DETERMINATION OF THE DRYING KINETICS AND ENERGY EFFICIENCY OF RED PEPPER (*CAPSICUM ANNUUM* L.) USING DIFFERENT DRYING METHODS AND MICROWAVE FINISH DRYING

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Abstract–– **The effects of different drying processes (microwave (MD), freeze (FD), convective (CD), and vacuum drying (VD) and combined drying methods (FD+MD and CD+MD)) on the drying characteristics, effective moisture diffusivity (D_{eff}), and activation energy of the red pepper powder and total energy consumption of dryers were investigated. All drying processes took place in the combined form of constant and falling rate periods for all drying experiments except for CD and CD+ MD. In order to determine drying kinetics of red pepper pulp (RPP) seven thin layer drying models were fitted to experimental data and Page (MD, FD, CD, VD, CD+MD) and Logarithmic (FD+MD) models which had the highest R^2 and lowest χ^2 and RMSE were found to satisfactorily describe the drying behavior of RPP. Findings indicated that compared to FD and CD alone, microwave finish drying resulted in D_{eff} values ($p < 0.05$). Specific energy consumption values ranged between 3.13 and 270.87 kWh/kg H_2O.**

Keywords–– **Red pepper; Microwave finish drying; Energy consumption; Activation energy; Effective moisture diffusivity.**

I. INTRODUCTION

Red pepper (*Capsicum annuum* L) which is rich in vitamin C, polyphenols, antioxidants, natural pigments, etc. is a widely used vegetable. Red pepper powder used as a food additive and food ingredient to provide spicy flavor and attractive color. Drying is one of the most common and economic methods used for red pepper processing and preservation because of its high moisture content and short shelf-life (Deng *et al.*, 2018). There are several studies on the drying of red pepper such as: sun (Arslan and Özcan, 2011), hot air (Deng *et al.*, 2018; Doymaz and Pala, 2002; Sanjuán *et al.*, 2003; Vega *et al.*, 2007; Çalışkan Koç, 2020), vacuum (Çalışkan Koç, 2020), pulse vacuum (Deng *et al.*, 2018), ultrasound-assisted vacuum (Tekin and Baslar, 2018), microwave (Arslan and Özcan, 2011, Çalışkan Koç, 2020), etc.

Different drying techniques have different advantages. In order to provide optimal drying kinetics as well as the quality of foods, the required energy may be supplied by combining different heat transfer mechanisms (convection coupled with conduction or radiation, dielectric heating simultaneously or in a pre-selected sequence) in a time-varying fashion (Chua *et al.*, 2003). The drying behavior of fruits and vegetables strongly depends on the drying conditions, type of dryer, and product. Determination of drying kinetics and mass transfer rate of the fruits and vegetables is important for controlling the drying process, selecting the optimum operating conditions, design and construction of new systems, determination of required energy, improvement of product quality, etc. (Onwude *et al.*, 2016). Taking only experimental drying conditions without mathematical modeling of drying kinetics into consideration can significantly affect the efficiency of dryers, increase the cost of production, and reduce the quality of the product. Thin-layer drying models are widely used for the determination of the drying kinetics of fruits and vegetables because of involving simultaneous heat and mass transfer, being practical, ease of use, requiring less data, etc. Thin-layer drying models can be classified into three categories as theoretical (Fick's second law of diffusion), semi-theoretical (Fick's second law of diffusion, or Newton's law of cooling), and empirical models (experimental data). The models derived from Fick's law of diffusion describe the drying behavior of fruits and vegetables better due to their theoretical basis (Erbay and Icier, 2009; Onwude *et al.*, 2016).

This study focused on the drying kinetics of red pepper pulp by emphasizing on many of the important factors effecting on drying behavior such as drying processes and conditions and microwave finish drying in order to choose the best fitting mathematical model and to calculate effective moisture diffusivity and activation energy values for all drying conditions. In addition, the moisture content, and water activity values of the red pulp pepper powder (RPPP) and the total energy consumption and efficiency of the selected dryers were determined in this study.

II. METHODS

A. Raw materials

The red peppers were purchased from a local supermarket in Izmir, Turkey. Then they were washed, the seeds and juice (juice extractor, Premier PRJ-607, Turkey) were removed and the red pepper pulp was obtained.

B. Drying of RPP (Experimental Procedure)

The red pepper pulp was dried in a domestic digital microwave oven (Arçelik MD595, Turkey 180-900W microwave powers), pilot-scale freeze dryer (Armfield, FT 33 Vacuum Freeze Drier, UK, under vacuum 13.33 Pa absolute pressure, at -48±2°C and +10±2 ºC condenser and heating plate temperatures), convective hot air dryer (Armfield Lim., Ringwood, Hampshire, UK, at 60- 80°C drying air temperature and 1 m/s air velocity), and vacuum oven (Nüve Laboratory and Sterilization Tech, EV018, Turkey, at 20 mbar pressure and 60- 80°C drying air temperature). Each experiment for increasing periods was carried out with new samples of equal mass (50.00±0.20g, red pepper pulp was spread over a petri dish (14cm diameter, 3mm side thickness) as a disk). The weight loss was measured for every 30s for MD, 1-hour for FD, 10 min for CD, and 30min for VD until the constant weight was reached (Ohaus AR2140, USA).

