

Full Length Research Paper

Microwave-vacuum drying effect on drying kinetics, lycopene and ascorbic acid content of tomato slices

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This study investigated the microwave-vacuum drying on the drying kinetics and quality attributes of dried tomatoes such as lycopene and ascorbic acid contents. Among the thirteen thin layer drying models that were used to fit the experimental data, the Midilli et al gave the highest correlation coefficient, lowest residual sum of squares, root mean square error, and reduced chi-square, thus indicating that the model of Midilli et al best described the microwave-vacuum drying of tomato slices. The highest ascorbic acid retention occurred in the samples dried at 200 W and 0.06 MPa, with a significant decrease ($p < 0.05$) from an initial mean value of 2.74 ± 0.29 to 1.87 ± 0.13 mg/g dry matter, representing a decrease of about 32% in relation to the fresh tomato. On the other hand, the lycopene content of the dried tomatoes significantly ($p < 0.05$) increased from 2.96 mg/100 g dry matter to a maximum value of 25.44 mg/100 g dry matter after microwave-vacuum drying at 700 W and 0.04 MPa.

Key words: Tomato slices, drying models, lycopene, ascorbic acid, microwave-vacuum.

INTRODUCTION

Tomato (*Lycopersicon esculentum*) is the second most important vegetable after potato due to its wide spread cultivation (Celma et al., 2009) and health benefit particularly in fighting prostate cancer, cervical cancer, cancer of the stomach and rectum as well as pharynx and oesophageal cancers (FAO, 2010; HSPH, 2010). Drying is an important process in the processing of agricultural materials. It does not only help address post-harvest challenges facing the agricultural sector but reduces the bulk volume of materials to an appreciable one. Burning of dried whole strawberries was found when microwave power of 600W was applied (Venkatachalapathy and Raghavan, 2000). Microwave drying has been found to produce poorer quality of dried mushrooms products (Walde et al., 2006).

In Poland, microwave drying of grains for propagation was found not to germinate at all. To help address some of the problems in microwave drying, microwave-vacuum drying has gained attention in the drying of fruits and vegetables. The idea to apply microwave-vacuum was to speed up drying process, to increase mass transfer by an increased pressure gradient between inner and outer layers, and to maintain drying process at low temperature (Pere and Rodier, 2002; Therdthai and Zhou, 2009). It is noted that in food drying processes, process engineers need simple, accurate, and analytical models with verified experimental data to carry out optimized unit operations (McMinn, 2006). The contribution of modeling in this respect is to help understand the heat and mass transfer phenomena, and computer simulations for designing new processes and improving existing ones (Kardum et al., 2001). It is a well known fact that thin-layer equations have found wide application in experimental convective air drying data, but its application to microwave vacuum

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drying is more limited. Previous work done support the argument that the Page, Lewis models could not adequately describe the experimental drying curves of microwave assisted drying of carrot (Prabhanjan et al., 1995), microwave vacuum drying of mint leaves (Therdthai and Zhou, 2009), microwave -vacuum drying of lactose powder (McMinn, 2006).

Various drying models have been developed for solar drying of organic tomatoes (Sacilik et al., 2006), microwave drying of carrot (Prabhanjan et al., 1995), okra (Dadali et al., 2007), microwave vacuum drying of mint leaves (Therdthai and Zhou, 2009), lactose powder (McMinn, 2006), ultrasonic drying of red bell pepper and apple slices (Schössler et al., 2012), and infrared drying of apple slices (Togrul, 2005). At present, there are limited models that adequately represent the drying of tomato slices in a microwave-vacuum dryer. Therefore, this study was undertaken to investigate the thin-layer drying kinetics of tomato slices in a microwave-vacuum dryer and to simulate the experimental data to the mathematical models available in scientific literature. In addition, the quality attributes of dried tomatoes such as lycopene and ascorbic acid contents were investigated.

MATERIALS AND METHODS

Sample preparation

The fresh tomatoes used in this study were tomatoes from the same cultivar procured from the Zhenjiang local Market, China. Selection was based on visual assessment of uniform colour and geometry. The initial moisture content of the tomatoes was determined at 105°C for 24 h. The tomato samples were washed under running tap water and stored in a refrigerator at a temperature of 4°C in order to slow down the physiological and chemical changes (Maskan, 2001; Karaaslan and Tuncer, 2008). Prior to drying, the individual tomatoes were cut into slices of thickness 7 mm using a cutting machine (SS-250, SEP Machinery Company Ltd, Guangzhou, China).

Combined microwave-vacuum drying

The microwave-vacuum experiment was conducted in a 4 × 3 factorial design with four microwave powers (200, 300, 500 and 700 W) in three treatments combinations with vacuum pump pressures (0.04, 0.05 and 0.06 MPa). All observations were replicated three times. A laboratory scale microwave-vacuum dryer (NJZ07-1, Jiangsu University, Zhenjiang, China) with maximum power output of 1000 W at 2500 MHz was used for this experiment.

The dimensions of the microwave cavity were 40 cm by 28 cm by 33 cm. The microwave was fitted with rotating table of diameter 230 mm, which is the load density of the dryer. The microwave dryer is combined with vacuum pump, which has maximum pressure of 0.1 MPa. In this machine the microwave dryer can only function when the pressure is at least 0.04 MPa. The schematic diagram of the combined microwave vacuum dryer is shown in Figure 1. Microwave powers of 200, 300, 500 and 700 W at vacuum pressures of 0.04, 0.05 and 0.06 MPa were used for this experiment at constant sample loading density of 100 g. The sample was put in thin layer in a bowl with one slice not touching the other and placed on the Teflon turn table in the microwave

vacuum cavity. Depending on the drying condition, the moisture loss was recorded every 1, 2 and 4 min until constant mass was observed for the determination of the drying curves (Karaaslan and Tuncer, 2008). After the set time, the sample was taken out of the drying chamber and weighed with an electronic balance (accuracy of 0.001 g) within 10 s (Karaaslan and Tuncer, 2008).

