Bulgarian Chemical Communications, Volume 49, Number 1, (pp. 92 – 100) 2017

Thin-layer drying kinetics of nectarine slices using IR, MW and hybrid methods

O. Ismail, A. S. Kipcak*, İ. Doymaz, S. Piskin

Yildiz Technical University, Department of Chemical Engineering, 34210, Istanbul, Turkey

Received June 13, 2015; Revised January 20, 2016

In this study, slices of nectarines (*var. nucipersica* or *var. nectarine maxim*) were dried using three different drying methods: microwave (MW), infrared (IR) and hybrid (combined IR and MW). MW drying method was applied with power levels between 90-600 W, while IR drying method was applied with a power level of 125 W. For the hybrid drying, 125 W of IR and 180 W of MW were consecutively applied. Along with the aforementioned methods a pre-treatment process with citric acid was also applied. Minimum drying time of 127 min was reached using the hybrid drying method. After obtaining the experimental drying values, drying kinetics was calculated using mathematical modeling by different methods widely used in the literature. Considering the high coefficient of determination (R^2), low root mean square error (RMSE) and low chi-square (χ^2) values, the Aghbashlo *et al*. model was found to be the best one.

Keywords:MW drying, IR drying, hybrid drying, Aghbashlo et al. model

INTRODUCTION

Nectarines (*var. nucipersica* or *var. nectarine maxim*) and peaches (*prunuspersica*) belong to the Rosaceae family. The nectarine is a peach with recessive genes and is referred to as a "shaved peach" or "fuzzless peach", due to its lack of fuzz or short hairs. There are also some differences including fruit size, shape, firmness, external color, aroma and flavor. Nectarine fruits, which can be yellow or white fleshed, have smooth skin, a distinctive flavor and texture, and are usually smaller [1, 2]. The worldwide peaches and nectarines production in 2012 was 21 083151 tons. The major producer countries are China, Italy, USA, Greece, Spain and Turkey. The production in Turkey in 2012 was 575730 tons [3].

Dehydration operations are important steps in food processing industry. The basic objective in drying food products is the removal of water in the solids up to a certain level, at which microbial spoilage is minimized. A wide variety of dehydrated foods including dried fruits, dry mixes and soups, etc., is today available to the consumer [4]. Hot air drying has many disadvantages such as low energy efficiency and long drying times, but nevertheless, it has been widely used [5, 6].

Infrared (IR) heating has many advantages compared to hot air drying. High heat transfer coefficients, short process time and low cost of energy are the characteristic properties of IR heating. Also, the IR equipment is compact with controllable parameters permitting to control overheating and fast heating [7]. There are many studies on the IR method used for the dehydration of several foods. Some examples are: paddy dried by Das*et al*., 2009, barley dried by Afzal and Abe,2000, onion dried by Sharma*et al*., 2005, carrots dried by Xu*et al*., 2014 and apple slices dried by Nowak and Lewicki, 2004 [8–12].

For the last 20 years microwave drying has been of interest in the area of water removal from agricultural products. The short drying time leads to lower energy consumption and better quality of the dried food [13]. Drying time is shortened due to quick absorption of energy by the water molecules, which causes rapid evaporation of water, resulting in high drying rates of the food. However, because of non-uniform heating, uneven distribution of the microwave field can occur. Also, overheating and quality deterioration can take place. To overcome these problems, the microwave drying technique has been combined with other drying methods [14]. Several studies were conducted using the microwave method, e.g., Yongsawatdigul and Gunasekaran, 1996, dried cranberries, Bouraoui *et al*., 1994, dried potatos, Funebo and Ohlsson, 1998, Prothon *et al*., 2001, Bilbao-Sainz *et al*., 2006, dried apples and Al-Harahsheh *et al*., 2009, dried tomato pomace [15–20].

Today, efforts have been focused on developing better products in accordance with consumer preferences of the drying processes. The biggest problem encountered in fruit drying is the inner surface color change of cut fruit. Several methods were used to obviate color changes, such as: osmotic pre-drying, hot water interaction, steaming, microwave pre-drying and citric acid treatment [21, 22].

While studies exist in the literature regarding dried peaches, there are no studies on the drying of nectarines which are a subgroup of peaches. Hence,

* To whom all correspondence should be sent:
E-mail: skipcak@yildiz.edu.tr, seyhunkipcak@gmail.com

the drying time and color quality is the most important stage of this study. Two different methods of MW and IR drying were used along with the hybrid drying process (IR and MW). Lewis, Henderson and Pubis, Page and Aghbashlo *et al*. models were fitted to the experimental data for obtaining the best model for the drying kinetics of nectarine slices.

MATERIALS AND METHODS

Materials

The experiments were carried out using nectarines purchased from a local market in Istanbul, Turkey. The nectarine samples were stored in a refrigerator at 4 ± 1 °C before commencement of the experiments.

