DRYING OF LIME SLICES BY MICROWAVE AND COMBINED MICROWAVE-CONVECTIVE METHODS

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ABSTRACT

This research deals with lime samples and aims to investigate the impacts of microwave and combined microwave-convective drying applications. According to the statistical outcomes, models of Midilli *et al*. and Page were discovered to give more suitable predictions than the other models. Increasing level of both temperature and microwave power, induced a significant reduction in the drying interval while increasing D_{eff} values. Drying experiment at power 90 W and temperature 55°C ensured the best values in color parameter of a* (greenness) and energy consumption. Experiments made with using different techniques will help to select the appropriate drying technique for the relevant sectors.

Keywords: activation energy, color, drying kinetics, effective moisture diffusivity, specific energy consumption

1. INTRODUCTION

The Persian lime (*Citrus latifolia* tanaka) belongs to the family of Rutaceae (citrus family) and also named as 'Shiraz Limoo', 'Bearss lime', and 'Tahiti lime', which is mainly grown in the Gulf Coast of Mexico (LAMBERT *et al*., 2015; SALIH, 2015; ARREDONDO *et al*., 2015). It is an economically significant horticultural crop (KAEWSUKSAENG *et al*., 2015). The major flavor components are neural, citral, geranial, α-terpineol, β-bisabolene, β-pinene, p-cymene, 1,4-cineole, 1,8-cineole, and 4-terpineol (YADAV *et al*., 2004). It had been used traditionally to treat sinusitis (SALIH, 2015) and stomachache. Also, the cleansing action of mesocarp usage as facial scrub helps in prevention of pimples. Besides, the rind is burnt against mosquitoes in some homes (AIBINU *et al*., 2007). Human benefit from lime to extract its juice, to prepare beverages, concentrates, squashes and other derivative products such as pectin and citric acid etc. (YADAV, 2004).

To preserve food, drying is an ancient and prevalent technique. In the food industry, the primary reason to dry food is to reduce packaging, storage, and transportation costs by downsizing end products in terms of both volume and weight. Hence, in the food industry, developing economical drying techniques have become a prominent research topic (PHOUNGCHANDANG *et al*., 2008; TASIRIN *et al*., 2014).

Long drying intervals or high temperatures in conventional air drying may distort the dried product (DIAZ *et al*., 2003). Many studies have shown that drying with microwave energy usage has many conveniences like shorter drying interval, higher energy efficiency, less space, and faster start-up and shut-down periods (GUO and ZHU, 2014). However, inhomogeneous distribution in the microwave cavity creates an uneven heating problem. To circumvent a number of the disadvantages of single microwave or hot-air dryers, combine microwaves with hot air one is another methodology (DARVISHI *et al*., 2014).

Microwave and/or microwave–air combined driers were carried out by several researchers to illustrate drying attributes of many agricultural products, for example, parsley (SOYSAL, 2004), peach (WANG and SHENG, 2006), mint leaves (ÖZBEK and DADALI, 2007), spinach (KARAASLAN and TUÇER, 2008), tomato pomace (AL-HARAHSHEH *et al*., 2009), onion slices (ARSLAN and ÖZCAN, 2010), seedless grapes (KASSEM *et al*., 2011), sage leaves (ESTURK, 2012), chili flesh (ZHAO *et al*., 2013), okra (KUMAR *et al*., 2014) and apple slices (ZAREIN *et al*., 2015). The aim of conducted research to scrutinize the thin-layer drying behavior of lime slices in both microwave and microwave-convective drying with existing thin-layer drying models. Also, effective moisture diffusivity, activation energy, color, energy consumption and specific energy consumption of the lime slices were studied.

2. MATERIAL AND METHODS

2.1. Drying equipment and drying procedure

Fresh lime samples were obtained from a local grocery one day before the experiments begin and kept at 4±0.5°C temperature. Samples had an average diameter of 40±0.08 mm and were sliced to 5±0.03 mm thickness by using a food slicer (Nicer Dicer, China). In the beginning, the moisture content of the fresh lime samples was identified to be 5.13 (g $H_2O \cdot$ g d.m.$^{-1}$) on a dry basis (d.b.) by using an oven drying at 105°C for 24 hours (ED115 Binder, Tuttlingen, Germany).

The drying experiments were conducted at room temperature. A microwave-convective oven (Whirlpool AMW 545, Italy) that works at ~230 V, 50 Hz with 2450 MHz frequency.