Ascorbic acid analysis

The ascorbic acid in the fresh and dried samples was determined volumetrically according to the method described by Sadasivam and Balasubraminan (1987). A dye solution was prepared by dissolving 52 mg of 2, 6-dichlorophenol indophenols in small volume of distilled water containing 42 mg of sodium bicarbonate and made up to 200 ml. The stock standard solution of concentration (1 mg/ml) was made with 100 mg standard ascorbic acid in 100 ml of 4% oxalic acid solution in a flask. Ten millilitre of the stock solution was taken and diluted to 100 ml with oxalic acid solution. To 5 ml of the working standard solution was added 10 ml of oxalic acid in a 100 ml conical flask and titrated against the dye (V_1 ml). The appearance of the pink colour, which persists for few minutes, indicates the end point and the dye consumed is equivalent to the amount of ascorbic acid. Ascorbic acid was extracted with 50 ml oxalic acid from 5 g fresh and 0.5 g grounded dried tomatoes and centrifuged at 4000 rpm for 10 min. To 5 ml of the supernatant was added 10 ml of oxalic acid and the mixture titrated against the dye (V_2 ml). The titration was done in triplicate. The ascorbic acid (AA) content in mg/g was calculated following Equation 1:

$$AA = \frac{0.5}{V_1} \times \frac{V_2}{5 \text{ ml}} \times \frac{50 \text{ ml}}{\text{Sample weight}} \quad (1)$$

Lycopene content analysis

The lycopene in the fresh and dried tomato samples was extracted in acetone and then taken up in petroleum ether following the protocol of Ranganna (Ranganna, 1976). The pigment was repeatedly extracted from 5 g of fresh tomato pulp and 0.5 g of dried tomatoes with acetone and assisted with ultrasound until the residue was colourless. The acetone extract was transferred into a separating funnel containing 20 ml petroleum ether and mixed gently. Then, 20 ml of 5% sodium sulphate solution was added and the separating funnel shaken gently. Another 20 ml of petroleum ether was added to make up for any evaporated petroleum ether. The coloured pigment noticed in the upper petroleum ether phase was separated and the lower phase re-extracted with additional petroleum ether until colourless. The petroleum ether was washed with a little distilled water and poured into a brown bottle containing 10 g of anhydrous sodium sulphate and kept for at least 30 min. The petroleum ether was decanted into a 100 ml volumetric flask through a cotton wool in a funnel. The sodium sulphate slurry was washed with petroleum ether until it was colourless and transferred into the volumetric flask. It was topped up to the mark with petroleum ether and the absorbance measured in a spectrophotometer at 503 nm with petroleum ether as blank. The lycopene content (mg/100 g sample) was calculated using Equation 2.

$$L_c = \frac{31.206 \times \text{Abs}_{503\text{nm}}}{W_t} \quad (2)$$

where L_c is the lycopene content (mg/100 g), Abs is the absorbance, and w_t is the weight of the sample (g).

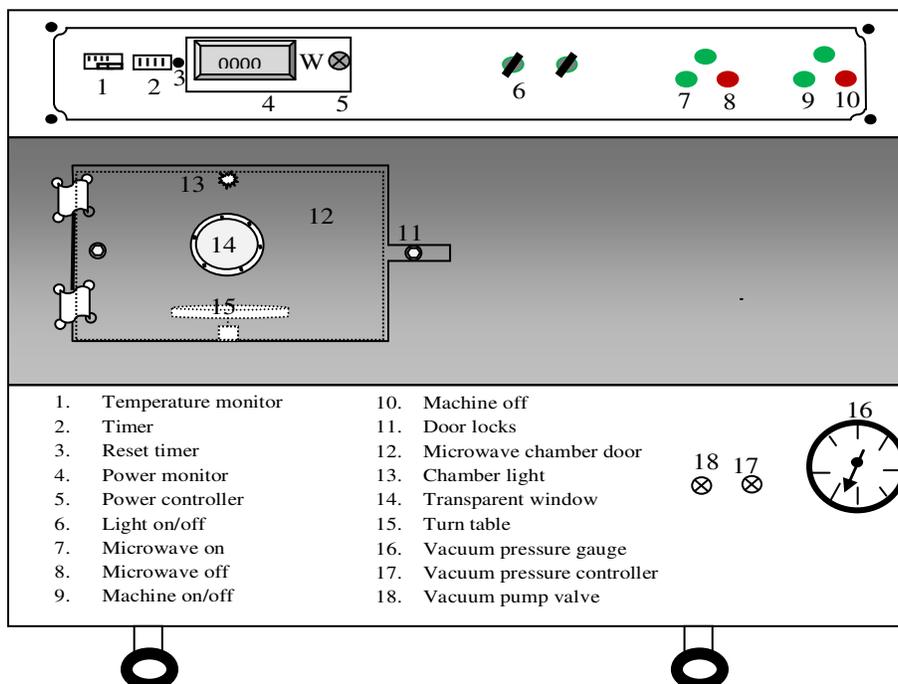


Figure 1. Schematic diagram of the microwave vacuum equipment.

Table 1. Mathematical models that was applied to the experimental data.

Model name	Model expression	Reference
Lewis	$MR = \exp(-kt)$	Lewis (1921)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified Page	$MR = \exp[-(kt)^n]$	Overhults et al. (1973)
Henderson and Pabis	$MR = a \exp(kt)$	Henderson and Pabis (1961)
Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	McMinn (2006)
Logarithmic	$MR = a \exp(-kt) + c$	McMinn (2006)
Two-term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	Sacilik et al. (2006)
Two-term exponential	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Sharaf-Eldeen et al. (1980)
Diffusion approach	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$	Kassem (1998)
Verma <i>et al.</i>	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	Verma et al. (1985)
Wang and Singh	$MR = 1 + at + bt^2$	Demir et al. (2007)
Midilli et al.	$MR = a \exp(-kt^n) + bt$	Midilli et al. (2002)
Parabolic	$MR = a + bt + ct^2$	Sharma and Prasad (2004)

Modeling of the experimental data

This experimental moisture ratio data were fitted to 13 thin-layer drying models presented in Table 1 to describe the microwave vacuum drying kinetics of tomato slices. The Non-linear regression analysis was performed with statistical package program SPSS 16.0 (SPSS, 2007). Regression and correlation analysis are very useful tools in modeling the drying behaviour of biological materials (Erbay and Icier, 2008). Four primary criteria used to assess the accuracy of fit to the models were: the correlation coefficient (R^2), residual sum of squares (RSS), the root mean square error (RMSE), and the reduced chi square (χ^2). In non-linear regression modeling, designing the fitting procedure to achieve a minimum RSS is very

crucial. The highest R^2 , and the lowest values of RSS, χ^2 and RMSE values were used to predict the goodness of fit. Several authors have used these criteria to select the best model for drying mistletoe (Kose and Erenturk, 2010), onion slices (Mota et al., 2010), aromatic plants (Akpinar, 2006), olive leaves (Erbay and Icier, 2008), okra (Doymaz, 2005), thyme (Doymaz, 2010), lactose powder (McMinn, 2006), and aloe vera (Vega et al., 2007).

