

## Drying kinetics and colour change of lemon slices

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**Abstract.** The effect of microwave-convective heating on drying characteristics and colour change of lemon slices was investigated. The drying experiments were carried out at 180, 360, 540 and 720 W and at 22°C, with air velocity of 1 m s<sup>-1</sup>. The values of effective moisture diffusivity were found to be in the range between 1.87 10<sup>-8</sup> and 3.95 10<sup>-8</sup> m<sup>2</sup> s<sup>-1</sup>, and the activation energy was estimated to be 10.91 W g<sup>-1</sup>. The drying data were fitted with six mathematical models available in the literature. The model describing drying kinetics of lemon slices in the best way was found. The colour change of the dried lemon slices was analysed and considered as a quality index affecting the drying quality of the product. The values of lightness/darkness, yellowness/blueness and hue angle increased, while the value of redness/greenness decreased with increasing microwave power.

**Key words:** drying kinetics, mathematical modelling, colour, lemon slice

### INTRODUCTION

The fresh weight of lemon fruits contains a high percentage of water (about 87% w.b.). Accordingly, they exhibit relatively high metabolic activity compared with other plant-derived foods such as seeds. This metabolic activity continues after harvesting, thus making most fruits highly perishable commodities (Atungulu *et al.*, 2004; Pendre *et al.*, 2012).

Drying improves the product shelf life without addition of any chemical preservative and reduces both the size of package and the transport cost (Al-Harashsheh *et al.*, 2009; Figiel, 2010; Singh *et al.*, 2010). Drying also assists in reducing post harvest losses of fruits and vegetables especially, which can be as high as 70% (Tunde-Akintunde and Ogunlakin, 2013).

High temperatures or long drying times in conventional air drying may cause serious damage to product flavour, colour and nutrients, reducing bulk density and rehydration

capacity of the dried product (Contreras *et al.*, 2008). The desire to avoid these problems to some extent, to prevent significant quality loss, and to achieve fast and effective thermal processing has resulted in the increasing use of microwaves for food drying. However, microwave processing has the disadvantage of non-homogeneous distribution in the microwave cavity, creating problems of non-uniform heating. To overcome some of the limitations of single microwave or hot air driers, one strategy is to combine microwaves with hot air. In the microwave-convective drying method, forced air is supplied to carry away the water vapour driven from the interior of the food to its surface.

Colour has to be considered as a special parameter that seems to be one of the first attributes of quality that a consumer perceives, and that may influence the consumer judgment of other attributes such as flavour (Chen *et al.*, 2005).

Simulation models may be used to develop new drier systems that result in energy savings and optimum processing conditions (Arumuganathan *et al.*, 2009; Hassan-Beygi *et al.*, 2009). A knowledge of effective moisture diffusivity is necessary for designing and modeling mass-transfer process such as dehydration, adsorption and desorption of moisture during storage.

There are many literature studies on the kinetics of changes in fruits and fruit derivatives, but little work has been conducted on the processing of lemon, and no kinetic studies related with the colour change during microwave or microwave-convective drying of this fruit were found in the literature.

In this study, the single layer drying behaviour of lemon slices in a microwave-convective dryer was investigated, and mathematical modelling by using single layer drying models available in the literature was performed. Colour parameters of the dried lemon slices were also studied.

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## MATERIAL AND METHOD

The citrus lemon fruits (*Citrus limon* L.) were obtained from local market and washed thoroughly to remove dust and other foreign materials. Samples were stored in a refrigerator at  $4\pm 1^\circ\text{C}$  until the drying process for preventing moisture losses. Prior to the drying experiment, the lemon fruits were cut into  $5\pm 1$  mm slices. The initial moisture content of the samples was determined by drying in a convective oven at  $105\pm 1^\circ\text{C}$  until the weight did not change any more. The initial moisture content of the samples was about 86.8% (w.b.).

The microwave-convective dryer consists of a microwave oven (M945, Samsung Electronics Ins) with maximum output of 1000 W at 2450 MHz, a variable speed fan, and a digital balance (GF-600, A & D, Japan) with accuracy of  $\pm 0.01$  g. The microwave-convective dryer was operated by a control terminal which could control both microwave power level and emission time. Air velocity was kept at a constant value of  $1\text{ m s}^{-1}$ , controlled by means of analogue controller. A sample tray in the microwave oven chamber was suspended on the balance with a nylon wire through a ventilation hole in the centre of the chamber ceiling. The samples were dried in the microwave-convective dryer at the 4 output powers of 180, 360, 540, 720 W and at an inlet temperature of drying air of  $22^\circ\text{C}$ , with initial load of  $20\pm 1$  g. Moisture loss of the sample was recorded by means of a weighing system at 15 s intervals during drying. Each drying process was applied until the initial moisture ratio was reduced to about zero. All experiments were performed in triplicates.