Sample preparation and pretreatment

Dry matter and moisture contents of the fresh samples were determined prior to the drying process.The moisture contents of the samples were obtained according to the Association of Official Analytical Chemists [23]. To determine the initial moisture content four sets of identical experiments were conducted. In these sets samples of 30 g were dried in an Ecocell LSIS-B2V/EC55 model incubator (MMM Medcenter Einrichtungen GmbH, Planegg, Germany) at 105 °C for 24 h. The average initial moisture content of the nectarine slices obtained from the four sets was found to be 84.0 ± 0.1% weight base.

As a pre-treatment, nectarine samples were cleaned with tap water from dust and foreign materials, then immersed into a solution of 5% citric acid and kept for 3 min at ambient temperature. Citric acid, which is known as lemon salt among the people, E330 food additive code, is used as a preservative inside the foods that reduces color conversion (becoming dark) and deterioration, also increases the shelf life of the fruits [24].

Drying equipments

Drying equipment of MW

Drying experiments were carried out in a microwave oven (Robert Bosch Hausgeräte GmbH, Germany) which has a maximum output of 800 W working at 2450 MHz. In the microwave drying process, the samples were evenly and homogeneously placedover the entire pan. The microwave oven has the capability of operating at five different microwave power levels of 90, 180, 360, 600 and 800 W.

Drying equipment of IR

Drying experiments were carried out in a moisture analyzer with one 250 W halogen lamp (Snijders Moisture Balance, Snijders bv Tilburg, Holland). During the infrared drying process, the samples were evenly and homogeneously placed over the entire pan.

Drying procedures

The MW, IR and hybrid (IR and MW) drying methods were used for the drying of nectarine slices. Before the experiments the nectarines were washed and kept in open air for 2-3 h, to become equal with the ambient temperature. Then the nectarines were cut into slices of 15 mm using a knife. These slices were used in the aforementioned drying methods.

MW drying method

The adjustment of microwave output power level and processing time was done with the aid of a digital control facility located on the microwave oven. Drying experiments were carried out using sliced nectarines of known weight of about 30±2 g arranged as a thin layer on the rotatable plate fitted inside the microwave oven cabinet. The rotating plate provides equal distribution of the microwave radiation energy throughout the sample. Drying was performed at a single power level at a time. In the microwave drying method, four power levels of: 90, 180, 360 and 600 W were used. Moisture loss was measured in 60 and 30 s intervals with a digital balance (Precisa, model XB220A, Precisa Instruments AG, Dietikon, Switzerland) with an accuracy of 0.001 g. Three replicates of each experiment were performed according to a preset microwave output power level and time schedule, and the average of these results was given. Microwave drying continued till the moisture was reduced to about 0.18 g water/g dry matter. After this point the nectarine slices burned. The average values of the moisture content were used for drawing the drying curves.

IR drying method

The most convenient power level for IR drying was reported as 125 W [25, 26]. So the drying experiments were performed at an infrared power level of 125 W. Moisture loss in the samples with initial load of 32 ± 1 g was measured with a digital balance at 30 min intervals. Drying was finished when the moisture content of the samples was approximately 0.06 g water/g dry matter. The experiments were triplicated and the average values of the moisture content were used for drawing the drying curves.

Hybrid drying method

In this method, IR and MW methods were consecutively applied to the same nectarine slices. According to the results obtained from MW and IR method, the details of the hybrid drying were determined.

Firstly IR method at a power level of 125 W was applied on nectarine slices weighing 36.0 ± 1.0 g. The IR method continued until the moisture content decreased to 50%, i.e., 2.15 g water/g dry matter. Then the MW method was applied at a power level of 180 W. The second drying step was continued until the moisture content of the samples decreased to 0.10 g water / g dry matter.

Calculations of the moisture content and drying rate

During the drying process, all weighings were completed in 10 s. Samples were weighed at intervals of 30 and 2 min, for the methods of IR and MW, respectively. Three replicates were taken and the average value was calculated on dry basis by the following equation:

$$M_{initial} = \frac{W_w - W_d}{W_d}, \quad (1)$$

where $M_{initial}$ is the initial moisture content of nectarine on dry matter (%), W_w is the wet weight and W_d is the dry weight of nectarine in g. The drying rate during the experiments was calculated using the following formula:

$$\frac{dM}{dt} = \frac{M_{t+dt} - M_t}{dt}, \quad (2)$$

where M_t and M_{t+dt} are the moisture content at t and moisture content at $t+dt$ (g water/g dry matter), respectively, and t is the drying time (min).

Color measurements

Color analysis for MW, IR and hybrid dried nectarine samples was done on three randomly selected slices. Color measurement was done using Chromameter CR-400 (Minolta, Japan) and an image analysis system. Color tests of the nectarine samples were replicated five times and average values were calculated."L" represents the lightness or darkness of the sample on the scale of 0–100 where white equals 100 and dark equals 0. "a" represents redness (+) or greenness (−). "b" represents yellowness (+) or blueness (−). The color difference (ΔE), chroma (C^*) and R (a/b) were determined using the following Eqns. [27, 28]:

$$\Delta E = \sqrt{\left((L_o - L)^2 + (a_0 - a)^2 + (b_0 - b)^2\right)}, \quad (3)$$

$$C^* = \sqrt{a^2 + b^2}, \quad (4)$$

$$R = \frac{a}{b}, \quad (5)$$

L_0, a_0 and b_0 are the parameters that are measured before drying of the fresh nectarine samples. The chroma value represents the saturation of the color, the chroma value being lowfor dim colors and high for vivid colors.