The microwave energy improves the drying process and decreases the drying time and energy consumption. For this reason, the microwave oven drying process applied as a finish drying of FD and CD for the semi-dried RPP in order to decrease total energy consumption (TEC) and drying time. The RPP was dried in a freeze dryer for 5 hours (where the moisture removal rate decreased). Then the semi-dried RPP was dried in a microwave oven (540W microwave power) until a constant weight was reached.

The water activity, TEC, and D_{eff} values are the primary criteria for the elimination of the drying temperature and microwave power. The RPP was dried in the convective hot air dryer (70±2°C drying air temperature, 1 m/s airflow rate) for 40 min (after initial temperature rise period where the moisture removal rate started to decrease). Then the semi-dried RPP was dried in a microwave oven (540W microwave power) until a constant weight was reached. The other drying air temperatures were eliminated due to the high water activity values which were very important for dried products (Fig. 1). 540W microwave power was chosen as a microwave finish drying. Higher microwave powers (720 and 900W) were eliminated due to high TEC and 180 and 360W microwave powers were eliminated due to the slow diffusion rates compared to 540W microwave power.

C. Analysis

Total energy consumptions of dryers were measured by a power measurement device (Makel M310.2218, Turkey). The effectiveness of the dryers was determined according to specific moisture extraction rate (SMER), moisture extraction rate (MER), and specific energy consumption (SEC) values (Chua *et al.,* 2002; Jindarat *et al.,* 2011).

The moisture content and water activity values of RPPP were determined according to AOAC (2000) and measured using a Testo-AG 400, Germany.

D. Mathematical Modelling and Calculation of Drying Rate, Effective Moisture Diffusivity, and Activation Energy

The moisture ratio (MR) of RPP during drying was calculated using the Eq. (1);

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

Where M_t, M_0, and M_e are the moisture content at any time, initial, and equilibrium (kg water (H_2O)/kg dry matter (DM)), respectively.

Drying curves were fitted to six well-known semi theoretical thin layer drying models (Lewis, Page, Henderson and Pabis, Logarithmic, Two-Term, and Approximate Diffusion models) and one empirical model (Wang and Singh model) (Onwude *et al.,* 2016). Nonlinear regression analysis was used to evaluate the parameters of the selected model using statistical software SPSS 20.0 (SPSS Inc., Chicago, IL, U.S.A). The goodness of fit was determined using the coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2) that can be described by the equations given by Erbay and Icier (2009).

Drying rate (DR, kg H_2O/kg DM.min.m^2) was defined as:

$$Drying\ Rate = \Delta M/(\Delta t^{*} S) \quad (2)$$

where M (kg H_2O/kg DM) is moisture content, t (min) is time, S (m^2) is the total surface area of RPP (Tekin and Baslar, 2018).

The D_{eff} (m^2/s) were calculated by Fick's law of diffusion as given in Onwude *et al.* (2016).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left[-(2n+1)^2\pi^2\frac{D_{eff}}{4L^2}t\right] \quad (3)$$

where t (s) is time and L (m) is the thickness of the sample. For sufficiently long drying times, a limiting case of Eq. (3) was assumed and expressed in the logarithmic form as in Eq. (4)

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

D_{eff} is typically calculated by plotting experimental MR in logarithmic form versus drying time. From the Eq. (3), a plot of lnMR versus drying time gives a straight line with a slope ($\pi^2\frac{D_{eff}}{4L^2}$).

The relation between the D_{eff} and drying air temperature or microwave powder are assumed to be an Arrhenius function (Eq. 5 and 6).

$$D_{eff} = D_0 exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

$$D_{eff} = D_0 exp\left(-E_a\frac{m}{P}\right) \quad (6)$$

where D_0 (m^2/s) is the preexponential factor, E_a (kJ/mol or W/g) is the activation energy, R (R=8.31451 J/mol/K) is the universal gas constant, T (Kelvin) is drying air temperature, P (W) is microwave output power, and m (g) is mass of the sample (Onwude *et al.,* 2016).

E. Statistical Analysis

All experiments were performed in duplicates and measurements were performed in triplicates. All data points shown in graphs represent the mean of triplicate analysis. Statistically significant differences between samples were determined using ANOVA (analysis of variance), the F-test for multiple samples or two samples with α = 0.05, and SPSS 20.0, (SPSS Inc., Chicago, IL, U.S.A.).