The system worked in microwave mode at 90 W and 160 W microwave output power levels and in combined microwave-convective mode at 90 W – 55 °C, 90 W – 65 °C, 90 W – 75 °C, 160 W – 55 °C, 160 W – 65 °C, and 160 W – 75 °C microwave output power and temperature combinations with 1 m s^{-1} air flow. All drying experiments were performed on a 400 mm diameter and 210 x 450 x 420 mm sized glass plate that rotates at the base of the oven. In order to figure out mass, a digital balance (Baster, Istanbul, Turkey) having ±0.01 g accuracy was positioned below the microwave oven device (Fig. 1). The loss of the moisture of the lime samples was noted down during drying interval in every 5 minutes. For each lime sample (100 g), these were applied three times and their mean was figured out.

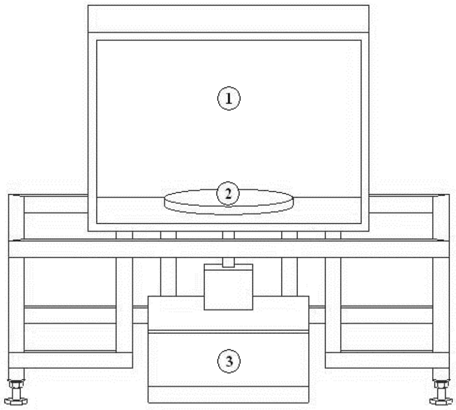

Figure 1. Schematic diagram of experimental microwave-convective drying system (microwave-convective drying chamber (1), rotating glass tray (2) and balance (3)).

2.2. Mathematical modelling of drying data

The data on moisture content were transformed into the moisture ratio (MR) and adapted by the aid of ten thin-layer drying models (Table 1).

Table 1. Selected thin layer drying models used to mathematically model the lime drying kinetics.

No	Model name	Model	References
1	Henderson and Pabis	$MR = a\exp(-kt)$	BHATTACHARYA *et al.* (2015).
2	Newton	$MR = \exp(-kt)$	SHARMA *et al.* (2005)
3	Page	$MR = \exp(-kt^n)$	BHATTACHARYA *et al.* (2015).
4	Logarithmic	$MR = a\exp(-kt) + c$	UNAL and SACILIK (2011)
5	Two Term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	SU *et al.* (2015)
6	Two Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	SHARMA *et al.* (2005)
7	Wang and Singh	$MR = 1 + at + bt^2$	SU *et al.* (2015)
8	Diffusion Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	UNAL and SACILIK (2011)
9	Verma *et al.*	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	OMOLOLA *et al.* (2014)
10	Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	UNAL and SACILIK (2011)

The moisture ratio was calculated with the equation presented below:

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

Above, M_t represents the moisture content (g water g dry matter^{-1}) at a particular time, M_0 represents the initial moisture content (g water g dry matter^{-1}), represents the equilibrium moisture content (g H_2O · g d. m.$^{-1}$). M_e values are proportionately less than M_t or M_0 values. In consequence, the moisture ratio was made simpler as presented below (ARUMUGANATHAN *et al.*, 2009):

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

2.3. Determination of effective moisture diffusivity

Drying of agricultural products in a falling rate period is embedded into a mass-diffusion equation in accordance with the second law of Fick on diffusion is presented in Eq. (3) below:

$$\frac{\partial M}{\partial t} = \nabla[D_{eff}(\nabla M)] \tag{3}$$

So as to ascertain the moisture ratio in Eq. (4), benefiting from the second law of Fick on unsteady state diffusion provided in Eq. (3) is possible. Crank (1975) put forward the clarification of the diffusion equation for an infinite slab and so uniform moisture distribution at the beginning, negligible shrinkage and external resistance, and constant diffusivity was assumed to be as follows:

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

Where: D_{eff} symbolizes effective moisture diffusivity in terms of ($m^2 \cdot s^{-1}$); t symbolizes an interval in terms of (s); L symbolizes half-thickness of samples in terms of (m), and n symbolizes a positive integer.