Mathematical modeling

In order to determine the moisture ratio as a function of drying time, four different thin-layer drying models, namely Lewis, Henderson & Pabis, Page, and Aghbashlo *et al*. models [29–32] were applied to IR and MW drying (Table 1).

The moisture ratio of the nectarines was calculated using the following Eqn.:

$$MR = \frac{M_t - M_e}{M_o - M_e}, \quad (6)$$

where MR is the moisture ratio, M_t, M_o and M_e are the moisture contents (g water/g dry matter) on dry basis at any time, initial and equilibrium, respectively. The equilibrium moisture content (M_e) was assumed to be zero for microwave and infrared drying and the MR equation (Equation 6) was simplified as Eqn. 7 [33, 26]:

$$MR = \frac{M_t}{M_o}, \quad (7)$$

Table 1. Thin-layer drying curve models considered

Model name	Model	Reference
Lewis	$MR = exp(-kt)$	[29]
Henderson and Pabis	$MR = a\,exp(-kt)$	[30]
Page	$MR = exp(-kt^n)$	[31]
Aghbashlo*et al*.	$MR = exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$	[32]

Statistical analysis

The statistical analysis of experimental data was performed using Statistica 8.0.550 (StatSoft, Inc., Tulsa, OK) software package, which is based on the Levenberg–Marquardt algorithm. Three criteria of statistical analysis were used to evaluate the fitting of the experimental data to the different models: coefficient of determination (R^2), reduced chi-square (χ^2) and root-mean-square error (*RMSE*). These parameters can be calculated as:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-z}, \quad (8)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2}, \quad (9)$$

where $MR_{exp,I}$ and $MR_{pre,i}$ are the experimental and predicted dimensionless *MR*, respectively, *N* is the number of data values, and z is the number of constants of the models. Higher R^2 and smaller χ^2 and *RMSE* values indicate a better fit of the experimental data to the model [34, 35].

RESULTS AND DISCUSSION

Drying Curves

First stage (MW drying)

In the first stage the nectarines were dried in the microwave oven as natural and pre-treated. From the results of the pre-treated nectarines it can be seen that the pre-treatment process did not affect the drying time. So the pre-treatment curves are not given. The effect of microwave oven on the drying curves of natural nectarines is shown in Fig. 1.

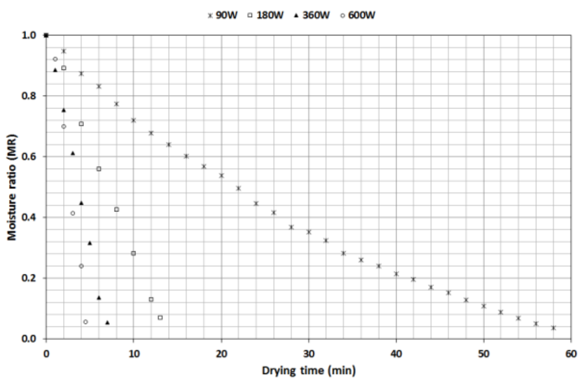

Fig. 1. Drying curves of nectarines at different microwave power level.

The final moisture content of the natural nectarines was reached for about 58 min at the microwave power level of 90 W, where at 180, 360 and 600 W, the final moisture content of the natural nectarines was reached after 13, 7 and 5 min, respectively.

Water molecules within the nectarines are exposed to a greater number of electromagnetic waves by the increase in microwave output frequency, so the drying time was shortened by the generation of heat inside the nectarines that increased the evaporation of the water molecules (Fig. 2).

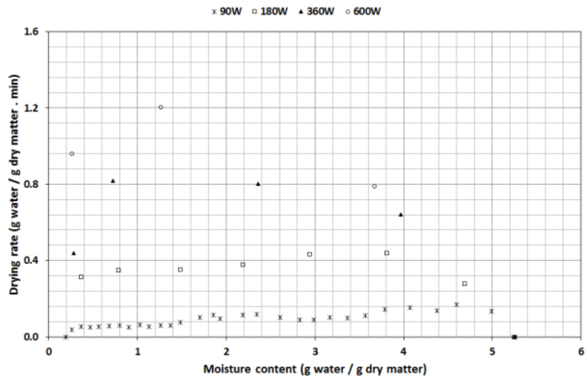

Fig. 2. Drying rate *versus* moisture content of nectarine slices at different microwave power levels.

In the high-moisture zone, the initial drying rates were high. Drying rates decreased over time while the moisture content of the nectarines dropped significantly.