Calculation of moisture diffusion coefficient and activation energy

The moisture ratio values for the various drying conditions were

generated according to the simplified diffusion equation given by Equation 3.

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \quad (3)$$

where, MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m^2/s), and L is half the thickness of slice of the sample (m), M is the moisture content at any time, t , M_e is the equilibrium moisture content, and M_0 is the initial moisture content. From Equation 3, D_{eff} of the tomato slices was obtained from the slope (K) of the graph of $\ln MR$ against the drying time. $\ln MR$ versus time results in a straight line with negative slope and K is related to D_{eff} by equation 4.

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

In a standard microwave drying process, the internal temperature of the sample is not a measurable variable. The tailored form of the Arrhenius type equation is used to illustrate the relationship between the diffusivity coefficient and the ratio of the microwave power output to sample thickness instead of the temperature, for the calculation of the activation energy. The equation as suggested by Dadali et al. (2007) is of the form:

$$D_{eff} = D_0 \exp\left[\frac{-E_a q}{P}\right] \quad (5)$$

where D_0 is the constant in the Arrhenius equation (m^2s^{-1}), E_a is the activation energy (W/mm), P is the microwave power (W), and q is the sample thickness (mm). Equation 5 can be rearranged into the form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a q}{P} \quad (6)$$

The activation energy for moisture diffusion was obtained from the slope of the graph of $\ln(D_{eff})$ against q/P . The drying rate of tomato slices was calculated using Equation 7 (Doymaz, 2010), where M_{t+dt} is the moisture content (kg water per kg dry matter) at $t + dt$, and t is the drying time (min).

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (7)$$

Statistical analysis

One-way analysis of variance (ANOVA) was carried out with SPSS 16.0 to determine the main influence of microwave-vacuum on the parameters studied. The Fishers least significance difference (LSD) was used to compare differences at the 95% probability level. Where significant differences exist, the Duncan Multiple range test was employed to separate the means.

The different statistical evaluation equations (8, 9, 10 and 11) were used to describe the goodness of fit of the dried tomato slices to the drying models applied.

$$R^2 = \frac{N \sum_{i=1}^N MR_{pred,i} MR_{expt,i} - \sum_{i=1}^N MR_{pred,i} \sum_{i=1}^N MR_{expt,i}}{\sqrt{\left(N \sum_{i=1}^N MR_{pred,i}^2 - \left(\sum_{i=1}^N MR_{pred,i} \right)^2 \right) \left(N \sum_{i=1}^N MR_{expt,i}^2 - \left(\sum_{i=1}^N MR_{expt,i} \right)^2 \right)}} \quad (8)$$

$$RSS = \frac{1}{N} \sum_{i=1}^N (MR_{expt} - MR_{pred})^2 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{expt,i} - MR_{pred,i})^2} \quad (10)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{expt,i} - MR_{pred,i})^2}{N - z} \quad (11)$$

where $MR_{expt,i}$ and $MR_{pred,i}$ are the experimental and predicted dimensionless MR respectively, N is the number of observations, and z is the number of model constants. The drying rate constants and coefficients of the model equations were determined with nonlinear regression of SPSS 16.0 (SPSS, 2007), and the goodness of fit of the curves was determined with correlation analysis.

RESULTS AND DISCUSSION

Effect of microwave power and vacuum pressure on drying kinetics

Figures 2 and 3 show the variation of moisture ratio versus drying time for the various microwave powers of 200, 300, 500 and 700 W and vacuum pressures of 0.04, 0.05 and 0.06 MPa. The initial average moisture content of the tomatoes was 24.71 kg water/kg dry matter, which reduced to 0.15 kg water/kg dry matter after drying. It is clear how drying followed a falling rate period and the increase in microwave power accelerated the drying process. As microwave power increased, moisture removal also increased and ultimately resulted in the reduction in drying time. Drying time reduced from 84 to 14 min as the microwave power increased from 200 to 700 W. This means that there was significant savings in time as microwave power increased. The results agree with what was reported by Contreras et al. (2008), Bai- Ngew et al. (2011), Figiel, (2009), Karaaslan and Tuncer (2008) for microwave drying of apple and strawberry, durian chips, beetroot, and spinach respectively.

The increase in vacuum pressure enhanced drying rate as shown in Figure 3. This was expected because as vacuum pressure increases there is an accelerated removal of moisture build-up in the microwave chamber, which consequently enhanced the drying process. The drying time was fitted to a linear model (that is, $\beta_0 + \beta_1 P_0 + \beta_2 P_r$), where β_0 , β_1 , β_2 , are estimated coefficient of the linear model, P_0 is microwave power, and P_r is vacuum pressure. The analysis of variance for the main or linear effect of microwave power and vacuum pressure indicated that microwave power was the significant model term (Table 2). Variations in the estimated coefficients show that there were different relative importance of the microwave power and vacuum pressure. From the model result shown in Table 2, it could be seen that the effect of microwave power was higher than vacuum pressure.