For long drying intervals, only the first term in Eq. (4) is significant and the equation is simplified to the one stated below:

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

Equation (5) can be articulated in a logarithmic format as can be seen below:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{5}$$

In Eq. (6), effective moisture diffusivity values were identified by plotting experimental drying data in ln (MR) versus drying interval. This plot generates a direct line with a slope calculated below (DOYMAZ *et al*., 2015):

$$Slope = \left(\frac{\pi^2 D_{eff}}{4L^2}\right) \tag{6}$$

2.4. Computation of activation energy

On the grounds that temperature inside the microwave dryer cannot be gauged precisely, modification of the revised Arrhenius equation is used to find the activation energy. In this technique, it is deemed that the effective moisture diffusion and the microwave output power ratio are associated with the sample weight (m p^{-1}) rather than air temperature. In this direction, Eq. (7) can be utilized in an efficient way, as noted below (ÖZBEK and DADALI, 2007):

$$D_{eff} \ = \ D_0\left(-\ \frac{E_a \mathrm{m}}{P}\right) \tag{7}$$

above E_a symbolizes the activation energy in terms of (W g^{-1}), m symbolizes the mass of raw sample in terms of (g), P symbolizes the microwave power in terms of (W), and lastly, D_0 symbolizes the pre-exponential factor in terms of (m^2 s^{-1}).

2.5. Energy and specific energy consumption

The experimental apparatus was plugged into the electricity via a digital electric counter (Kaan, Type 101, Turkey) that has a precision of 0.01 kWh. With the use of the counter, the total energy consumption (E_t) was measured for whole drying process (KOWALSKI and PAWŁOWSKI, 2011). Energy consumption to dry 100 g fresh lime sample was obtained by applying Equation 8. The E_{kg} and W_0 symbolize the specific energy needed and the primary mass of the sample, respectively (MOTEVALI *et al*., 2012).

$$E_{kg} = \frac{E_t}{w_0} \tag{8}$$

2.6. Colour measurement

The flesh color of fresh and dried lime samples was determined with Hunterlab Color Analyzer (MSEZ-4500L, Reston, Virginia, USA) in the *L*, *a*, *b* color scale. Color measurements were conveyed in a three-dimensional color space namely L^*, a^*, and b^*, where L^* indicates darkness/lightness value, a^* indicates redness value (if positive) and greenness value (if negative), and b^* indicates the yellowness value (if positive) and blueness value (if negative). On the other side L_0^*, a_0^* and b_0^* are color parameters for fresh lime samples. After the calibration of colorimeter against a standard white surface and black one, six replicate measurements were performed for each sample and L^*, a^*, b^*, L_0^*, a_0^* and b_0^* color values were recorded. To illustrate the color changes, Chroma (*C*), Hue angle (*α*), and total color variance (*ΔE*) values were defined by the following equations (ARGYROPOULOS *et al*., 2011):

$$C = \sqrt{(a^2 + b^2)} \tag{9}$$

$$\alpha = \tan^{-1}(\frac{b}{a}) \quad (10)$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (11)$$

2.7. Statistical analysis

This research was realized by the aid of randomized plots factorial design of experimental type. In the course of calculation of the inspected items, three replicates were utilized. While interpreting the outcomes, MATLAB (MathWorks Inc., Natick, MA) and JMP (Version 7.0, SAS Institute Inc., Cary, NC, USA) software technologies were employed. Significance levels of mean differences were tested and the least significant difference (LSD) test resulted in a 5% significance level. It has been determined that the most convenient model that expresses the drying attributes of lime samples in a thin layer is the one that has lowest reduced chi-squared (χ^2) value, lowest root mean square error (RMSE) value and the highest coefficient of determination (R^2) (ARUMUGANATHAN *et al.*, 2009). The statistical figures mentioned above are formulated below:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{N - n} \quad (12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (MR_{pre,i} - MR_{\exp,i})}{N}} \quad (13)$$

where:

$MR_{exp,i}$, symbolizes the experimental moisture ratio for test number i,

$MR_{pre,i}$, symbolizes the estimated moisture ratio for test number i,

N symbolizes the observation number,

n symbolizes the number of constants in the drying model (DOYMAZ and ISMAIL, 2011).