In most studies carried out on drying, diffusion is generally accepted to be the main mechanism during the transport of moisture to the surface to be evaporated. The effective moisture diffusivity can be determined from the slope of the normalised plot of the unaccomplished moisture ratio,  $\ln(MR)$  vs. time, using the following equation:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t, \quad (1)$$

where:  $MR$  is the moisture ratio (%),  $t$  is the drying time (s),  $D_{eff}$  is the effective moisture diffusivity ( $\text{m}^2\text{ s}^{-1}$ ), and  $L$  is the half-thickness of thin layer sample (m).

For mathematical modelling, the thin layer drying equations in Table 1 were tested to select the best model for describing the drying curve of lemon slices. The coefficient of determination ( $R^2$ ), reduced chi-square ( $\chi^2$ ) and root mean square error (RMSE) were used to determine the quality of the fit. The higher the value of  $R^2$ , and the lower the values of  $\chi^2$  and RMSE, the better goodness of fit is observed.

A HunterLab Colorflex (CFLX 45-2 Model Colorimeter, HunterLab, Reston, VA) was used to measure Hunter  $L^*$  (lightness/darkness),  $a^*$  (redness/greenness) and  $b^*$  (yellowness/blueness) values of dried samples. Hue angle ( $h^*$ ) was also calculated.

## RESULTS AND DISCUSSION

The moisture ratio versus drying time for the fresh lemon slices at the selected microwave powers is shown in Fig. 1. As indicated by the curve in this figure, with increasing drying power the amount of moisture removed from lemon slices increased, and the time to achieve zero of moisture ratio in finished products was reduced. The time required for the lowering of moisture content of lemon slices to zero level from 86.8% wet basis varied between 3.25 and 5.5 min, depending on the microwave power level. The

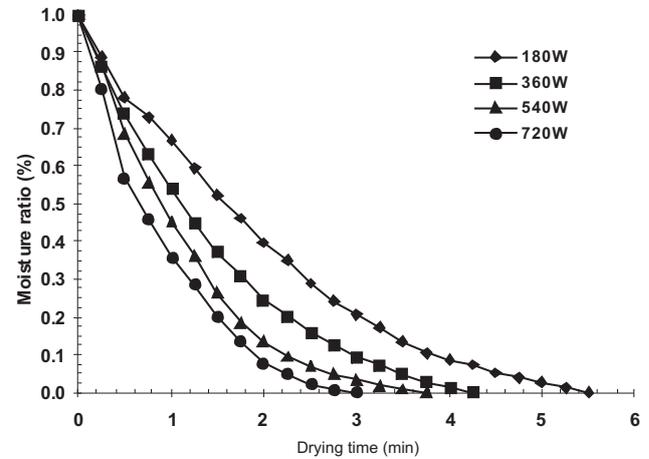


Fig. 1. Variation of  $MR$  with time for citrus lemon slices under different microwave powers.

Table 1. Mathematical models applied to the drying curves

No.	Model name	Model	References
1	Newton	$MR = \exp(-kt)$	Lee and Kim (2009)
2	Page	$MR = \exp(-kt^n)$	Arumuganathan <i>et al.</i> (2009)
3	Henderson and Pabis	$MR = a \exp(-kt)$	Aghbashlo <i>et al.</i> (2009)
4	Midilli <i>et al.</i>	$MR = a \exp(-kt^n) + bt$	Midilli <i>et al.</i> (2002)
5	Wang and Singh	$MR = 1 + bt + at^2$	Hassan-Beygi <i>et al.</i> (2009)
6	Logarithmic	$MR = a \exp(-kt) + b$	Doymaz (2011)

results indicate that mass transfer within the sample was more rapid during higher microwave power heating because more heat was generated within the sample, creating a large vapour pressure difference between the centre and the surface of the product due to characteristic microwave volumetric heating.