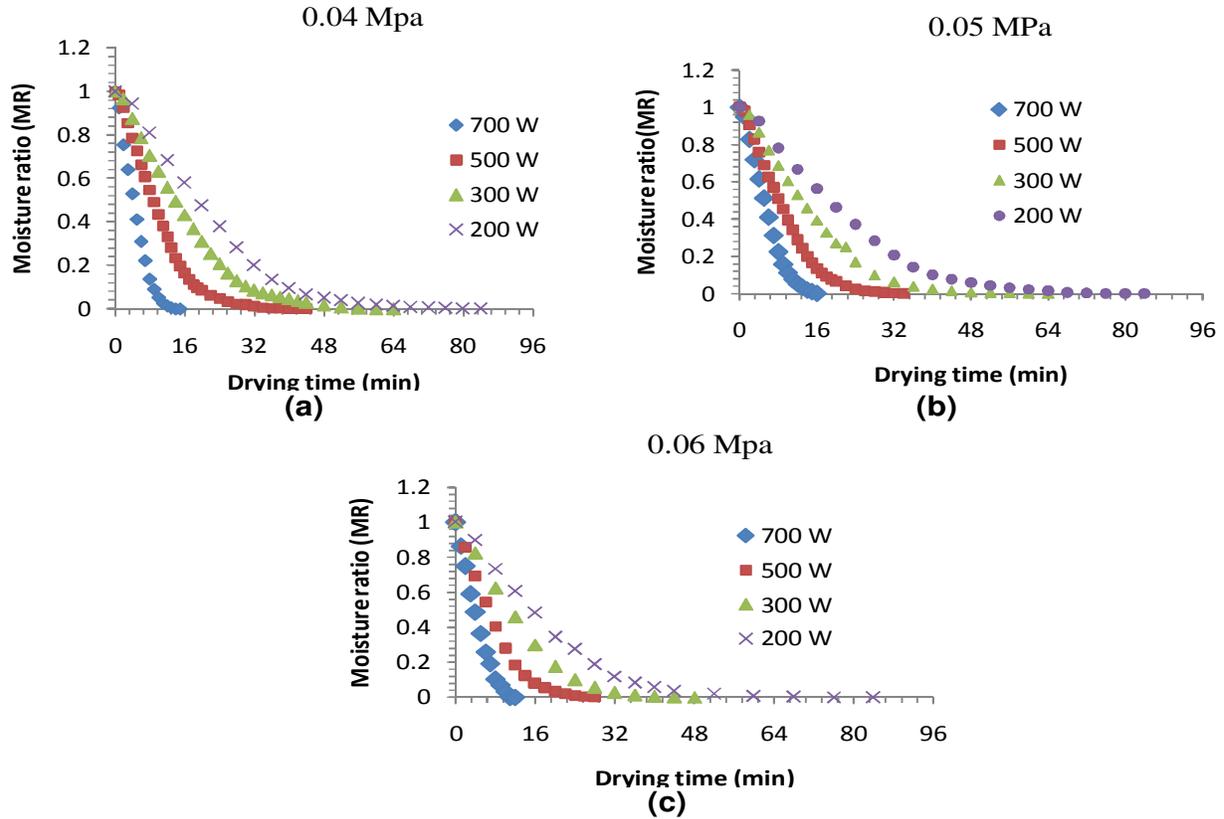


Figure 2. Variation of moisture ratio versus drying time at various microwave powers at a vacuum pressures of 0.04, 0.05, and 0.06 MPa.

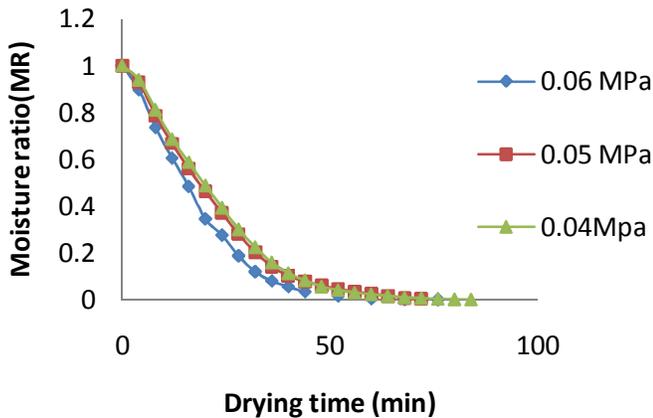


Figure 3. Variation of moisture ratio versus drying time for the various vacuum pressures at 200 W microwave powers.

The drying rates against moisture content for the various drying conditions are illustrated in Figures 4 and 5. It was observed from the Figure 4 that two types of drying rates period were observed; the constant rate and the falling rate period. The two drying rates period were mostly observed in the various microwave powers at 0.04 and 0.05 MPa. However, there was no constant rate period

observed for the samples dried at 700 W and 0.06 MPa. The constant rate period was noticed in the sample moisture content range of 17.96 to 5.98, 14.08 to 7.17, and 18.19 to 8.57 kg water/kg dry matter for the 0.04, 0.05 and 0.06 MPa vacuum pressures respectively. The drying rate trend indicated for 700 W and 0.06 MPa show that at higher microwave power and vacuum pressure, the drying rate may cause excessive and unexpected burning if care is not taken. This trend is further explained by the drying rate and moisture content plot for 500W and various vacuum pressures of 0.04, 0.05 and 0.06 MPa displayed in Figure 5.

Effect of drying parameters on coefficients of effective moisture diffusion

The variation of Ln(MR) against drying time plot for the various microwave-vacuum drying conditions is shown in Figure 6. The slopes of the straight line generated by the plot of Ln(MR) against drying time were used to determine the effective moisture diffusion values. The plot gave a straight line with high correlation coefficients ranging between 0.9069 and 0.9825. The effective moisture diffusion values ranged between 6.74×10^{-9} and $41.71 \times 10^{-9} \text{ m}^2/\text{s}$.

Table 2. Analysis of variance for main effect of microwave power and vacuum pressure on drying time.

Source	Coefficient estimate	Sum of squares	df	Mean square	F Value	p-value Prob > F
intercept	47.75					
Model		8238.75	5	1647.75	50.06	< 0.0001*
P	36.25	8030.25	3	2676.75	81.32	< 0.0001*
Pr	4.0	208.50	2	104.25	3.17	0.1151**
R ²	0.9766					

*Significant ; ** not significant at p<0.05.