3. RESULTS AND DISCUSSION

3.1. Drying kinetics of dried lime

Fig. 2 illustrates the drying curves of the lime samples that are dried under distinct microwave and microwave-convective drying settings. Drying phase of lime samples took 225, 120, 130, 115, 100, 105, 85 and 75 minutes at 90W, 160W, 90 W – 55°C, 90 W – 65°C, 90 W – 75°C, 160 W – 55°C, 160 W – 65°C, and 160 W – 75°C, respectively. Outcomes of the experiments implied that drying intervals of lime samples dried by microwave-convective technique at 90 W – 75°C and 160 W – 75°C reduced 55.6% and 41.7% in comparison to only 90 W and 160 W microwave powers, respectively. The outcomes stated above are in good harmony with former researches. GOWEN *et al*. (2008), MOHANTA *et al*. (2014), CHAYJAN *et al*. (2015) found that the use of combined microwave convective technique ensured considerable time savings in drying interval for soybean, ginger and hawthorn samples, respectively. In addition, the average total drying interval at 160 W – 75°C become shorter by 46.2% as against the drying interval at 90 W – 55°C. It can be said that increasing the microwave power level and temperature level ended in a significant reduction in the drying interval of lime samples in combined microwave-convective drying technique. In agreement to our study, KARAASLAN and TUNCER (2010) combined fan-assisted convection (100, 180 and 250°C) and microwave (180 and 540 W) drying and the time to reduce the moisture content of banana slices from the initial 80 % (w.b.) to the final 15 % (w.b.) was highest at 180 W – 100°C and lowest at 540 W – 250°C, respectively. Similarly, SADEGHI *et al*. (2013) were measured drying time of lemon slices about 80, 78 and 73 minutes, respectively, when applying 0.97 W g^{-1} microwave power at 50, 55 and 60°C convective drying.

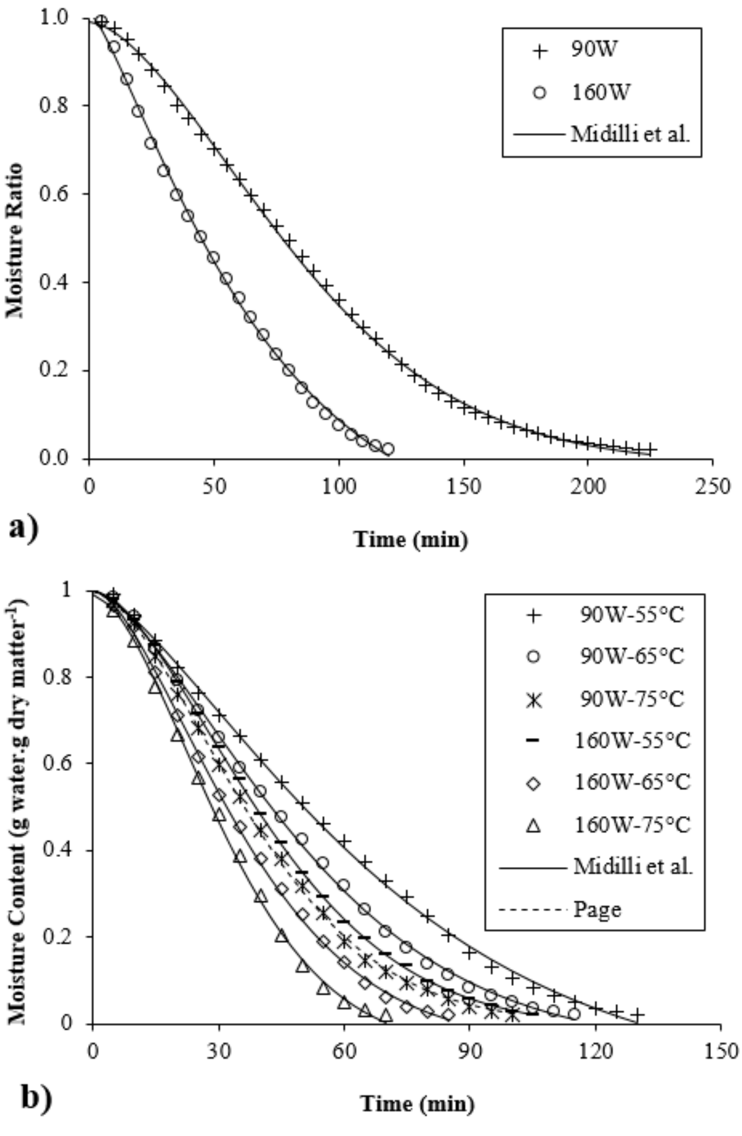

Figure 2. A comparison of the experimental and theoretical moisture ratios predicted by the Midilli *et al*. and Page models at specific drying times under selected drying conditions (microwave (a) and microwave-convective (b)).