III. RESULTS

A. Energy Consumption and Efficiency of Drying Systems

The drying time of RPP and TEC of dryers are given in Table 1. The drying times of the samples ranged between 0.16h and 15h. The effect of different drying techniques and conditions were found to be significant on the drying time of RPP ($p < 0.05$). The drying times of lemon peels were found to be 55min for MD (120W), 33h for air drying (25-30ºC), 6h for FD (0.125 mbar and −70ºC), and 39 min for CD (68.91ºC and 1.8 m/s, Tekgül and Baysal, 2018). The lowest TEC which is one of the indicators for a successful drying process was observed for MD because of the low drying time. Alibas (2009) reported that MD is a widely used drying technique due to low drying time and homogenous energy distribution on the material. Total energy consumption values of microwave oven significantly increased depending on the increase in the microwave power, while the drying time decreased ($p < 0.05$). Moradi *et al*. (2013) reported that the mass transfer in the sample is rapid at high microwave power due to the high heat generation in the sample which resulted in high vapor pressure differences between the center and surface of the product. For this reason, a higher heat generation rate may result in a higher evaporation rate and lower drying time. In CD and VD, when the drying air temperature was increased, the moisture removal accelerated, and thus, drying time and TEC values reduced. Similar findings were also obtained by Süfer *et al*. (2017). In the freeze dryer, the energy is used to keep condenser and plate temperatures constant and to provide a vacuum for the system. In this study, the TEC of the initial freezing process was not measured. TEC of FD was found to be significantly lower compared to CD ($p < 0.05$). Similar results were also obtained by Caliskan and Dirim (2017). The highest TEC values were observed for the CD because of the long drying time and also two blowers which inserted in the present system. While the highest drying times were observed for VD of RPP, TEC values were found to be lower compared to other drying techniques except for MD. In VD, the heat transferred from outside to the inside of the RPP, but the water diffused in the opposite direction (inside to outside). This situation causes a slow evaporation rate of water which eventually leads to a long drying period. Higher TEC values were obtained from VD of red pepper (1.7- 2.7 kWh) at four different temperatures (45-75ºC) by Tekin and Baslar (2018). Chua *et al*. (2003) reported that in order to obtain optimum TEC values, the energy demand of the product during drying with the external supply of energy using several possible mechanisms of heat transfer can be provided. The FD and CD drying time of RPP can be decreased by combining them with MD around 43.33% and 86.72%, respectively. Similarly, TEC can be decreased by around 42.70% and 59.69% for FD+MD and CD+MD compared to FD and CD alone. Similar results were also obtained by Zhao *et al.* (2014) for carrot slices dried by CD (60°C drying air temperature, 0.92±0.01kWh) and CD+MD (60°C drying air temperature, 140W microwave power, 0.88±0.01kWh). In addition, Demiray *et al.* (2017) reported that under CD conditions at the beginning of the drying the moisture removal rate is high, however, at the low moisture content values, the CD was not advantageous due to the slow diffusion rate. For this reason, it can be stated that the CD+MD combination is more advantageous with a higher evaporation rate and lower TEC compared to CD alone.

Required of latent heat for moisture evaporation from the food material causes high energy consumption. For this reason, energy efficiency and product quality can be considered as a key factor for drying experiments (Çalışkan Koç and Dirim, 2018). SMER, MER, and SEC values ranged between 0.01 and 0.32 kg H_2O/kWh, 0.01 and 0.27 kg H_2O /h, and 3.13 and 270.87 kWh/kg H_2O, respectively (Table 1). The SMER decreased, whereas MER and SEC increased with the increasing microwave power. It may be due to increasing TEC and decreasing drying time depending on the increase in the microwave power. Altay *et al.* (2019) also reported that MER increased depending on the increase in the microwave power and the highest MER values were obtained from MD compared to FD and CD. Similarly, in this study, the highest MER values were obtained from MD. Differences between SMER values of FD, CD, FD+MD, and CD+MD, and differences between MER values of FD, CD, VD, and FD+MD were not found to be statistically significant ($p > 0.05$). It may be due to a similar amount of removal water in all experiments (0.042-0.044 kg H_2O). In addition, the high TEC of FD, CD, FD+MD, and CD+MD resulted in low SMER values. Similarly, the high drying times of FD, CD, VD, and FD+MD resulted in low MER values. Duan *et al.* (2016) reported that SMER in industrial vacuum freeze-dryer is in the range of 0.4 kg H_2O /kWh or below. The obtained result for FD is in the limits are given by Duan *et al*. (2016). The SMER values of VD process increased depending on the increase in the drying air temperatures. The significantly highest SEC values were observed for CD, whereas the lowest values were observed for MD ($p < 0.05$). The highest TEC values were also observed for CD because of the long drying time and also two blowers which inserted in the present system. It may be also a reason for the highest SEC values of CD. Although SEC values increased according to the increasing microwave power, the opposite effect was observed for increasing drying air temperature. Depending on the increase in the microwave power, TEC values increased, and as a result, SEC values increased, however, the opposite effect was observed for CD and VD. The low TEC values of MD may be the reason for the low SEC values. Baker and McKenzie (2005) reported that the low SEC values indicated that the dryer is highly efficient. Depending on this explanation, it can be stated that MD is highly efficient compared to other dryers. In addition, Altay *et al.* (2019) reported that MD was more efficient than FD and CD. The long drying times of FD, CD, VD, and FD+MD caused higher TEC values which is the reason for the higher SEC values. Although the drying time is one of the effective parameters on the SEC value, different dryers resulted in different TEC values. In addition, it can be stated, the SEC values of FD and CD can be significantly decreased by combining these techniques by MD ($p < 0.05$).