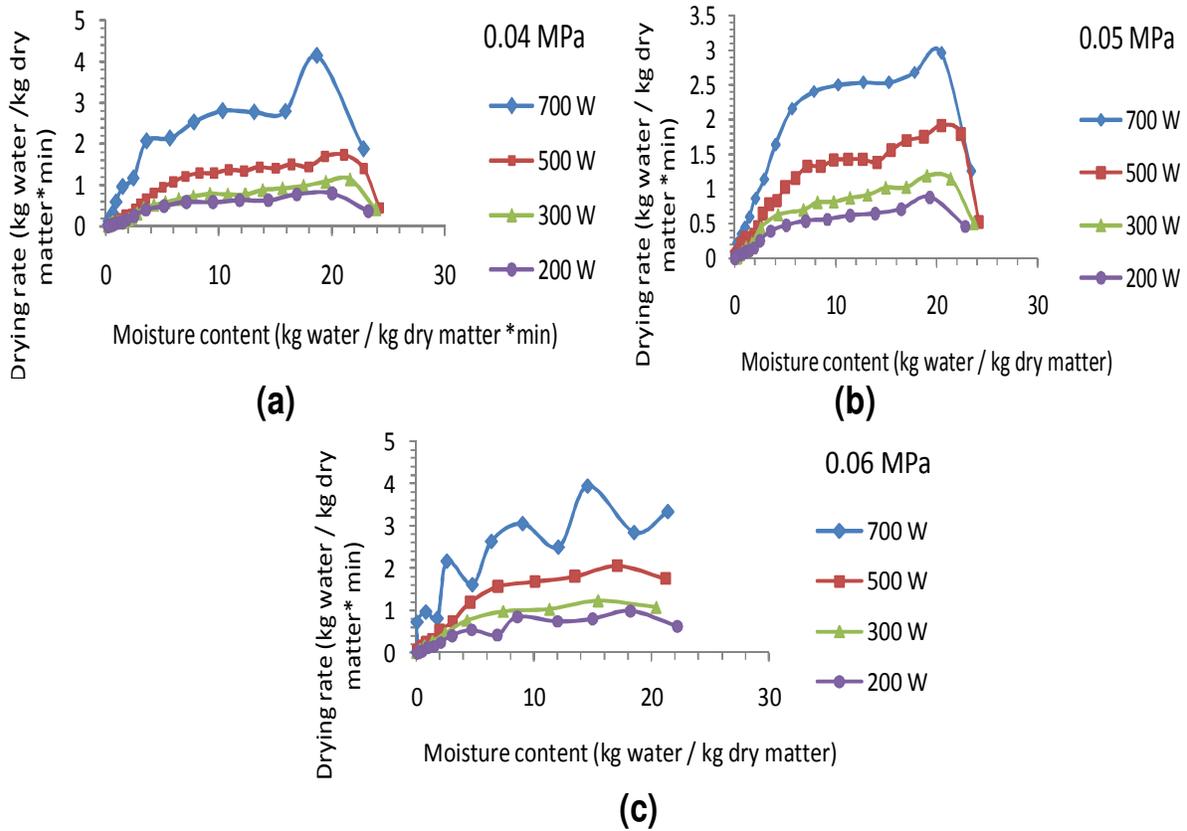


Figure 4. Drying rate against moisture content for various microwave power levels at a vacuum pressures of (a) 0.04 MPa, (b) 0.05 MPa, and (c) 0.06 MPa.

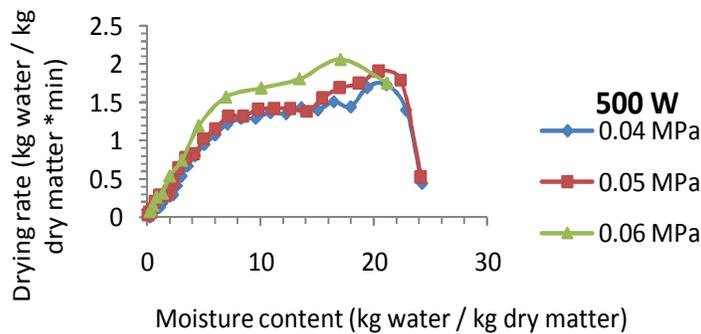


Figure 5. Drying rate against moisture content various microwave vacuum pressures at a microwave power of 500 W.

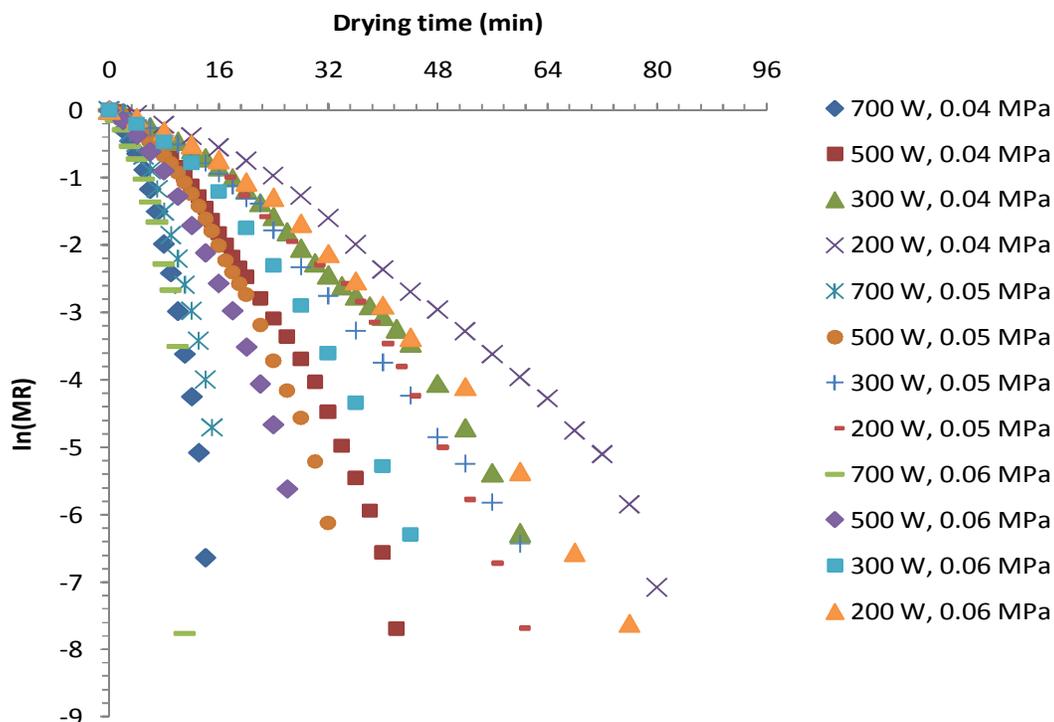


Figure 6. Variation of $\ln(MR)$ against drying time plots for the various drying condition.

The variation of microwave power and vacuum pressures on the effective moisture diffusion coefficients are displayed in Figures 7 and 8 respectively. It can be observed from the Figure 6 that increases in microwave power corresponding increased exponentially the effective moisture diffusion coefficients. A similar exponential increase with increasing vacuum pressure was observed for the diffusivity values within the microwave power range of 200 and 500 W. However, a fluctuation in effective moisture diffusivity which is best described by a second order polynomial was realized for the 700 W microwave powers at various vacuum pressures. The D_{eff} values recorded in this study lie within the general range of 10^{-12} to 10^{-8} m^2/s for drying agricultural materials (Doymaz, 2010). The effect of the microwave power was however higher than the vacuum pressure (Figures 7 and 8 and Table 2).

The Arrhenius type microwave power dependence activation energy was calculated using equation (10) and illustrated in Figure 9 showing the microwave power dependence on the activation energy at various vacuum pressures with their statistical coefficient of correlation. It could be observed from the Figure 9 that the activation energy values recorded at the vacuum pressure of 0.04 MPa was the highest, followed by the 0.06 MPa, and the 0.05 MPa drying condition. The results gave activation energy in the range of 47.8 and 58.94 W/mm for the three vacuum pressures used in this study. The results agree with microwave vacuum drying of mint leaves by

Therdthai and Zhou (2009). The activation energy recorded in this study was higher than the activation energy of 36.40 W/mm reported (Darvishi et al., 2012) for drying of carrot slices, 23.83 W/g for sweet pomegranates (Minaei et al., 2012) and lower than 554 W/100 g for okra (Dadali et al., 2007).