The drying rates were determined from the amount of water removed per unit time and per unit dry base. The drying rate curves for lemon slices dried at different microwave output powers are given in Fig. 2. As can be observed, the moisture content of the lemon slices was very high during the initial phase of the drying, which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the lemon slices caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. The drying rates increased with the increasing microwave power levels. Therefore, microwave power level has an important effect on the drying rates. Depending on the drying conditions, average drying rates of lemon slices

ranged from 1.209 to 1.869 kg (H<sub>2</sub>O) kg<sup>-1</sup> d.b. min<sup>-1</sup> for output power between 180 and 720 W, respectively. A constant rate period was not observed in drying of lemon slice samples. The entire drying process for the samples occurred in the range of falling rate period in this study. This shows that diffusion is the dominant physical mechanism governing moisture movement in the samples. Similar results have been observed in the drying of different fruits and vegetables: kiwifruit (Femenia *et al.*, 2009), hazelnut (Uysal *et al.*, 2009), carrot pomace (Kumar *et al.*, 2011), amelia mango (Dissa *et al.*, 2009), pineapple, mango, guava and papaya (Marques *et al.*, 2009) and apple (Wang *et al.*, 2007).

The moisture contents of lemon slices at different microwave powers were converted to the moisture ratio (MR) and fitted to the 6 selected thin-layer drying models listed in Table 1. Table 2 shows the results of statistical tests (R<sup>2</sup>, RMSE, and  $\chi^2$ ) performed in the proposed models. The values of mentioned tests were in the range of 0.981-0.999 for R<sup>2</sup>, 0.0118-0.00002 for  $\chi^2$ , 0.0419-0.0035 for RMSE. Based on the criteria of the highest R<sup>2</sup> and the lowest RMSE and  $\chi^2$ , the model of Midilli *et al.* (2002) was selected as the most suitable model to represent the thin-layer drying behaviour of lemon slices. Figure 3 compares the experimental data with those predicted with the logarithmic model for lemon slices at 180, 360, 540 and 720 W. The prediction using the model showed MR values banded along the straight line, which showed the suitability of these models in describing drying characteristics of lemon slices.

Values of effective diffusivity ( $D_{eff}$ ) for different microwave powers are presented in Table 3. It can be seen that  $D_{eff}$  values increased greatly with increasing microwave power level. The higher power level caused an increase of effective moisture diffusivity because of higher mass transfer. These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of 10<sup>-11</sup> to 10<sup>-9</sup> m<sup>2</sup>s<sup>-1</sup> for food materials (Arslan and Ozcan, 2010; Kumar *et al.*, 2011; Wang *et al.*, 2007). The values of  $D_{eff}$  are comparable with the reported values of 1.046×10<sup>-8</sup> to 9.153×10<sup>-8</sup> m<sup>2</sup> s<sup>-1</sup> mentioned for apple pomace microwave drying (Wang *et al.*, 2007), 1.14×10<sup>-9</sup> to 6.09×10<sup>-9</sup> m<sup>2</sup> s<sup>-1</sup> for tomato pomace microwave drying at 160-800W (Al-Harahsheh *et al.*, 2009), and 5.5×10<sup>-8</sup> to 3.5×10<sup>-7</sup> m<sup>2</sup> s<sup>-1</sup> for Gundelia tournefortii microwave drying at 90-800W (Evin, 2011). The relationship between effective moisture diffusivity and microwave power can be represented as:

$$D_{eff} = 1.482 \cdot 10^{-8} \exp(0.0014P) \quad R^2=0.992. \quad (2)$$

In this study, as the temperature is not a measurable variable in the standard microwave oven used for the drying process, the Arrhenius equation was used, in a modified form, to illustrate the relationship between the kinetic rate constant and the ratio of the microwave output power to sample amount instead of temperature for the calculation of