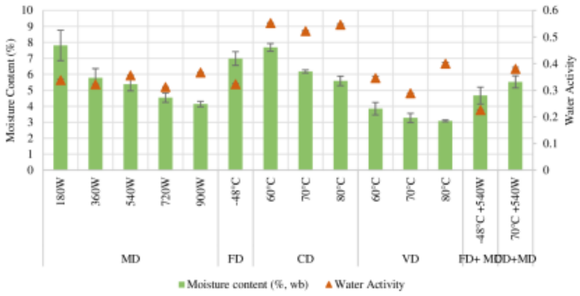


Figure 1: Moisture content and water activity values of RPPP

B. Moisture content and water activity of RPPP

The moisture content and water activity values of RPPP are given in Fig. 1. The moisture content of RPP was found to be as 88.19±3.52%. In several studies, the drying process was stopped when the moisture content of red pepper decreased to 10-12% (Deng *et al*., 2018; Doymaz and Pala, 2002; Tekin and Baslar, 2018). In this study, the drying experiments were completed when the weight change reached the 0.01 gram, for this reason, the moisture content values of RPPP were found to be lower than given values (10-12%). As expected, increasing microwave power and drying air temperature (for CD and VD) resulted in a significant decrease in the moisture content of the RPPP ($p < 0.05$). Similarly, Akdoğan *et al.* (2017) reported that the moisture content value of microwave dried corn husk powder decreased depending on the increase in the microwave power due to the high transfer rate at high microwave power. The high drying air temperatures resulted in an increase in the driving force of mass transfer and accelerating the rate of water vapor diffusion. This situation may have resulted in the lower moisture content of RPPP. In addition, the moisture content of FD and CD dried samples can be significantly decreased by combining them with MD (around 33% for FD and 10.5% for CD, $p < 0.05$). The significantly higher moisture content values were observed for CD samples compared to other drying techniques ($p < 0.05$). It may be due to crust formation which does not let to remove the moisture from the RPP.

The water activity value of RPP was found to be as 0.982. The water activity values of RPPP ranged between 0.226 (for FD+MD) and 0.553 (for CD-60°C). Similar to moisture content results, the higher water activity values were observed for convectively dried samples. The lower water activity values were observed for 70°C drying air temperature (for CD and VD) compare to the other drying air temperatures ($p < 0.05$). Drying at 60°C may not be effective for heat and mass transfer while 80°C may cause the crust formation due to high-temperature drying. Similar to the moisture content results, the powders dried by FD+MD and CD+MD have lower water activity values compared to the powders dried by FD and CD alone ($p < 0.05$).

C. Evaluation of the drying behavior of RPPP

The change in the experimental and predicted MR values of RPP versus drying time with the model equations and statistical results are shown in Fig. 2. Figure 2 showed an exponential tendency in the drying curves of RPP except for CD+MD. It is also observed that the different drying methods have a significant effect on the drying kinetics of RPP.

The highest R^2 value was one of the primary criteria for selecting the best model to define the drying behavior of RPP (Erbay and Icier, 2009). The R^2 values of models generally were found to be higher than 0.88 except for the models which were fitted to CD+MD dried sample (Data was not given). Page model which showed the highest R^2 value was chosen as the most suitable model for determining MD, FD, CD, VD, and CD+MD characteristics of RPP at different drying techniques and conditions (Fig. 2). In the literature, the researchers reported that the Page model could adequately describe the hot air (Doymaz and Pala, 2002), vacuum (Tekin and Baslar, 2018), and oven drying (Arslan and Özcan, 2011; Tekin and Baslar, 2018) behavior of red pepper. The highest R^2 value was calculated for the Logarithmic model for FD+MD characteristic of RPP.

Drying rate values of RPP were calculated and plotted against the free moisture content as shown in Fig. 3. According to Fig. 3, it can be seen that drying took place in a combined form of the constant and falling rate periods for all drying experiments except for CD and CD+ MD. The high drying rate values were observed at the initial phase of the drying for all drying experiments (except for CD+MD Fig. 3 (f)) due to the high moisture diffusion