Effect of microwave-vacuum on ascorbic acid

Table 3 presents the ascorbic acid content of the fresh and dried tomatoes at various microwave-vacuum conditions. The ascorbic acid content decreased significantly from an initial mean value of 2.74 ± 0.29 mg/g dry matter of the fresh tomatoes to a least value of 0.91 ± 0.04 mg/g dry matter after drying at 500 W and 0.06 MPa. This represents a maximum decrease of about 66% in ascorbic acid. On the other hand, the samples dried at 200 W and 0.06 MPa had the least reduction to 1.87 ± 0.13 mg/g dry matter, representing a decrease of about 32% in relation to the fresh tomato. The reduction of ascorbic acid content observed during microwave-vacuum drying may be due to the destruction of vitamin C by the electromagnetic waves of the microwave power as the samples were dried. This is because thermal damage and irreversible oxidative reactions are the two main causes of ascorbic acid degradation during drying as a result long drying times. In this study, the drying times were relatively short compared with hot air drying.

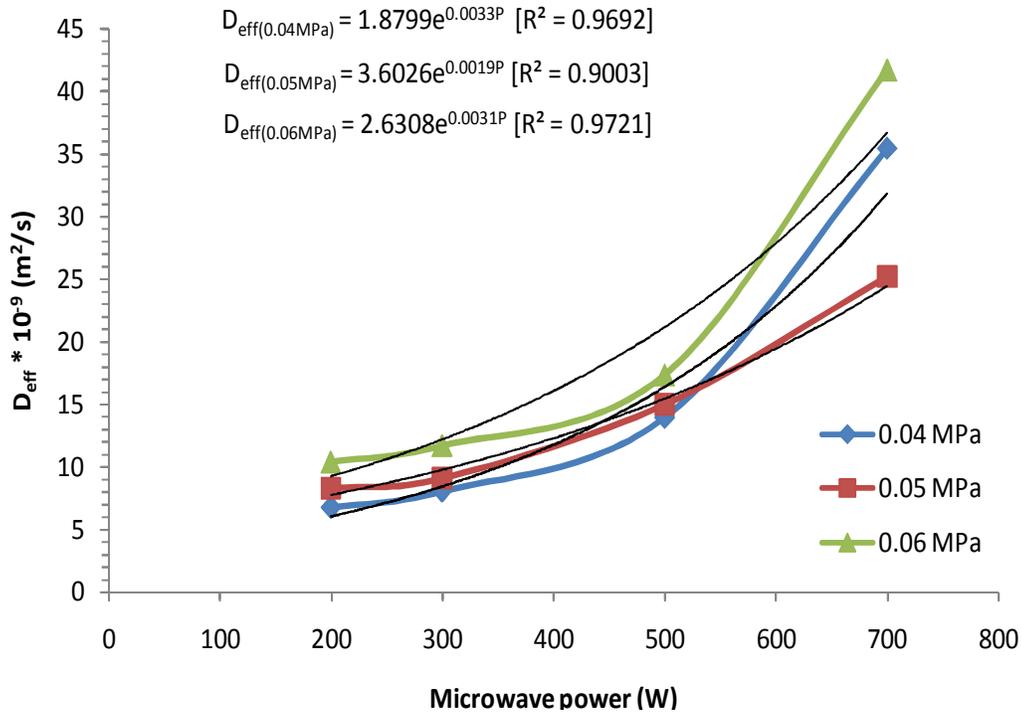


Figure 7. Effect of microwave power on the on the effective moisture diffusion coefficient.

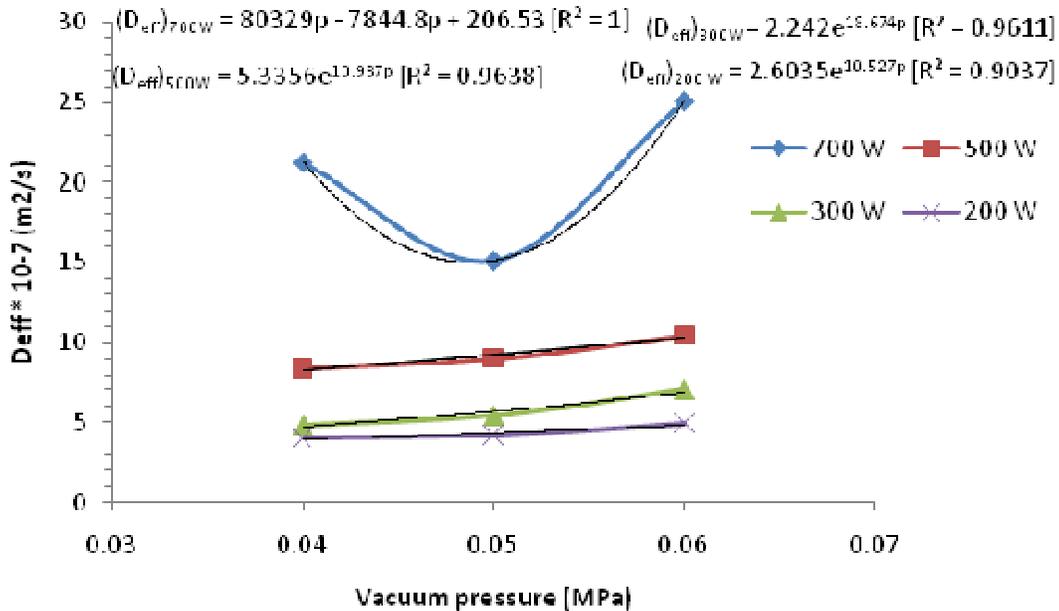


Figure 8. Effect of vacuum pressure on the effective moisture diffusion coefficient.

Therefore, the degradation in AA content may be thermal damage resulting from the microwave energy as it impinges on the tomato surface. Alibas Ozkan et al. (2007) found a similar decrease in ascorbic acid content of dried spinach in the microwave power range of 350 to 1000 W. In their studies, there was a reduction in ascorbic

acid content from 50.18 ± 1.36 to 23.30 ± 1.93 mg/100 g. A similar trend was observed for microwave cooking treatment of broccoli in a study by Zhang and Hamauzu (2004).