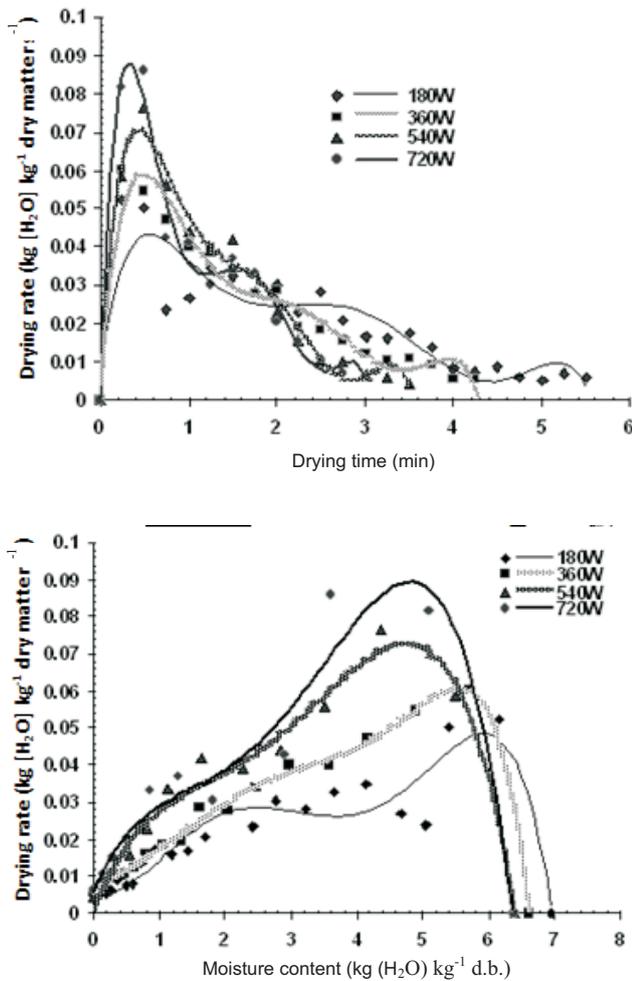


Fig. 2. Variation in the drying rate in relation to the: a – drying time, b – moisture content of lemon slices.

**Table 2.** Thin layer drying model constants and statistical parameters of sliced lemon

Model name	P(W)	Model parameter	R <sup>2</sup>	χ <sup>2</sup>	RMSE
Newton	180	k = 0.506	0.981	0.0018	0.0419
	360	k=0.699	0.989	0.0010	0.0315
	540	k = 0.891	0.986	0.0002	0.0378
	720	k = 1.101	0.991	0.0009	0.0287
Henderson and Pabis	180	a = 1.048; k= 0.529	0.983	0.0016	0.0388
	360	a = 1.041; k = 0.727	0.991	0.0009	0.0282
	540	a = 1.059, k = 0.939	0.989	0.0012	0.0325
	720	a = 1.025; k = 1.127	0.992	0.0009	0.0274
Wang and Sing	180	a =0.0348; b = -0.3694	0.998	0.0002	0.0128
	360	a = 0.0658; b =-0.5070	0.996	0.0004	0.0183
	540	a = 0.1001; b = -0.6316	0.996	0.0004	0.0196
	720	a =0.1510; b = -0.7735	0.989	0.0013	0.0328
Logarithmic	180	a = 1.17; k = 0.365; b = -0.174	0.998	0.0002	0.0147
	360	a = 1.119; k = 0.561; b = -0.111	0.999	0.00004	0.0055
	540	a = 1.115; k = 0.765; b = -0.083	0.997	0.0004	0.0180
	720	a = 1.078; k = 0.927; b = -0.076	0.998	0.0003	0.0145
Page	180	k = 0.410; n = 1.244	0.994	0.0006	0.0226
	360	k = 0.631; n = 1.187	0.998	0.0002	0.0146
	540	k = 0.821; n = 1.261	0.999	0.0001	0.0111
	720	k = 1.084; n = 1.126	0.995	0.0006	0.0218
Midilli <i>et al.</i> (2002)	180	a = 0.976; k = 0.381; n = 1.160; b = -0.013	0.998	0.0002	0.0128
	360	a = 0.996; k = 0.603; n = 1.085; b = -0.014	0.999	0.000002	0.0035
	540	a = 0.998; k = 0.803; n = 1.219; b = -0.005	0.999	0.0001	0.0089
	720	a = 1.003; k = 0.999; n = 1.009; b = -0.020	0.998	0.0003	0.0147

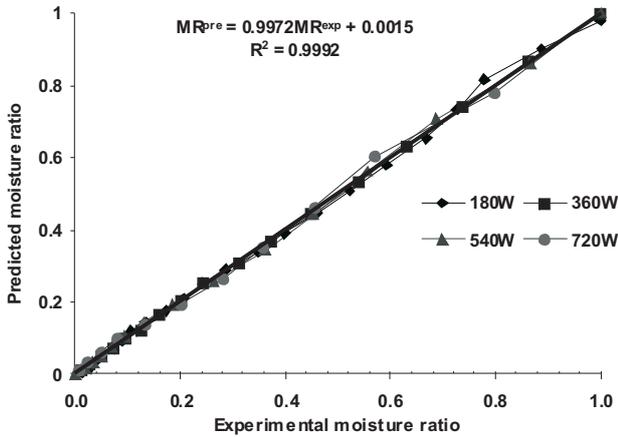
the activation energy. After evaluation of the data, the dependence of the kinetic rate constant on the ratio of microwave output power to sample amount was represented with an exponential Eq. (3) derived by Dadali *et al.* (2007):

$$k = k_0 \exp\left(\frac{-E_a m}{P}\right), \quad (3)$$

where: k is the drying rate constant obtained by using model of Midilli *et al.* (2002) ( $\text{min}^{-1}$ ),  $k_0$  is the pre-exponential constant ( $\text{min}^{-1}$ ),  $E_a$  is the activation energy ( $\text{Wg}^{-1}$ ),  $P$  is the microwave output power (W) and  $m$  is the mass of raw sample (g). The values of k versus  $m/P$  shown in Fig. 4

accurately fit to Eq. (3) with coefficient of determination ( $R^2$ ) of 0.957. Then,  $k_0$  and  $E_a$  values were estimated at  $1.232 (\text{min}^{-1})$  and  $10.911 \text{Wg}^{-1}$ .