In the microwave drying of nectarines, constant rate and falling rate periods were consecutively seen. Constant rate period was seen at the microwave power levels of 90 and 180 W in the high moisture zone, then reduced speed period was seen by the decreasing moisture content. In contrast, falling-rate period was seen at the power levels of 360 and 600 W. As a result, the microwave output power level had a crucial effect on the drying rate. Similar results were reported in previous studies [36–38].

Second stage (IR drying)

Fig. 3 shows the experimentally determined moisture ratios of natural and pre-treated nectarines *versus* drying time at infrared power level of 125 W. The moisture ratio of the nectarines was calculated by the simplified Eqn. 7. The moisture ratio decreased continuously with drying time. The drying curves are typical for those for similar fruits and vegetables. Drying curves were used to determine the effect of pre-treatment (citric acid) on the drying time and it can be easily seen that pre-treatment conditions very little affect the drying time. Drying was continued until the moisture content of the sample reached 0.06 g water/g dry matter and drying times were determined as 225 min and 210 min for natural and citric acid treated samples, respectively.

Similar results were reported during air-drying of citric acid treated banana by Ayim *et al*., 2012 [39].

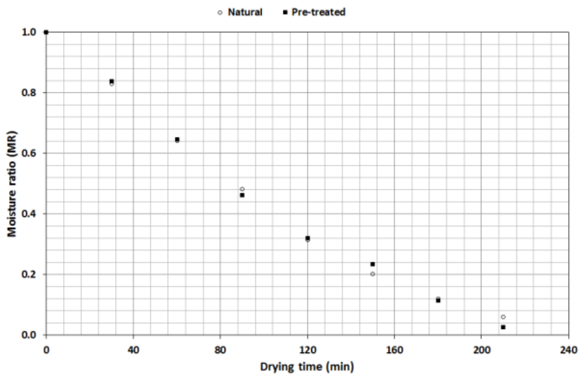

Fig. 3. Experimentally determined moisture ratios of natural and pre-treated nectarines *versus* drying time at infrared power level of 125 W.

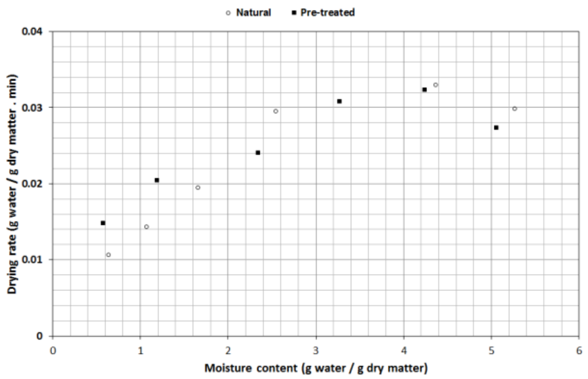

Fig. 4. Drying rate *versus* moisture content of nectarine slices at infrared power level of 125 W.

Curves of drying rate *versus* moisture content for pre-treated and natural samples are presented in Fig. 4. As can be seen, there are three drying rate periods in these curves. At the beginning of the drying process, under all drying conditions, there are short heating up periods after which the drying rates gradually decrease and two falling rate periods occur during the drying process. The results are consistent with the observations made by different authors on drying various agricultural products [40–42].

Third stage (Hybrid drying)

The hybrid drying curves of nectarines are shown in Figs. 5, 6 and 7. As seen from Fig. 5, the total moisture content reaches 50% for 120 minutes. Natural and pre-treated nectarines were dried to 0.30 and 0.27 g water/g dry matter in the falling-rate periods, respectively. The pre-treatment process had no effect on natural nectarine drying. The remaining moisture content was removed using MW at the 180 W power level (small graph inside Fig. 5) and the moisture content decreased to 0.10 g water/g dry for a period of 7 min.

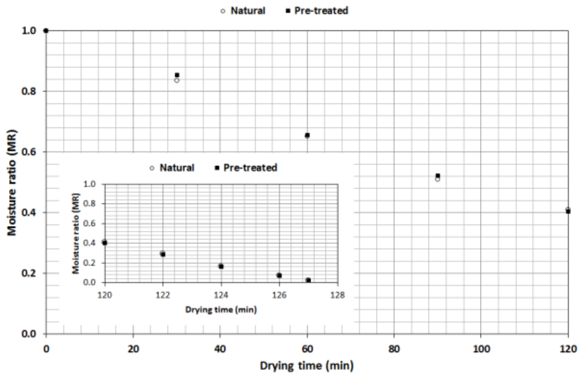

Fig. 5. Experimentally determined moisture ratio of nectarine slices *versus* drying time during the hybrid process.

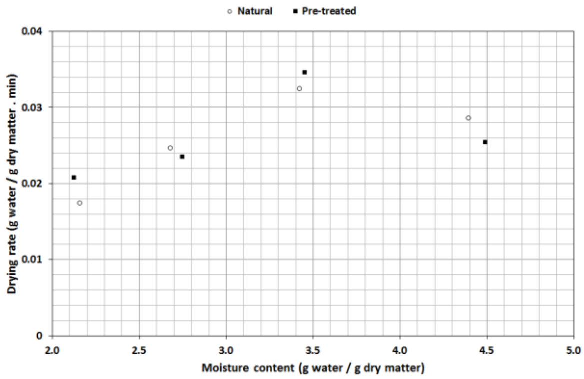

Fig. 6. Changes in drying rate with moisture content at 125 W infrared power level.

