffusion*. 2nd Edition, Clarendon Press, Oxford.
10. Çağlar, A., Toğrul Türk, I. and Toğrul, H. 2009. Moisture and Thermal Diffusivity of Seedless Grape under Infrared Drying. *Food Bioprod. Process*., **87:** 292–300.
11. Darvishi, H., Khoshtaghaza, M. H., Najafi, G. and Nargesi, F. 2013. Mathematical Modeling of Green Pepper Drying in Microwave-Convective Drying. *J. Agr. Sci. Tech*., **15:** 457-465.
12. Darvishi, H., Asl, A. R., Asghari, A., Azadbakht, M., Najafi, G. and Khodaei, J. 2014. Study of Drying Kinetics of Pepper. *J. Saudi Soc. Agr. Sci*., **13**: 130–138.
13. Darvishi, H., Khoshtaghaza, M. H. and Minaei, S. 2014. Fluidized Bed Drying Characteristics of Soybeans. *J. Agr. Sci. Tech*., **16:** 1017-1031.
14. Deng, L.Z., Yang, X. H., Mujumdar, A.S., Zhao, J. H., Wang, D., Zhang, Q., Wang, J., Gao, Z. J. and Xiao, H. W. 2018. Red Pepper (*Casicum annuum* L.) Drying: Effects of Different Drying Methods on Drying Kinetics, Physicochemical Properties, Antioxidant Capacity, and Microstructure. *Dry. Technol*., **36(8)**: 893-907.
15. Doymaz, İ. and Kocayiğit, F. 2012. Effect of Pre-Treatments on Drying, Rehydration, and Color Characteristics of Red Pepper (‘Charliston’ variety). *Food Sci. Biotechnol.*, **21**: 1013-1022.
16. Esmaeili Adabi, M., Nikbakht, A.M., Motevali, A. and Mousavi Seyedi, S. R. 2013. Investigation of Black Mulberry Drying Kinetics Applying Different Pretreatments. *J. Agr. Sci. Tech*., **15**: 23-34.
17. Famurewa, J. A. V., Oluwamukomi, M. O. and Adenuga, A. L. 2006. Dehydration of Osmosised Red Bell Pepper (*Capsicum annuum*). *J. Food Technol*., **4**: 249-252.
18. Horuz, E., Bozkurt, H., Karataş, H. and Maskan, M. 2017. Drying Kinetics of Apricot Halves in a Microwave-Hot Air Hybrid Oven. *Heat Mass Transfer*., **53**: 2117-2127.
19. Igual, M., Garćia-Martinez, E., Martín-Esperza, M. E. and Martínez-Navarrete, N. 2012. Effect of Processing on the Drying Kinetics and Functional Value of Dried Apricot. *Food. Res. Int*., **47**: 284–290.
20. Kim, S. S. and Bhowmik, S. R. 1995. Effective Moisture Diffusivity of Plain Yogurt Undergoing Microwave Vacuum Drying. *J. Food Eng*., **24**: 137-148.
21. Kostaropoulos, A. E. and Saravacos, G. D. 1997. Thermal Diffusivity of Granular and Porous Foods at Low Moisture Content. *J. Food Eng*., **33**: 101–109.
22. Kowalski, S. J. and Mierzwa, D. 2011. Hybrid Drying of Red Bell Pepper: Energy and Quality Issues. *Dry. Technol*., **29**: 1195-1203.
23. Lu, L., Tang, J. and Ran, X. 1999. Temperature and Moisture Changes during Microwave Drying of Sliced Food. *Dry. Technol*., **17**: 414-431.
24. Luning, P. A., Yuksel, D., Vuurst-De-Vries, R. V. and Roozen, J. P. 1995. Aroma Changes in Fresh Bell Peppers (*Capsicum annuum*) after Hot-Air Drying. *J. Food Sci.*, **60(6):** 1269-276.
25. Madamba, P. S., Driscoll, R. H. and Buckle, K. A. 1995. Models for the Specific Heat and Thermal Conductivity of Garlic. *Dry. Technol*., **13**: 295-317.
26. Mazandarani, Z., Aghajani, N., Garmakhany, A. D., Ardalan, M. J. B. and Nouri, M. 2017. Mathematical Modeling of Thin Layer Drying of Pomegranate (*Punica granatum* L.) Arils: Various Drying Methods. *J. Agr. Sci. Tech*., **19**: 1527-1537.
27. Mortezapour, H., Ghobadian, B., Khoshtaghaza, M. H., Minaei, S. 2014. Drying Kinetics and Quality Characteristics of Saffron Dried with Assisted Hybrid Photovoltaic-Thermal Solar Dryer. *J. Agr. Sci. Tech.*, **16**: 33-45.
28. Motavali, A., Minaei, S., Banakar, A., Ghobadian, B. and Darvishi, H. 2016. Energy Analyses and Drying Kinetics of Chamomile Leaves in Microwave-Convective Dryer. *J. Saudi Soc. Agr. Sci.*, **15**: 179-187.
29. Szadzińska, J., Łechtańska, J., Kowalski, S. J. and Stasiak M. 2017. The Effect of High Power Airborne Ultrasound and Microwave on Convective Drying Effectiveness and Quality of Green Pepper. *Ultrason. Sonochem*., **34**: 531-539.
30. Sham, P. W. Y., Scaman, C. H. and Durance, T. D. 2001. Texture of Vacuum Microwave Dehydrated Apple Chips as Affected by Calcium Treatment, Vacuum Level, and Apple Variety. *J. Food Sci.*, **66**: 1341-1347.