3.2. Fitting of drying curves lime

Table 2 reveals the statistical analysis values obtained from the 10 distinct thin layer drying models, covering the drying model coefficients and the comparison criteria that are benefited from to evaluate the congruous quality, R^2, *RMSE,* and χ^2. For the statistical parameters, the values varied between 0.9143 and 0.9998 for R^2, between 0.0042 and 0.1037, 0.1659 x 10^{-4} and 106.3810 x 10^{-4} for *RMSE* and χ^2, respectively. In Table 3, the Page *et al.* model presented greater R^2 and smaller *RMSE* and χ^2 values in comparison to other thin-layer drying models for microwave-convective combinations of 90W – 75°C, while the Midilli *et al*. model displayed more suitable statistical values for all other drying settings. In all cases, values of R^2, *RMSE* and χ^2 in the Midilli *et al*. and Page models were ranged from 0.9984 to 0.9998, 0.0042 to 0.0143 and 0.1659 x 10^{-4} to 1.8507 x 10^{-4}; and 0.9958 to 0.9997, 0.0046 to 0.0211 and 0.1956 x 10^{-4} to 4.3222 x 10^{-4}, in return. Based on the statistical values, the Midilli *et al*. model was the most convenient one for all drying conditions tested, except for drying with the microwave-convective combinations of 90 W – 75°C where the Page model is the best one. Fig. 2 presents the comparison between the predicted values and experimental ones using the most convenient models with drying interval at chosen drying conditions of lime. As can be seen from these figures, the Midilli *et al*. and Page models slightly over-predicted or under-predicted the experimental values, but they are quite close to the experimental results. Accordingly, it could be deduced that models of Midilli *et al*. and Page sufficiently explained the thin layer drying attributes of lime under the experimental conditions. Similar outcomes have been stated by UNAL *et al*. (2011), BHATTACHARYA *et al*. (2015) and SU *et al*. (2015) for Midilli *et al*. and SHARMA *et al*. (2005), DOYMAZ and İSMAIL (2011), THERDTHAI *et al*. (2011) for Page model.

Table 2. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of lime using microwave (90 and 160 W) method.

No	90 W				160 W			
	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$
1	a=1.164; k=0.01247	0.9632	0.0641	40.4278	a=1.123; k=0.02029	0.9695	0.0566	32.0739
2	k=0.01078	0.9374	0.0836	69.1906	k=0.01803	0.9522	0.0709	50.5494
3	k=0.000555; n=1.641	0.9990	0.0104	1.0139	k=0.002511; n=1.483	0.9958	0.0211	4.3222
4	a=1.403; k=0.00734 c=-0.3089	0.9888	0.0354	12.2592	a=1.505; k=0.01025 c=-0.4523	0.9969	0.0181	3.1788
5	a=-23.08; k_0=0.02414 b=24.08; k_1=0.02306	0.9955	0.0224	4.8956	a=-14.31; k_0=0.03806 b=15.32; k_1=0.03578	0.9929	0.0274	7.3938
6	a=0.0000627; k=171.7	0.9360	0.0845	70.7869	a=0.0000608; k=296.6	0.9501	0.0725	52.7683
7	a=-0.00774; b=0.0000141	0.9861	0.0394	15.2627	a=-0.01276; b=0.0000362	0.9954	0.0221	4.8176
8	a=-21.79; k=0.02327 b=0.9567	0.9943	0.0252	6.0009	a=-30.8; k=0.03781 b=0.9704	0.9934	0.0264	6.5723
9	a=-33.45; k=0.02396 g=0.02321	0.9956	0.0221	4.7390	a=-13.74; k=0.03845 g=0.036	0.9934	0.0265	6.8890
10	a=0.9905; k=0.0005298 n=1.645; b=-0.0000446	0.9992	0.00946	0.8400	a=1.016; k=0.005021 n=1.272; b=-0.000886	0.9987	0.0119	1.2692

Table 3. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of lime using combined microwave-convective method.