Drying rate *versus* moisture content of the first step of hybrid drying (IR at 125 W) is given in Fig. 6. The drying rate, although showing a short-term increase at the beginning of the drying process, shows a declining trend later for both natural and pre-treated nectarines. Constant rate drying was not observed.

The second step (MW at 180 W), of the drying rate curves for the nectarine slices is given in Fig. 7. As can be seen, in the first two minutes the drying rate increases, then decreases for both natural and pre-treated samples. As a result, the moisture content of the nectarines was very high during the initial phase of the drying process, which resulted in a higher absorption of microwave power level and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power level and resulted in a fall in the drying rate. Similar findings were reported in previous studies [43, 44].

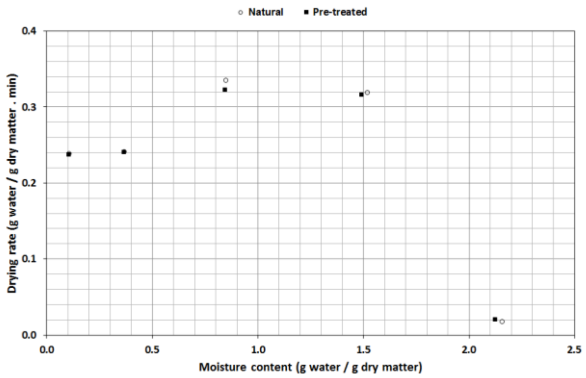

Fig. 7. Changes in drying rate with moisture content at a microwave power level of 180 W

Effect of drying and pre-treatment on the color of nectarine slices

One of the quality parameters of food and agricultural productsis the color. Too big color change affects the quality of the product and leads to negative marketing conditions. For the dried products high "L" and low "R" values are preferred. In Table 2, "L", "a", "b", "ΔE", "C*" and "R" values of the control group and nectarines dried by different methods are given.

In comparison with natural nectarines, the lightness values of the pre-treated hybrid dried nectarines decreased a little; on the contrary, the redness and yellowness values increased. Citric acid pre-treatment prior to the hybrid drying process increased the lightness value. The highest values of "L", "a", "b" and "R" were observed for IR and hybrid dried nectarines. Similar results were obtained for various agricultural products [45, 46].

The highest and the lowest total color change (ΔE) values were found as 27.67 and 12.32 for the MW method (600 W) and the IR method with pre-treated nectarines, respectively. The highest chroma(C*) values were obtained for the IR and hybrid methods.

The pictures of nectarines dried by different drying methods are shown in Fig. 8.

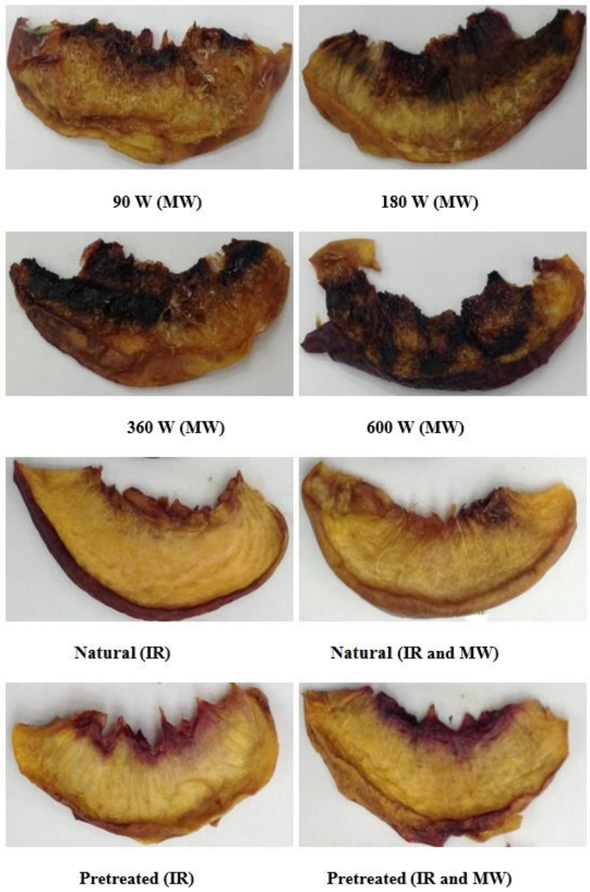

Fig. 8. Colors of dried nectarine slices

Table 2. Color parameters of fresh and dried nectarine slices

Drying Method	Power level	Nectarine	Color parameters			ΔE	C^*	R
			L	a	b			
-	-	Fresh	65.10	6.00	21.56	-	22.37	0.28
MW	90 W	Natural	53.85	11.10	19.47	12.53	22.41	0.57
	180 W	Natural	51.42	13.89	20.41	15.83	24.68	0.68
	360 W	Natural	49.85	13.57	19.69	17.13	23.91	0.70
	600 W	Natural	40.68	11.90	9.97	27.67	15.52	1.19
IR	125 W	Natural	63.86	14.22	34.45	15.34	37.27	0.41
		Pre-treated	64.02	12.03	30.99	12.32	33.24	0.39
Hybrid	125 W (IR) & 180 W (MW)	Natural	52.15	15.14	28.43	17.28	32.21	0.53
		Pre-treated	63.93	15.67	30.13	12.97	33.96	0.52