31. Soysal, Y., Ayhan, Z., Eştürk, O. and Arıkan, M. F. 2009. Intermittent Microwave-Convective Drying of Red Pepper: Drying Kinetics, Physical (Colour and Texture) and Sensory Quality. *Biosyst. Eng.*, **103**: 455-463.
32. Sunkja, P. S., Rennie, T. J., Beaudry, C. and Raghavan, G. V. S. 2004. Microwave Convective and Microwave-Vacuum Drying of Cranberries: A Comparative Study. *Dry. Technol*., **22**: 1217-1231.
33. Tunde-Akintunde, T. Y., Afolabi, T. J. and Akintunde, B. O. 2005. Influence of Drying Methods on Drying of Bell-Pepper (*Capsicum annuum*). *J. Food Eng*., **68:** 439-442.
34. Varith, J., Dijkanarukkul, P., Achariyaviriya, A. and Achariyaviriya, S. 2007. Combined Microwave Hot Air Drying of Peeled Longan. *J. Food Eng*., **81:** 459–468.
35. Zarein, M., Samadi, S. H. and Ghobadian, B. 2015. Investigation of Microwave Dryer Effect on Energy Efficiency during Drying of Apple Slices. *J. Saudi Soc. Agr. Sci.*, **14**: 41-47.
36. Zhang, M., Tang, J., Mujumdar, A. S. and Wang, S. 2006. Trends in Microwave-Related Drying of Fruits and Vegetables. *Trends Food Sci. Technol.*, **17**: 524-534.
37. Zogzas, N. P., Maroulis, Z. B. and Marinos-Kouris, D. 1996. Moisture Diffusivity Data Compilation in Foodstuff. *Dry. Technol.*, **14**: 2225–2253.
38. Zomorodian, A and Moradi, M. 2010. Mathematical Modeling of Forced Convection Thin Layer Solar Drying for *Cuminum cyminum*. *J. Agr. Sci. Tech*., **12**: 401-408.
39. 39. Zwietering, M. H., Jongenburger, I., Rombouts, F. M. and Van't Riet, K. 1990. Modeling of the Bacterial Growth Curve. *J. Appl. Environ. Microbiol*., **56**: 1875-1881.

ویژگی های خشک کردن فلفل قرمز با ترکیب میکروویو-روش مرسوم: مدل سازی، مشخصات دما، پخشیدگی، و انرژی فعال سازی

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چکیده

خشک کردن همراه با میکروویو یک روش جایگزین است که می تواند برای خشک کردن مواد غذایی به ویژه میوه جات و سبزیجات از آن استفاده کرد زیرا که در آن، زمان خشک کردن کوتاه و راندمان انرژی بیشتراست. در این پژوهش، اثر خشک کردن با روشی هیبریدی(میکروویو- روش مرسوم) روی سینتیک، مدل سازی، مشخصات دمایی، پخشیدگی رطوبت و حرارت، و انرژی فعال سازی فلفل قرمز در یک اجاق ویژه ساخت محلی بررسی شد. به این منظور، ازسه سطح از توان میکروویو(۱۵۰، ۱۲۰، و ۱۸۰ وات) و سه دمای هوا (۵۰، ۶۰، و ۷۰ درجه سلسیوس) استفاده شد. در طی تمامی فرایند خشک کردن،هر دو منبع انرژی همزمان به کار گرفته شد. فرایند خشک کردن تا زمانی که مقدار رطوبت فلفل قرمز به ۱۰٪ برمبنای وزن تر رسید، ادامه یافت. طول زمان خشک کردن با افزایش توان میکروویو و افزایش دما، کاهش یافت. در ۶۰ دقیقه آغازین، دمای برش های فلفل قرمز سریعا افزایش یافت و سپس با محیط خشک کننده به تعادل رسید و نهایتا در اواخر فرایند خشک کردن افزایش یافت. برای تعیین رفتار نمونه ها در حین خشک شدن، تعداد ۹ مدل نیمه-تئوری به کار گرفته شد. مدل تغییر یافته لجستیک (Modified Logistic model) به عنوان بهترین مدل تعیین شد زیرا کمترین مقدار RMSE و χ^2 و بیشترین مقدار R^2 را داشت. مقادیر رطوبت موثر و

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پخشیدگی حرارتی با افزایش توان میکروویو و دمای هوا افزایش یافت و به ترتیب در محدوده 8.86×10^{-10} تا 4.23×10^{-9} m^2/s و 4.57×10^{-10} تا 1.81×10^{-9} m^2/s قرار داشت. همچنین، انرژی فعال سازی برش های فلفل قرمز بین ۲۹/۳۰ تا ۵۶/۶۱ کیلو ژول در مول بود. بنا بر این می توان از خشک کن هیبرید به عنوان روش جایگزین برای خشک کردن فلفل قرمز استفاده کرد.

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