The reduction agrees with results obtained by Zheng and Lu (2011) for microwave pretreatment on the kinetics

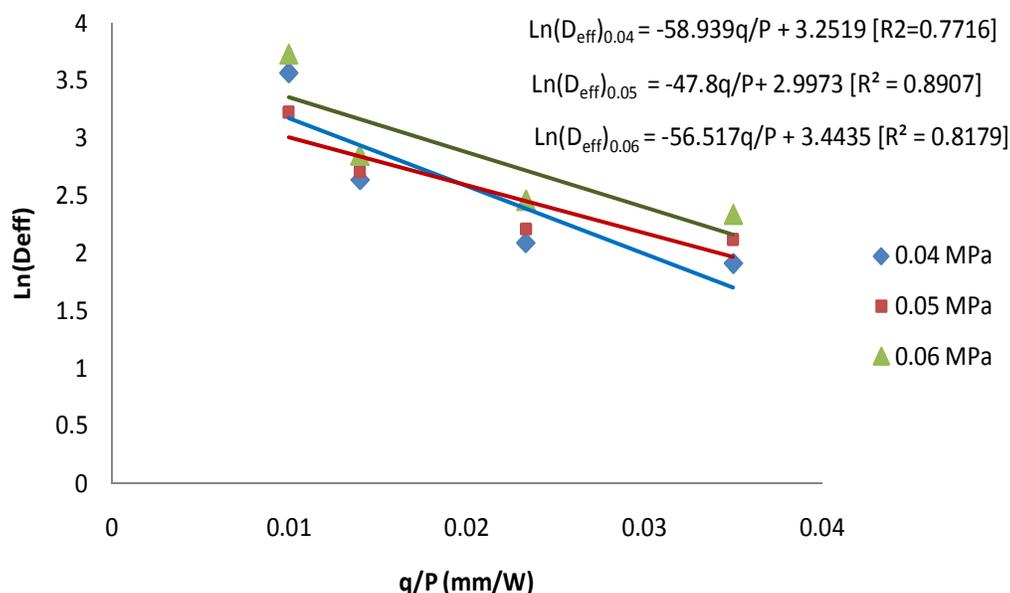


Figure 9. Ln(Deff) against q/P plot at various vacuum pressures.

Table 3. Ascorbic acid content (mg/g dry matter) of the fresh and microwave-vacuum dried samples

Drying condition	0.04 MPa	0.05 MPa	0.06 MPa
Fresh	2.74±0.29 ^c	2.74±0.29 ^c	2.74±0.29 ^c
200 W	1.32±0.08 ^{b1}	1.45±0.12 ^{ab1}	1.87±0.13 ^{b2}
300 W	1.01±0.13 ^{a1}	1.27±0.09 ^{a2}	1.84±0.09 ^{b3}
500 W	1.19±0.04 ^{ab2}	1.69±0.12 ^{b3}	0.91±0.04 ^{a1}
700 W	1.24±0.13 ^{ab1}	1.56±0.13 ^{ab2}	1.86±0.13 ^{b3}

Mean values within a column (^{a-c}) and in a row (¹⁻³) bearing the same letters are not significantly different at the 0.05 level *Values are means ±standard deviation.

Table 4. Lycopene content (m g/100g dry matter) of the fresh and microwave-vacuum dried samples

Drying condition	0.04 MPa	0.05 MPa	0.06 MPa
Fresh	2.960±0.002 ^a	2.960±0.002 ^a	2.960±0.002 ^a
200 W	9.278±0.095 ^{b1}	12.253±0.157 ^{d3}	11.359±0.108 ^{e2}
300 W	17.018±3.536 ^{c2}	7.843±0.036 ^{b1}	9.278±0.095 ^{c1}
500 W	9.695±0.157 ^{b2}	11.088±0.095 ^{c3}	8.217±0.072 ^{b1}
700 W	25.44±0.343 ^{d3}	13.939±0.157 ^{e2}	10.776±0.036 ^{d1}

Mean values within a column (^{a-e}) and in a row (¹⁻³) bearing the same letters are not significantly different at p=0.05 *Values are means ±standard deviation

of ascorbic acid in different parts of green asparagus. Marfil et al. (2008) investigated ascorbic acid content in osmotic drying of tomato halves at 50, 60 and 70 °C and observed an ascorbic acid reduction from 4.00 ± 0.30 mg/g to 2.19 ± 0.24 mg/g dry matter, representing 35% reduction. In a study of microwave vacuum drying of carrot slices and microwave drying of potatoes, Lin et al. (1998) and Khraisheh et al. (2004) reported a decrease

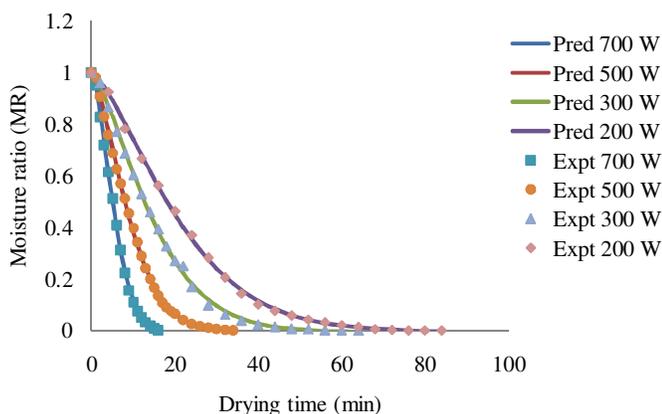
of 21 and 25% ascorbic acid content respectively.

Effect of microwave-vacuum on lycopene content

To examine the influence of microwave-vacuum on the lycopene content, the dried tomato slices lycopene content were compared with that of the fresh (Table 4).

Table 5. Results of the fitting of the experimental data to the drying models, N=27.