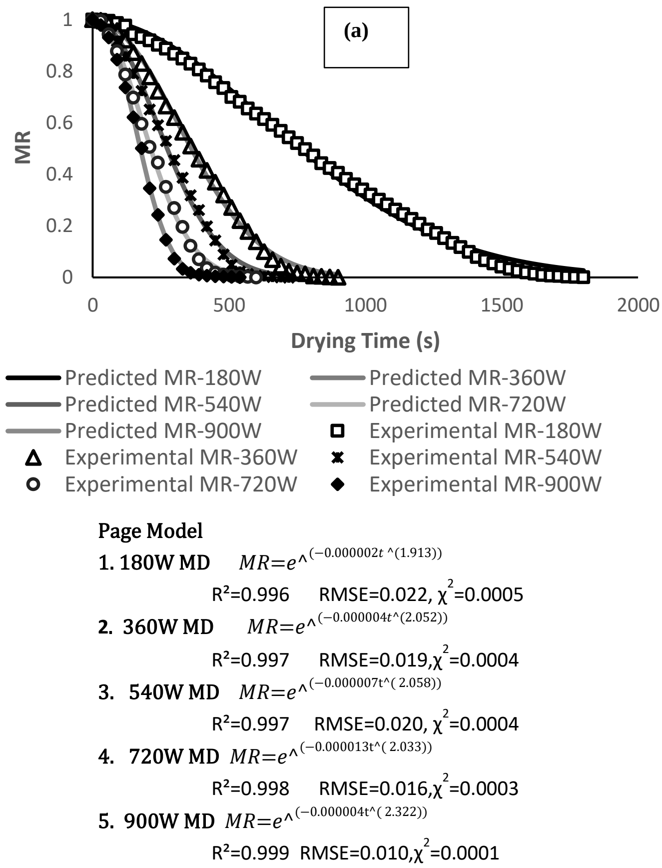
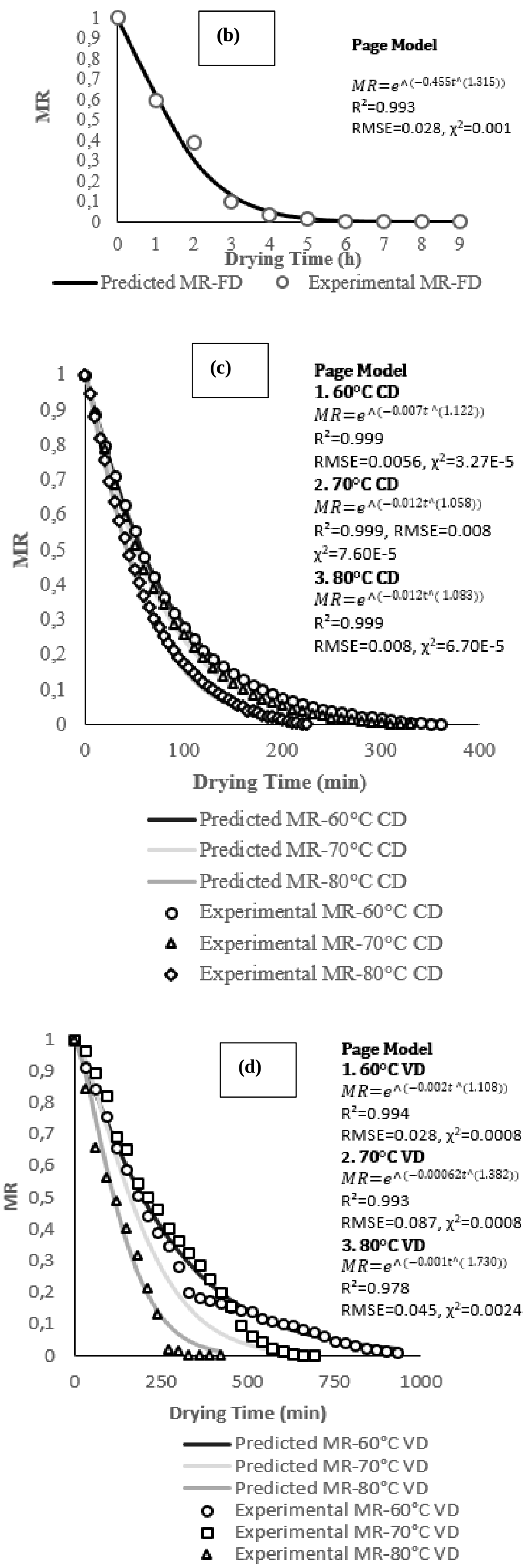


Figure 2: The experimental and predicted moisture ratio values of RPP (a) MD.



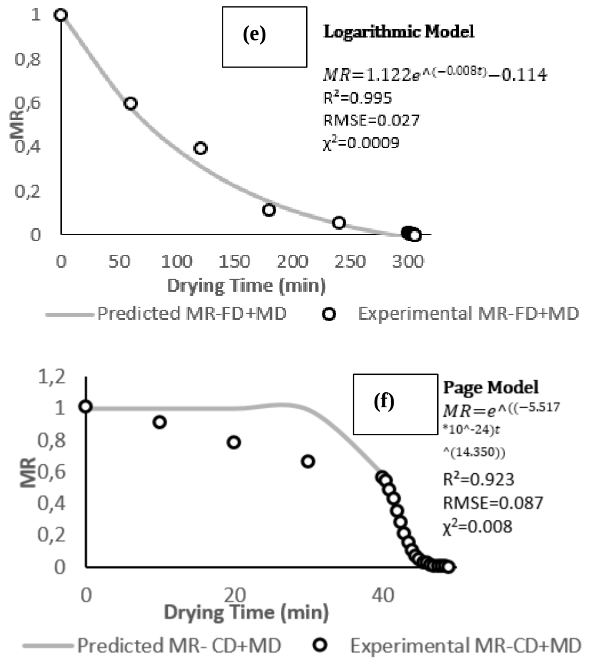


Figure 2: The experimental and predicted moisture ratio values of RPP ((b); VD (c); FD, (d); CD (e); FD+MD (f); CD+MD)