As can be seen in Fig. 8, on increasing microwave output power level, excessive browning of the nectarine slices (burning) occurred. This burning decreased on lowering the microwave output power level. In the IR method, the color quality of both natural and pre-treated nectarines was found to be the best among the other methods (Table 2). During hybrid drying, the color values were close to those of the IR method, which means that the hybrid drying method leads to promising results. Another conclusion ensuing from Fig. 8 is that the pre-treatment process had a positive impact on the color quality.

RESULTS OF THE MATHEMATICAL MODELING

Mathematical modeling results of MW dried nectarines are given in Table 3.

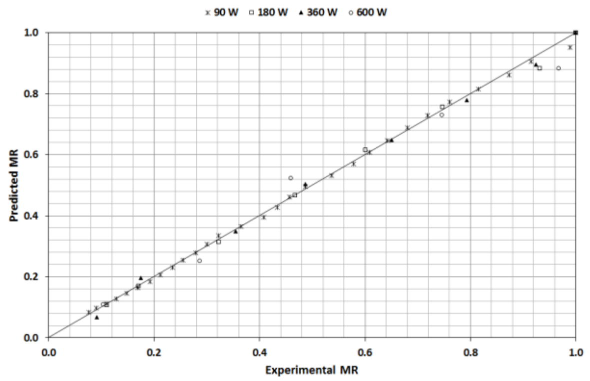

Fig. 9. Comparison of experimental and predicted moisture ratio values using the Aghbashloet al. model for nectarine slices at different MW power levels

From the R^2, RMSE and χ^2values obtained, the Aghbashlo *et al*. model was found as the optimum one.For the model of Aghbashlo *et al*., the R^2 values were found as 0.9988, 0.9966, 0.9970 and 0.9910 for the MW power level of 90, 180, 360 and 600 W, respectively. RMSE and χ^2 values were calculated as 0.037362, 0.029480, 0.039507, 0.062795 and 000098, 0.000444, 0.000389, 0.001928 for the MW power level of 90, 180, 360 and 600 W, respectively.

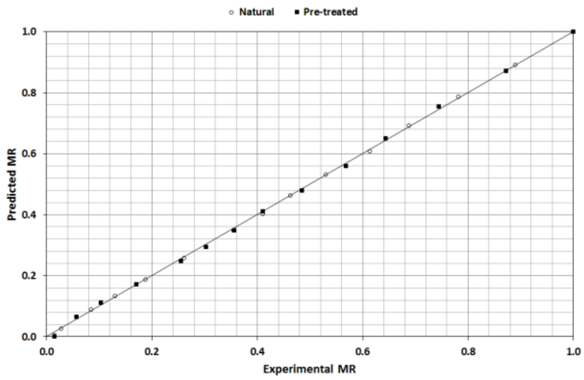

Fig. 10. Comparison of experimental and predicted moisture ratio values using the Aghbashlo *et al*. model for nectarine slices at different IR power level.

The comparison of the experimental and the predicted values is given in Fig. 9. Mathematical modeling results of the IR dried nectarines are given in Table 4.

Table 3. Curve fitting criteria for the various mathematical models and parameters for nectarine slices at different MW power levels.

Power level (W)	Model	R^2	χ^2	RMSE
90	Lewis	0.9779	0.001816	0.205167
	Henderson and Pabis	0.9864	0.001147	0.145434
	Page	0.9969	0.000254	0.069229
	Aghbashlo *et al.*	0.9988	0.000098	0.037362
180	Lewis	0.9193	0.009011	0.213650
	Henderson and Pabis	0.9386	0.008041	0.200565
	Page	0.9944	0.000722	0.052846
	Aghbashlo *et al.*	0.9966	0.000444	0.029480
360	Lewis	0.9029	0.011143	0.234195
	Henderson and Pabis	0.9242	0.010146	0.217807
	Page	0.9953	0.000618	0.052454
	Aghbashlo *et al.*	0.9970	0.000389	0.039507
600	Lewis	0.8409	0.021674	0255297
	Henderson and Pabis	0.8709	0.021981	0.258622
	Page	0.9918	0.001381	0.058116
	Aghbashlo *et al.*	0.9910	0.001928	0.062795

Table 4. Curve fitting criteria for the various mathematical models and parameters for IR dried nectarine slices