No	90 W – 55°C				90 W – 65°C				90 W – 75°C			
	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$
1	a=1.135; k=0.01856	0.9609	0.0651	43.1892	a=1.142; k=0.02208	0.9617	0.0659	42.9539	a=1.149; k=0.02614	0.9592	0.0696	49.2828
2	k=0.01632	0.9404	0.0804	66.3224	k=0.01936	0.9402	0.0824	67.7189	k=0.02285	0.9367	0.0867	76.2392
3	k=0.001448; n=1.58	0.9962	0.0202	3.9792	k=0.001695; n=1.606	0.9981	0.0145	1.8601	k=0.001792; n=1.66	0.9996	0.0073	0.6060
4	a=1.637; k=0.008336 c=-0.5794	0.9951	0.0231	5.2789	a=1.511; k=0.01135 c=-0.4383	0.9919	0.0302	8.4956	a=1.461; k=0.01441 c=-0.3763	0.9873	0.0388	15.2013
5	a=-46.82; k_o=0.0353 b=47.82; k_1=0.03455	0.9919	0.0297	8.8554	a=-32.98; k_o=0.04255 b=34; k_1=0.04126	0.9943	0.0255	6.1631	a=-35.94; k_o=0.05143 b=36.95; k_1=0.04992	0.9965	0.0203	4.4728
6	a=0.0000609; k=267.5	0.9379	0.0819	68.9980	a=0.0000627; k=308.7	0.9374	0.0842	70.8216	a=0.0000636; k=359.3	0.9333	0.0889	80.2788
7	a=-0.01129; b=0.0000262	0.9931	0.0274	7.7391	a=-0.01364; b=0.0000412	0.9894	0.0347	11.6260	a=-0.01629; b=0.000061	0.9842	0.0432	18.9157
8	a=-24.67; k=0.03574 b=0.9605	0.9921	0.0293	8.2467	a=-20.28; k=0.0433 b=0.9505	0.9949	0.0241	5.2427	a=-40.28; k=0.05181 b=0.9731	0.9970	0.0189	3.7127
9	a=-43.46; k=0.03522 g=0.03443	0.9921	0.0293	8.6181	a=-42.65; k=0.04245 g=0.04144	0.9949	0.0240	5.5011	a=-15.08; k=0.053 g=0.04934	0.9970	0.0190	3.9366
10	a=1.002; k=0.002416 n=1.42; b=-0.0006716	0.9986	0.0121	1.3012	a=1.003; k=0.002283 n=1.514; b=-0.0003645	0.9989	0.0114	0.9357	a=1.001; k=0.001906 n=1.641; b=-0.0000735	0.9995	0.0074	0.6163
No	160 W – 55°C				160 W – 65°C				160 W – 75°C			
	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$	Model coefficients	R^2	RMSE	$\chi^2(10^{-4})$
1	a=1.151; k=0.02433	0.9590	0.0694	49.2496	a=1.143; k=0.0294	0.9560	0.0728	51.7650	a=1.137; k=0.03362	0.9393	0.0872	74.3240
2	k=0.02119	0.9352	0.0873	78.1182	k=0.02579	0.9346	0.0888	76.5298	k=0.02962	0.9204	0.0999	98.7500
3	k=0.001568; n=1.665	0.9997	0.0046	0.1956	k=0.002196; n=1.661	0.9986	0.0131	1.7386	k=0.001827; n=1.779	0.9972	0.0188	3.1235
4	a=1.498; k=0.01294 c=-0.4127	0.9882	0.0373	14.2787	a=1.568; k=0.01441 c=-0.4931	0.9897	0.0352	11.5807	a=1.89; k=0.01257 c=-0.8272	0.9869	0.0405	16.0290
5	a=-29.68; k_o=0.04847 b=30.69; k_1=0.04673	0.9971	0.0183	3.4801	a=-18.37; k_o=0.05935 b=19.38; k_1=0.05599	0.9950	0.0246	5.3362	a=-22.73; k_o=0.06944 b=23.74; k_1=0.06613	0.9872	0.0400	14.7394
6	a=0.0000597; k=354.9	0.9319	0.0894	82.0501	a=0.0000647; k=398.8	0.9305	0.0915	81.3402	a=0.0000758; k=390.9	0.9143	0.1037	106.3810
7	a=-0.015; b=0.0000502	0.9842	0.0431	19.3033	a=-0.01796; b=0.0000689	0.9864	0.0405	15.1585	a=-0.01974; b=0.000069	0.9844	0.0443	19.6322
8	a=-14.75; k=0.04954 b=0.9292	0.9975	0.0171	2.8964	a=-21.74; k=0.05933 b=0.9512	0.9955	0.0233	5.1105	a=-24.99; k=0.06934 b=0.9558	0.9890	0.0372	11.7403
9	a=-15.14; k=0.04946 g=0.04604	0.9975	0.0171	3.0502	a=-14.52; k=0.06004 g=0.05575	0.9955	0.0233	5.4618	a=-20.43; k=0.0702 g=0.06641	0.9890	0.0372	12.7526
10	a=1.002; k=0.001717 n=1.638; b=-0.0000823	0.9998	0.0042	0.1659	a=1.007; k=0.002971 n=1.564; b=-0.0004321	0.9991	0.0104	1.0207	a=0.9896; k=0.002083 n=1.714; b=-0.0006544	0.9984	0.0143	1.8507