rate. As can be seen from Fig. 3 (a), 180W MD had a low drying rate compared to other microwave powers, and the drying rate increased depending on the increase in the microwave power. Marzec *et al.* (2010) reported that high microwave power resulted in high evaporation rate and moisture loss which is related to the drying rate. In addition, during the initial phase of MD, the absorption of microwave power is high due to the high moisture content of the RPP. As a result, the high drying rate values of RPP was observed due to the high moisture diffusion rate. As the drying progressed, the low moisture content of RPP resulted in a decrease in the absorption of the microwave power and drying rate. Similar results were also obtained by Moradi *et al.* (2013). With regard to other drying techniques, MD process resulted in the highest drying rate. In CD, the whole drying process took place in a falling-rate period which indicates that the internal moisture diffusion phenomenon controlled the drying process except for the initial temperature-rise period. Zhao *et al.* (2014) reported that the non-existence of a constant rate period is commonly known for CD of fruits and vegetables due to case hardening which resisting of moisture removal. As expected, the drying rate increased depending on the increase in the drying air temperature for the CD. The lowest drying rate values were observed for VD. The higher temperature difference between the drying medium and sample resulted in an increase in the heat transfer coefficient which is related to higher heat and mass transfer rate. The drying rate of FD and CD of RPP can be increased by combining these techniques by MD. In addition, Maskan (2000) reported that higher drying rate values observed during MD due to the internal heat generation caused by microwaves establishing a greater vapor pressure difference between the surface and center of

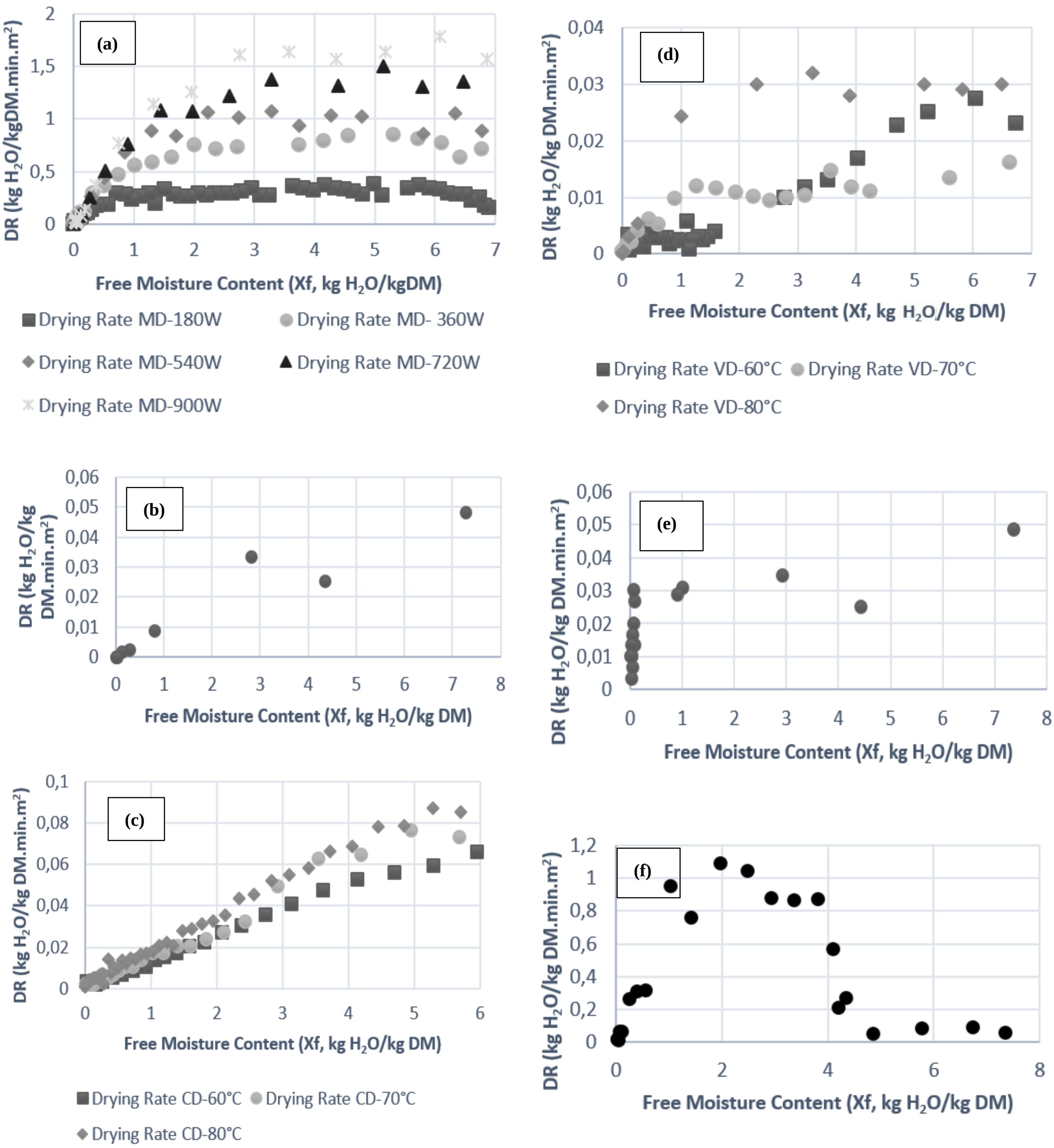


Figure 3: The drying rate of RPP ((a); MD, (b); FD, (c); CD (d); VD (e); FD+MD (f); CD+MD)

the product, thus increasing the D_{eff} of product. It may be the reason for the higher drying rate of FD+MD and CD+MD samples at the late stages of the drying.