Pretreatment	Model	R^2	χ^2	RMSE
Natural	Lewis	0.9632	0.004590	0.162364
	Henderson and Pabis	0.9699	0.004292	0.157089
	Page	0.9969	0.000439	0.041236
	Aghbashlo *et al.*	0.9990	0.000138	0.025463
Pre-treated	Lewis	0.9624	0.004549	0.137584
	Henderson and Pabis	0.9692	0.004341	0.133052
	Page	0.9954	0.000649	0.042771
	Aghbashlo *et al.*	0.9976	0.000329	0.035763

From the obtained results for the R^2, RMSE and χ^2values, the Aghbashlo *et al*. model was again found as the optimum one. For the model of Aghbashlo *et al*., the R^2 values were found as 0.9990 for natural and 0.9976 for pre-treated nectarine slices. The RMSE and χ^2 values were calculated as 0.025463, 0.000138 for natural and 0.035763, 0.000329 for pre-treated nectarines, respectively.

The comparison of the experimental and the predicted values is given in Fig. 10.

As it is seen from Figs. 9 and 10, all values are placed near the control line, meaning that the experimental and predicted values are very close.

CONCLUSIONS

Turkey has an important place in nectarine fruit production. Nectarines, mostly consumed fresh, have a significant value in terms of human nutrition. The acquisition of new productsfrom dried nectarines, the nectarine production/ processing will increase the income and will allow the consumption of nectarines in every month of a year. Considering the described reasons, in this study, an appropriate method and conditions for drying nectarine slices was found.

In MW drying of both natural and pre-treated nectarines, the drying process was not successful because of the burning of the sugar content (7-12%) inside the nectarines. The nectarines were partly cooked. In IR drying, the drying process was successful with drying times of 210 and 225 min, for natural and pre-treated nectarines, respectively. Even if there is no significant difference in the drying time between natural and pre-treated nectarines, the color quality of pre-treated nectarines was better than that of natural dried nectarines. In the hybrid drying method, the drying time was 127 min, meaning that the drying time was reduced by 40% and 44%, for the pre-treated and natural nectarines, respectively. Likewise, in the IR method the pre-treatment did not affect the drying time but affected the color quality.

The most suitable model for the mathematical modeling of MW and IR drying methods was that of Aghbashlo *et al*.

As a result, considering all aforementioned parameters, the best method for nectarine drying was found to be the hybrid drying method.

REFERENCES

1. W. Len-Chi,K. E. Koch, W. B. Sherman, *J. Am. Soc. Hortic. Sci.*,**120**, 101 (1995).
2. G. El-Sherief, G. B. Gado, E. M. Rizk, *J. Am.Sci.*,**8**, 139 (2012).
3. http, //faostat3.fao.org/download/Q/QC/E.
4. M. K. Krokida,D. Marinos-Kouris, *J. Food Eng.*, **57**, 1 (2013).
5. H. Feng, J. Tang, *J. Food Sci.*,**63**, 679 (1998).
6. Z. Pan, R. Khir, L. D. Godfrey, R. Lewis, J. R. Thompson, A. Salim, *J. Food Eng.*, **84**, 469 (2008).
7. N. Sakai, T. Hanzawa,*Trends Food Sci. Technol.*, **5**, 357 (1994).
8. I. Das, S. K. Das, S. Bal,*J. Food Eng.*, **95**,166 (2009).
9. T. M. Afzal, T. Abe,*Comput. Electron Agr.*, **26**, 137 (2000).
10. G. P. Sharma, R. C. Verma, P. B. Pathare,*J. Food Eng.*, **67**, 361 (2005).
11. C. Xu, Y. Li, H. Yu, *J. Food Eng.*, **136**, 42 (2014).
12. D. Nowak, P. P. Lewicki, *Innov. Food Sci. Emerg. Technol.*, **5**, 353 (2004).
13. E. Sanga, A. S.Mujumdar, G. S. V. Raghavan, Principles and application of microwave drying. In, Mujumdar AS. (Ed.), Drying Technology in Agriculture and Food Sciences. Science Publishers, Inc., Enfield, NH, 2000.
14. P. Puligundla, A. S. Abdullah, W. Choi, S. Jun, S. E. Oh, S. Ko, *J. Food Process. Technol.*, **4**, 1000278 (2013).
15. J. Yongsawatdigul, S. Gunasekaran, *J. Food. Process. Pres.*,**20**, 145 (1996).
16. M. Bouraoui, P. Richard, T. Durance, *J. Food Process. Eng.*, **17**, 353 (1994).
17. T. Funebo, T. Ohlsson T. *J. Food Eng.*, **38**, 353 (1998).