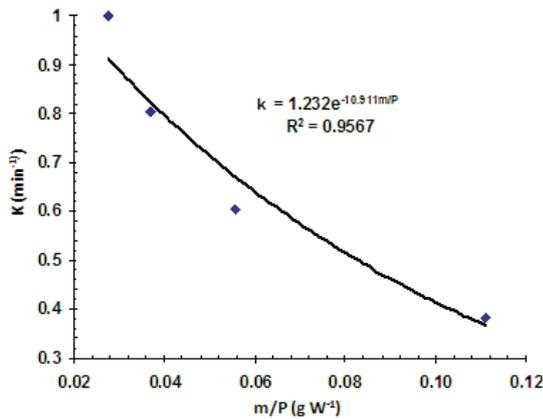
Table 4 shows the colour parameters  $L^*$ ,  $a^*$ ,  $b^*$  and  $h^*$  values for dried lemon slice samples as a function of drying microwave power. The ranges of values recorded were 39.92-43.39, 4.68-5.96, 12.58-16.12 and 64.63-72.99 for the  $L^*$ ,  $a^*$ ,  $b^*$  and  $h^*$ , respectively. It can be seen from Table 4 that the values of  $L^*$  parameter for dried lemon slices increase with microwave power, thus the luminance of the lemon slices is improved by microwave-convective drying. Also the values of  $a^*$  parameter decreased slightly with drying microwave power, which means that drying process



**Fig. 3.** Comparison of experimental moisture ratio ( $MR_{exp}$ ) with predicted moisture ratio ( $MR_{pre}$ ) from the Midilli *et al.* (2002) model for lemon slices.

**Table 3.** Values of effective diffusivities obtained for lemon slices at different microwave powers

$P(W)$	$D_{eff} 10^{-8} (m^2 s^{-1})$
180	1.87
360	2.48
540	3.29
720	3.95



**Fig. 4.** Relationship between the values of drying rate constant versus sample amount/power.

preserves or enhances slightly the green colour of the lemon slices. As with the case of lightness parameter,  $b^*$  is also affected by drying microwave power. The  $b^*$  values merely showed that all the dried samples were more yellow in colour, thus less browning. This is clearly indicated by the values of hue angles ( $h^*$ ). Microwave drying pushes liquid onto the surface and the liquid is usually converted into vapour. This process results in drying without causing surface overheating phenomena. Therefore, in terms of surface

**Table 4.** Colour parameters for lemon slices at different drying microwave powers

Drying power	$L^*$	$a^*$	$b^*$	$h^*$
180	39.92	5.96	12.58	64.63
360	41.85	5.31	14.95	70.44
540	40.20	4.93	16.12	72.99
720	43.39	4.68	14.26	71.82

colour degradation, preservation of the product colour was good. A larger value of hue angle indicates greater shift from red to yellow. Hawlader *et al.* (2006) stated that a decrease in hue angles values is an indication of more browning colour and shifting away from yellowness, which is not the case in this study, where the values of hue angles increased with drying microwave powers, shifting towards yellow and red. Microwave drying causes a smaller increment of redness  $a$ , which means the final products are less brown than conventional air-dried ones (Vadivambal and Jaya, 2007).

CONCLUSIONS

1. Drying time of the samples was significantly reduced from 5.5 and 3.25 min as the power input increased from 180 to 720 W.
2. The entire drying process occurred in the falling rate period and constant rate period was not observed.
3. Average drying rates of lemon slices ranged from 1.209 to 1.869  $kg [H_2O] kg^{-1} dry matter min^{-1}$  for the output power between 180 and 720 W, respectively.
4. The model of Midilli *et al.* was the best mathematical model for describing drying kinetics of lemon slices.
5. The effective moisture diffusivity ranged from  $1.87 \cdot 10^{-8}$  to  $3.95 \cdot 10^{-8} m^2 s^{-1}$  and the activation energy was found to be  $10.911 W g^{-1}$ .
6. The values of colour parameters, lightness/darkness, yellowness/blueness and hue angle increased and redness/greenness decreased with increasing drying microwave power.

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