D. Calculation of the D_{eff} and E_a

The D_{eff}, E_a, and D_0 values are given in Table 2. The D_{eff} of RPPP ranged between 2.55E-10 and 4.82E-8 m^2/s which are in the same range of D_{eff} of fruits and vegetables (10^{-12}-10^{-6} m^2/s) (Erbay and Icier, 2009; Onwude *et al*., 2016). In the literature, the D_{eff} of red pepper ranged between 2.65-7.82E-9 m^2/s for oven drying, 3.44-6.78E-9 m^2/s for VD, and 2.62-8.10E-9 m^2/s for ultrasound-assisted VD (Tekin and Baslar, 2018). The D_{eff} values of MD-RPPP were generally found to be significantly higher compared to the other drying techniques except for 180 microwave power ($p < 0.05$). Similar results were also obtained by Süfer *et al.* (2017) and Arslan and Özcan (2011). The D_{eff} of RPP increased with the increase of the microwave power, and this increase was found to be significant ($p < 0.05$). Sadeghi *et al.* (2013) reported that an increase in the microwave power enhances the moisture diffusivity through rotating bipolar

Table 1. The drying time, total energy consumption, and energy efficiency (SMER, MER, and SEC) values of selected dryers

Drying Technique	*Drying Conditions*	*Drying Time (h)*	*TEC (kWh)*	*SMER (kg H_2O/kWh)*	*MER (kg H_2O /h)*	*SEC (kWh/kg H_2O)*
MD	**180W**	0.48±0.04^{d}	0.135±0.010^{a}	0.32±0.03^{f}	0.09±0.01^{c}	3.13±0.12^{a}
	360W	0.25±0.01^{c}	0.150±0.006^{b}	0.29±0.01^{ef}	0.17±0.01^{d}	3.46±0.09^{b}
	540W	0.20±0.00^{b}	0.165±0.004^{c}	0.27±0.02^{e}	0.22±0.01^{e}	3.83±0.05^{c}
	720W	0.18±0.01^{a}	0.179±0.006^{d}	0.24±0.01^{de}	0.25±0.02^{f}	4.12±0.07^{d}
	900W	0.16±0.01^{a}	0.185±0.002^{d}	0.23±0.01^{d}	0.27±0.01^{f}	4.28±0.13^{d}
FD	**-48°C**	9.00±0.00^{j}	5.031±0.001^{j}	0.01±0.00^{a}	0.01±0.00^{a}	117.89±5.98^{j}
CD	**60°C**	6.08±0.12^{h}	11.512±0.5210^{l}	0.01±0.00^{a}	0.01±0.00^{a}	270.87±15.84^{m}
	70°C	5.42±0.59^{g}	10.310±0.649^{l}	0.01±0.00^{a}	0.01±0.00^{a}	220.77±9.78^{l}
	80°C	3.83±0.00^{f}	8.242±0.524^{k}	0.01±0.00^{a}	0.01±0.00^{a}	198.70±6.47^{k}
VD	**60°C**	15.00±0.00^{l}	1.100±0.028^{g}	0.04±0.01^{b}	0.01±0.00^{a}	25.47±2.42^{g}
	70°C	12.50±0.00^{k}	0.917±0.023^{f}	0.05±0.01^{b}	0.01±0.00^{a}	21.19±1.56^{f}
	80°C	7.50±0.00^{i}	0.550±0.014^{e}	0.08±0.01^{c}	0.01±0.00^{a}	12.68±3.23^{e}
FD+ MD	**-48°C +540W**	5.10±0.11^{g}	2.883±0.008^{h}	0.01±0.00^{a}	0.01±0.00^{a}	66.36±7.58^{h}
CD+ MD	**70°C +540W**	0.72±0.08^{e}	4.156±0.002^{i}	0.01±0.00^{a}	0.06±0.01^{b}	95.84±2.89^{i}

$^{a-m}$ show the significant differences between the samples ($p < 0.05$).

Table 2. The effective moisture content diffusivity (D_{eff}), activation energy (E_a), and pre-exponential factor (D_0) values

Drying Technique	**Drying Conditions**	**D_{eff} (m^2/s)**	**R^2**	**E_a (W/g for MD, kJ/mol for CD and VD)**	**D_0 (m^2/s)**	**R^2**
MD	**180W**	8.57E-9±2.58E-10^{ab}	0.846±0.013			
	360W	1.71E-8±2.06E-9^{bc}	0.855±0.003			
	540W	3.72E-8±1.03E-9de	0.879±0.009	7.925±0.191	7.03E-8±0.37E-8^{a}	0.939±0.034
	720W	4.29E-8±1.81E-9^{f}	0.894±0.008			
	900W	4.82E-8±3.10E-9^{g}	0.953±0.016			
FD	**-48°C**	9.13E-10±2.58E-10^{a}	0.981±0.002			
CD	**60°C**	7.30E-10±0.00^{a}	0.990±0.003			
	70°C	1.10E-9±0.00^{a}	0.990±7.07E-5	30.439±4.920^{a}	1.42E-5±0.19E-5^{b}	0.966±0.039
	80°C	1.28E-9±2.58E-10^{a}	0.968±0.009			
VD	**60°C**	2.55E-10±5.16E-11^{a}	0.977±0.001			
	70°C	7.12E-10±5.41E-10^{a}	0.942±0.022	39.090±1.014^{b}	2.11E-3±0.10E-4^{c}	0.999±0.013
	80°C	1.28E-9±2.58E-10^{a}	0.884±0.017			
FD+MD	**-48°C +540W**	7.30E-10±5.16E-11 (for FD)^{a}	0.912±0.014			
	-48°C +540W	3.21E-08±4.13E-9 (for MD)^{cde}	0.908±0.003			
CD+MD	**70°C +540W**	7.30E-10±1.03E-10 (for CD)^{a}	0.992±0.037			
	70°C +540W	4.56E-08±5.16E-10 (for MD)^{bcd}	0.936±0.014			