18. F. Prothon, L. M. Ahrne, T. Funebo, S. Kidman, M. Langton, I. Sjoholm, *LWT- Food Sci. Technol.*, **34**, 95 (2001).
19. C. Bilbao-Sáinz, A. Andrés, A. Chiralt, P. Fito, *J. Food Eng.*, **74**, 160 (2006).
20. M. Al-Harahsheh, A. H. Al-Muhtaseb, T. R. A. Magee, *Chem. Eng. Process*, **48**, 524 (2009).
21. M. K. Krokida, C. T. Kiranoudis, Z. B. Maroulis, D. Marinos-Kouris, *Drying Technol.*, **18**, 1239 (2000).
22. İ. Doymaz, B. Bilici,*Int.J. Food Eng.*, **10**, 829 (2004).
23. AOAC. Official methods of analysis. Association of Official Analytical Chemists, Arlington, USA, 1990.
24. F. H. Verhoff, Citric Acid, Ullmann's Encyclopedia of Industrial Chemistry, Weinheim, Wiley-VCH, 2005.
25. H. Kocabiyik, D. Tezer, *Int. J. Food Sci.Technol.*, **44**, 953 (2009).
26. İ. Doymaz, *J. Food Process Pres.*, **39**, 933-939.
27. F. D. Jarad, B. W. Moss, C. C. Youngson, M. D. Russell, *Dent. Mater.*, **23**, 454 (2007).
28. S. Phoungchandang, S. Saentaweesuk, *Food Bioprod.Process.*,**89**, 429 (2011).
29. J. S. Roberts, D. R. Kidd, O. Padilla-Zakour, *J. Food Eng.*,**89**, 460 (2009).
30. H. M. Ghodake, T. K. Goswami, A. Chakraverty, *Drying Technol.*,**24**, 159 (2006).
31. A. Kaleta, K. Górnicki, R. Winiczenko, A. Chojnacka, *Energ. Convers. Manage.*, **67**, 179 (2013).
32. M. Aghbashlo, M. H. Kianmehr, S. Khani, M. Ghasemi, *Int. Agrophys.*, **23**, 313 (2009).
33. A. Calín-Sánchez, A. Figiel, A. Wojdylo, M. Szaryez, A. A. Carbonell-Barrachina, *Food Bioprocess. Technol.*, **7**, 398 (2014).
34. A. Kaleta, K. Górnicki, *Energ. Convers. Manage.*, **51**, 2967 (2010).
35. K. O. Falade, O. S. Ogunwolu, *J. Food Process. Pres.*, **38**, 373 (2014).
36. I. Alibas, *J. Food Eng.*, 10, 69 (2014).
37. I. Hammouda, D. Mihoubi, *Energ. Convers.Manage.*, **87**, 832 (2014).
38. N. Izli, G. Yıldız, H. Unal, E.Işık, V. Uylaşer, *Int. J. Food Sci. Technol.*, **49**, 9 (2014).
39. I. Ayim, E. A. Amankwah, K. A. Dzisi, *J. Anim. Plant Sci.*, **13**, 1771 (2012).
40. S. Mongpraneet, T. Abe,T. Tsurusaki, *Trans. Am. Soc. Agric. Eng.*, **45**, 1529 (2002).
41. J. Shi, Z. Pan, T. H. Mchugh, D. Wood, E. Hirschberg, D. Olson, *LWT- Food Sci. Technol.*, **41**, 1962 (2008).
42. E. Akhondi, A. Kazemi, V. Maghsoodi, *Sci. Iran.*, **18**, 1397 (2011).
43. Y. Soysal, *Biosyst. Eng.*, **89** (2), 167 (2004).
44. L. V. Mana, T. Orikasab, Y. Muramatsuc, A. Tagawaa, *J. Food Process. Technol.*, **3**, 1000186 (2012).
45. R. K. Toor, G. P. Savage, *Food Chem.*, **94**, 90 (2006).
46. F. H. Sahin, T. Aktas, H. Orak, P. Ulger, *Bulg. J. Agric. Sci.*, **17**, 867 (2011).

КИНЕТИКА НА СУШЕНЕ НА ТЪНКИ СЛОЕВЕ ОТ НЕКТАРИНИ ПРИ IR, MW И ХИБРИДНИ МЕТОДИ

О. Исмаил, А.С. Кипчак*, И. Доймаз, С. Пишкин

Департамент по инженерна химия, Технически университет Йълдъз, 34210, Истанбул, Турция

Постъпила на 13 юни, 2015 г.; приета на 20 януари, 2016 г.

(Резюме)

В тази работа се изследва сушенето на резени от нектарини (*var. nucipersica* или *var. nectarine maxim*) по три различни метода: микровълново (MW), инфрачервено (IR) и хибридно (комбинирани IR и MW). MW-методът е прилаган при мощности между 90 и 600 W, докато IR-методът на сушене е прилага при мощност от 125 W. При хибридния метод последователно се прилагат IR-методът при мощност от 125 W и MW-методът при 180 W. Заедно с описаните методи се прилага и предварително третиране с лимонена киселина. Минимално време за сушене се постига при хибридния метод. Кинетиката на сушене е определена от експерименталните резултати с помощта на математично моделиране. Като най-добър кинетичен модел е определен този на Aghbashlo et al. на базата на висок коефициент на корелация (R^2), малка средно-квадратична грешка (RMSE) и ниска стойност на χ^2-критерия.