3.3. Effective moisture diffusivity

Effective moisture diffusivity of microwave and microwave-convective dried lime slices ranged from 1.95 x 10^{-9} and 5.84 x 10^{-9}. It is clear in Table 4 that D_{eff} values showed an increase with the rise in microwave power and heating temperature. 160 W - 75 °C drying setting has the maximum effective moisture diffusivity value and 90 W has the minimum effective moisture diffusivity value. This can be explained by the higher heat caused the higher mass transfer. The diffusivity values derived from the present study were in agreement with values proposed in the literature. DOYMAZ *et al*. (2015) stated that D_{eff} values for dried agricultural products were generally varied between 10^{-8} and 10^{-12} m^2/s. DARVISHI *et al*. (2014) found that D_{eff} values of lemon slices dried at 180, 360, 540 and 720 W microwave power level were 1.87, 2.48, 3.29 and 3.95 x 10^{-8}, respectively. Similarly, SADEGHI *et al*. (2013) studied on lemon slices dried by using combined microwave - convective drying method at 50, 55 and 60°C inlet hot-air temperatures and microwave powers of 185.5 W and 388.5 W. The lowest and highest values of D_{eff} are 5.45 × 10^{-10} (185.5 W - 50°C) and 1.25 × 10^{-9} m^2 s^{-1} (388.5 W – 60°C), respectively. All of the outcomes above verify the rule that the rise in D_{eff} leads to decline in the drying interval.

3.4. Activation energy

The results indicated that Ea values of lime are 1.05 W g^{-1} during microwave drying and 15.99-19.33 W g^{-1} for microwave-convective drying combinations at 90 W and 160 W, in return. These findings are in congruence with the former researchers. To give an example, ZAREIN *et al*. (2015) found that the Ea of microwave dried apple samples at 200, 400 and 600 W was 12.15 W g^{-1}. The similar trend was determined by AMIRI CHAYJAN *et al*. (2015) for hawthorn fruit drying with microwave-convective drying technique. In general, the obtained results of the current study were well consistent with previous high moisture agricultural and food materials studies (RAVULA *et al*., 2017).

3.5. Energy analysis

Based on the benchmarking of the energy and specific energy consumption figures obtained during drying experiments of lime samples, it is found that in the 90 W – 55 °C combination required the minimum volume of energy and specific energy, whereas 90 W required the maximum volume of energy and specific energy. Out of these drying experiments, the microwave-drying ones consume more energy and they are not cost-effective to dry lime samples, whereas the microwave-convective drying combinations are energy-efficient and they consume less energy to dry lime samples. Taking into consideration that energy costs high all around the world, a combination of microwave-convective drying method seems to be an outstanding alternative. According to Table 5, the specific energy requirement is a function of air temperature and microwave power, such that when the microwave power level is constant, specific energy requirement to dry lime surges with the rise in air temperature. As drying rate is associated with microwave power and air temperature linearly, it could be detected that the surge in the microwave power and the air temperature consequently end up with the decline in drying interval. Similarly, DEMIREL and ISMAIL (2017) stated that total energy consumption depends on the overall drying interval. Out of all the drying techniques, the optimal energy consumption arose through microwave drying at 180 W power level with 0.042 kWh energy consumption. The overall energy consumption in all of the combined microwave-convective drying test processes of nectarine was found between 2.03 - 4.25

kWh. As VARITH *et al*. (2007) investigated the peeled longan drying with microwave-hot air combination. The least required specific energy consumption was found 29.7 MJ kg^{-1} water with MW400-300/40-60 and specific energy consumption can reduce the up to 48.2%.

Table 4. Effective moisture diffusivities of dried lime samples.

Drying method	D_{eff} (m^2 s^{-1})
90 W	1.95×10^{-9}
90 W - 55 °C	3.24×10^{-9}
90 W - 65 °C	3.89×10^{-9}
90 W - 75 °C	4.54×10^{-9}
160 W	3.24×10^{-9}
160 W - 55 °C	3.89×10^{-9}
160 W - 65 °C	5.19×10^{-9}
160 W - 75 °C	5.84×10^{-9}

Table 5. Energy consumption values of dried lime samples.