$^{a-e}$ show the significant differences between the samples ($p < 0.05$)

molecules at higher velocities. It may be the reason for high $\boldsymbol{D_{eff}}$ values at high microwave powers. In addition, the high moisture content of the RPP and high generation rate at high microwave powers which resulted in the high activity of water molecules may be the reason for this situation. The results are also consistent with Demiray et al. (2017) and Akdoğan *et al.* (2017). In addition, Demiray *et al.* (2017) reported that $\boldsymbol{D_{eff}}$ and drying rate have a directly proportional relationship. Similar to the drying rate, the VD-RPPP had the lowest $\boldsymbol{D_{eff}}$ while MD-RPPP had the highest $\boldsymbol{D_{eff}}$. The differences between the D_{eff} values of MD-180W, FD, CD, and VD were not found to be statistically significant ($p > 0.05$). An increase in the drying air temperature resulted in an increase in the $\boldsymbol{D_{eff}}$ of CD and VD samples ($p > 0.05$). High drying air temperature provides a high driving force for heat and mass transfer which increases the $\boldsymbol{D_{eff}}$ of RPPP. In addition, Caliskan and Dirim (2017) reported that higher $\boldsymbol{D_{eff}}$ is related to the fast water movement to the surface subsequent evaporation rate at a high temperature. Similar findings were also obtained by Deng *et al.* (2018) and Demiray *et al.* (2017). Since two different kinetics were observed for combined drying techniques two different $\boldsymbol{D_{eff}}$ were calculated (Table 2). It may be due to the changes in the heat transfer mechanism and structure of the RPP. Higher $\boldsymbol{D_{eff}}$ values were observed for MD compared to FD and CD due to rapid moisture transfer in the MD. As expected, the D_{eff} of FD-RPPP and CD-RPPP can be significantly increased by combining these techniques by MD ($p < 0.05$). Similar results obtained by Sadeghi *et al.* (2013) who reported that in the MD–CD technique, the presence of the hot-air flow helps moisture to extract and leave the surface of the product which resulted in a higher drying rate and $\boldsymbol{D_{eff}}$.

The $\boldsymbol{E_a}$ values were calculated as 7.925 W/g, 30.439 kJ/mol, and 39.090 kJ/mol for MD, CD, and VD red pepper pulp powders, respectively. The $\boldsymbol{E_a}$ values were in the order of VD> CD which indicates that the D_{eff} of RPPP dried by VD is more susceptible to temperature change compared to RPPP dried by CD ($p < 0.05$). There is a direct correlation between E_a and the energy needed to facilitate diffusion. The E_a value was lower for CD compared to VD. It can also be stated that CD required less energy consumption which was needed to facilitate diffusion. Onwude *et al.* (2016) and Erbay and İçier (2009) reported that the E_a values of foods are in the range of 12.32 to 130.61kJ/mol. The calculated E_a for CD and VD are in a similar range of given values. The E_a of MD-RPPP are in the same range of microwave dried fruits and vegetables 7.90 and 27.149 W/g (Akdoğan *et al.*, 2017; Demiray *et al.*, 2017; Moradi *et al.*, 2013). The higher R^2 values demonstrated the microwave power and temperature dependency of RPP. The E_a values of hot air-dried red pepper were found to be as 48.90 kJ/mol by Deng et al. (2018), 58kJ/mol by Sanjuán *et al.* (2003), and 39.70 kJ/mol by Vega *et al.* (2007). The E_a of VD and MD-RPPP were found to be as 24.047 kJ/mol by Tekin and Başlar (2018) and 14.19 W/g by Darvishi *et al.* (2014), respectively. The differences between the E_a of RPP may be due to the chemical composition, tissue structure, surface area, variety, drying method, etc.

IV. CONCLUSIONS

The findings of this study are believed to give an idea to the producers about the design of the red pepper drying process, the optimization of the process parameters, the TEC and efficiency of the dryers, and moisture content and water activity of the obtained RPPP. Page model which showed the highest R^2 value was chosen as the most suitable model for determining MD, FD, CD, VD, and CD+MD characteristics of RPP at different techniques and conditions. The drying processes took place in a combined form of the constant and falling rate periods for all drying experiments except for CD and CD+MD. Drying rate and D_{eff} of RPPP significantly increased depending on the increase in the microwave power ($p < 0.05$), however, the effect of drying air temperature on the D_{eff} of RPPP was found insignificant ($p > 0.05$). Microwave finish drying significantly increased the drying rate and D_{eff}, and significantly decreased the drying time, moisture content, TEC, and SEC values ($p < 0.05$). The E_a values were in the order of VD > CD which is similar to the D_0. The effect of the drying processes on the chemical composition of the RPPP could be studied in further studies.

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