Model name	Model constants	R ²	RSS	RMSE	$\chi^2 \times 10^{-3}$
Lewis	k:0.101	0.9585	0.105	0.0623	4.038
Page	k:0.033, n:1.465	0.9988	0.003	0.0105	0.12
Modified Page	k:0.033, n:1.465	0.9988	0.003	0.0105	0.12
Henderson and Pabis	k:0.120, a: 1.188	0.9842	0.040	0.0385	1.60
Modified Henderson and Pabis	k:0.120, a: 0.396, b: 0.397	0.9842	0.040	0.0385	1.904
Logarithmic	k:0.099, a: 1.224, c:-0.082	0.9921	0.020	0.0272	0.833
Two-term	a:96.816, b:-95.685, k ₀ :0.064, k ₁ : 0.064	0.9941	0.015	0.0236	0.652
Two-term exponential	k:0.157, a:1.984	0.9964	0.009	0.0182	0.36
Diffusion approach	k:0.100, a: 1.00, b: -20.262	0.9586	0.105	0.0623	4.375
Verma et al.	k:0.095, a: 1.00, g:-2.00	0.9546	0.115	0.0652	0.68
Wang and Singh	a:-0.074, b: 0.001	0.9933	0.017	0.0251	0.0869
Midilli et al.	k:0.031, a: 0.989, n:1.482, b: 0.000	0.9992	0.002	0.0086	0.0869
Parabolic	a: 1.047, b: -0.079, c: 0.001	0.9961	0.01	0.0192	0.4167

**Figure 10.** Fitting of microwave-vacuum drying of experimental and simulated data to the Midilli et al. model.

The lycopene levels of the dried tomatoes significantly ($p < 0.05$) increased from an initial value of 2.96 mg/100 g dry matter to a maximum value of 25.44 mg/100 g dry matter after microwave-vacuum drying. It has been reported that in tomatoes, lycopene content degradation depends on many factors including processing temperature, that is, the heat energy from the microwave power. Lycopene of the fresh tomato can isomerizes from its trans-form into the cis-lycopene as a result of thermal treatment or degrade into colorless form (Sharma and Le Maguer, 1996).

Many studies have recently indicated that common heat treatments of tomato products do not result in a shift in the distribution of cis-lycopene isomers (Goula et al., 2006). Thus, the increase in lycopene content reported in this study from the microwave heat treatment may be due to a progressive conversion from the all-trans lycopene to a less strongly colored, less intensely absorbing cis form than an actual degradation of lycopene. The values of the lycopene content obtained after microwave-vacuum were relatively lower than the 82.90 mg/100 g reported by

Takeoka et al. (2001) for tomato paste and 65.28 mg/100 g dry matter reported by Abano et al. (2011) for hot air drying of tomato slices at 80°C. The lower values recorded in this study might be due to the electromagnetic waves in the microwave-vacuum, which might have negatively affected the lycopene in the tomatoes.

Modeling of the drying curves

The dimensionless moisture ratio against drying time for the experimental data of the 0.05 MPa vacuum pressures at various microwave powers was fitted to thirteen thin-layer drying models available in scientific literature. The results of such fitting obtained with SPSS 16.0 software are displayed in Table 5, which show the values of the estimated constants with their corresponding statistical R², χ^2 , and RMSE values characterizing each fitting. From the results obtained, it was evident that the experimental data fitted to the models used in this study. The correlation coefficients obtained are in the range of 0.9546 to 0.9992. This means that the thirteen models could satisfactorily describe the microwave-vacuum drying of tomato slices. The relatively high values of correlation coefficients, low reduced chi-square, and low root mean square errors indicate a good predicting capacity for the microwave-vacuum drying conditions tested over the entire duration of the drying process. Among the thirteen thin-layer drying models tested, Midilli et al. model obtained the highest R² values and the lowest χ^2 , and RMSE values in the microwave-vacuum drying conditions studied. Figure 10 displays the fitting of the experimental and simulated points to the Midilli et al. model. It can be seen from Figure 11 that the experimental data are closely bounded to the simulated data for Midilli et al. model around logarithmic curves. The consistency of the midilli model for the microwave vacuum drying of tomato slices is evident in Figure 12, showing the predicted and simulated data points. Figure

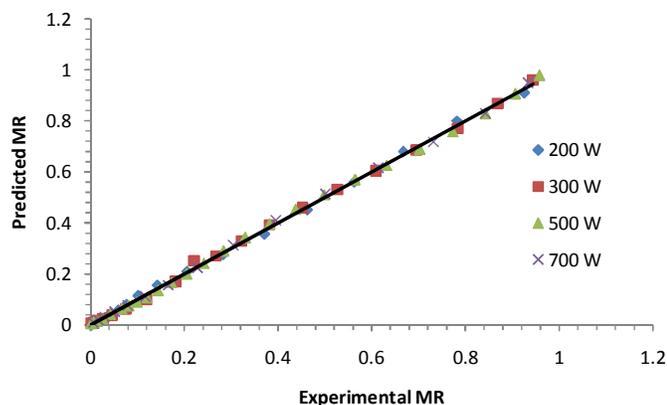


Figure 11. Predicted and experimental moisture ratio for 0.05 MPa vacuum pressures.

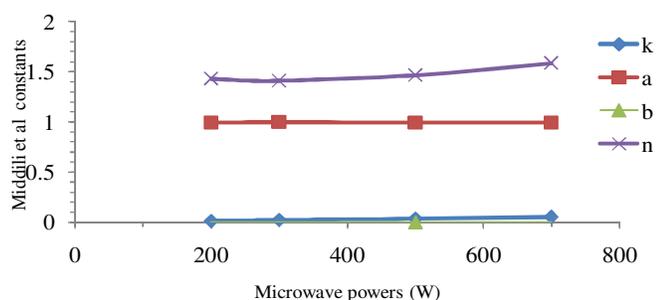


Figure 12. Variation of drying constants against microwave powers for the Midilli *et al.* model.

12 shows the variation of drying constants against microwave powers in the Midilli *et al.* model. It can be verified from Figure 12 that the drying rate constant k indicating drying behaviour for the models tested increased with increasing microwave power in the Midilli *et al.* model. The increase in drying rate constant with increasing microwave power indicates an enhancement of drying potential. Additionally, drying rate constant increased exponentially with increasing vacuum pressure. Multiple non-linear regression analysis for this exponential relationship between drying rate constant k , microwave power (P_0), and vacuum pressure (P_r), for the Midilli *et al.* model was:

$$k = 6.8 \times 10^{-3} \exp^{0.002P_0} [R^2=0.9724]$$

$$k = 2.3 \times 10^{-3} \exp^{31.43P_r} [R^2=0.9999]$$

Conclusion

The effect of four microwave powers and three vacuum pressures on drying time lycopene content and ascorbic acid content was studied. The drying time reduced from 84 to 14 min as the microwave power increased from 200

to 700 W. It was shown that increase in microwave power and vacuum pressure enhanced the drying rate and significantly reduced the drying time of tomato slices. The effect of microwave power on the drying time was however higher than vacuum pressure. It was observed that the lycopene levels of the tomatoes increased significantly after drying whereas the ascorbic acid content reduced. Among the thirteen thin-layers drying models that were fitted to the experimental data, the Midilli *et al.* model showed the best fit although all the models could satisfactorily describe the microwave-vacuum drying kinetics of tomato slices. The drying rate constant in the Midilli *et al.* model increased exponentially with microwave power and vacuum pressures.

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