Drying method	Drying time (min)	Energy consumption (kWh)	Specific energy consumption (kWh kg^{-1})
90 W	269	0.85	10.36
90 W - 55 °C	131	0.57	6.93
90 W - 65 °C	118	0.60	7.40
90 W - 75 °C	97	0.67	8.17
160 W	131	0.57	7
160 W - 55 °C	120	0.61	7.48
160 W - 65 °C	77	0.62	7.5
160 W - 75 °C	33	0.63	7.64

3.6. Colour analysis

Because of to being highly appreciated quality parameter, the effect of drying on the color should be minimized (VEGA-GÁLVEZ *et al*., 2009). The results concerning the color changes under different experimental conditions are compared to the fresh sample in Table 6.

As the increase in drying air temperature at constant microwave power lead to decreases in L* values and increases in values of b*. The decrease of L* value implies darker color for all dried lime samples. While negative a* value (greenness) was seen for fresh lime samples (-3.79), it has turn to positive value (redness) in all dried lime samples. Besides, the drying at 160 W (28.08) has less negative effect than 90 W (29.21) in color value of b*. According to the ΔE parameter, there were no significant differences except 160 W – 65°C and 160 W – 75°C drying conditions ($p<0.05$).

Previous studies such as FADAVI and MEHRABI (2013), who considered the different temperature treatments (Shadow, sun-dried, 40, 105 and 200°C) effect on dried lime and defined that the attractive color is a necessary quality parameter. Similar outcomes have been put forward by DÍAZ *et al*. (2011).

Table 6. Color values of fresh and dried lime samples.

Drying method	Color parameters					
	*L**	*a**	*b**	*C*	*α*°	*ΔE*
Fresh	62.58±0.06[a]	-3.79±0.08[a]	26.39±0.05[a]	26.67±0.06[a]	98.14±0.17[a]	-
90 W	57.52±0.34[d]	5.14±0.06[cd]	29.21±0.33[cd]	29.66±0.33[cd]	80.06±0.01[c]	16.84±0.19[a]
90 W - 55 °C	60.78±0.35[b]	2.90±1.58[b]	30.81±2.19[de]	30.96±2.31[de]	84.80±2.66[b]	16.64±2.61[a]
90 W - 65 °C	58.88±0.03[c]	3.60±0.01[b]	30.10±0.02[de]	30.31±0.01[de]	83.23±0.01[b]	16.56±0.02[a]
90 W - 75 °C	52.78±0.19[g]	5.62±0.91[cd]	27.10±0.88[ab]	27.69±0.67[ab]	78.29±2.25[cd]	17.59±0.24[a]
160 W	54.16±0.23[f]	4.84±0.49[c]	28.08±1.53[bc]	28.50±1.42[bc]	80.21±1.55[c]	17.18±1.01[a]
160 W - 55 °C	57.79±0.08[d]	3.42±0.01[b]	31.30±0.03[e]	31.49±0.03[e]	83.81±0.02[b]	17.85±0.01[a]
160 W - 65 °C	56.05±0.04[e]	5.81±0.02[cd]	29.97±0.01[de]	30.53±0.01[de]	79.08±0.01[cd]	18.26±0.02[ab]
160 W - 75 °C	49.24±0.09[h]	6.19±0.03[d]	26.98±0.06[ab]	27.68±0.06[ab]	77.12±0.02[d]	19.95±0.03[b]

[a-g] mean that different letters in same column with differ significantly ($p < 0.05$).

The rise of drying temperature from 60 to 70 °C without pretreatment resulted color degradation in 3 and 5 mm lime slices. However, the pretreated drying processes end up with fewer color changes and culminate in a product quality analogous to the fresh fruit.

4. CONCLUSIONS

In this research, the influences of microwave and combined microwave-convective drying techniques on the kinetics of drying, color, effective moisture diffusivity, activation energy and energy consumption of lime samples were studied. The obtained outcomes showed that the combined microwave-convective drying technique enabled significantly higher time-saving than microwave drying. The experimental moisture ratio data were tailored to the chosen 10 different thin-layer drying models and the drying attributes are illustrated better in the models of Midilli *et al*. and Page. The optimal color parameter of a* (greenness) and energy consumption values are achieved in 90 W – 55°C. Alternative techniques should be used to save time or energy in the industrial food process.

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Paper Received June 13, 2018 Accepted February 1, 2019