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Evaluation of the drying methods and conditions with respect to drying kinetics, colour quality and specific energy consumption of thin layer pumpkins

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In this study, the effects of dry air temperature and power levels when drying pumpkin (Cucurbita pepo L.) slices by five different methods was investigated experimentally. Pumpkin slices were dehydrated by five different drying methods: open-sun, vacuum, microwave, infrared and hot air drying. In particular, the experiments were carried out at two different microwave power levels (90 and 180 W), infrared power levels (83 and 125 W) and hot air temperatures (50 and 70 ºC) to investigate the effects of these factors on the microwave, infrared and hot-air drying, respectively**.** The vacuum drying experiment was carried out in one vacuum oven dryer at a constant temperature of 50 °C and a pressure of 0.1 kPa. The experimental moisture data was fitted to some models (namely Lewis, Henderson and Pabis, Page, Logarithmic, Aghbashlo et al.,Verma et al. and Midilli et al. models) available in the literature and according to the results, the Midilli et al. model is superior to the others in explaining the drying behavior of pumpkin slices. The energy efficiency and diffusion coefficients increased with the increase in microwave power. In terms of colour criteria the best values were obtained by the hot-air and open-sun drying methods.

Keywords:colour, drying models, mathematical models.

INTRODUCTION

In accordance with the botanical classification Cucurbitaceae is part of the Dicotyledoneae class, Cucurbitales team, Cucurbitaceae genus. Approximate 118 kinds and 825 species are present in the Cucurbitaceae genus. In the genus of Cucurbitaceae, Cucurbita pepo L. is a species with a high economic value [1].

Pumpkin (Cucurbita pepo L.) is one of the most important vegetables grown in Turkey. In 2012, pumpkin's world production reached 24616115 tons meanwhile in Turkey its producion was 395986 tons. The five major pumpkin producing countries in the world are China, India, Ukraine, Egypt and the United States [2].

Pumpkins, which grow in the different regions of Turkey, are a seasonal crop and for this reason a processing step is often used to preserve pumpkin products. Depending upon the processing possibilities, inadequateness of seasonal fresh vegetables and fruits, Turkey as well as in many countries are experiencing big economic losses. It was reported that in the developing countries approximately 30 to 40 percent of the seasonal fresh vegetables and fruits are cast away due to spoilage [3].

The excess quantity of agricultural produce can't be consumed immediately and its life span is too short. These products can be kept fresh after special processing. Great numbers of preserving techniques such as freezing, heat treatment, drying etc. are used to increase the endurance of foodstuffs. In food products with respect to protection of the vitamin value, maintenance of a good outward appearance, taste preservation, the emergence of a decreasing mass advantage, the improvement of storage and transportation facilities, drying is the most appropriate method [4, 5].

The most common drying method used for drying fruits and vegetables in the world and in Turkey is open-sun and outdoors drying. Because the solar energy is renewable, clean and cheap, open-sun drying is carried out commonly in the tropical countries. As there are no energy requirements and a maintenance expense, open-sun drying is a cost-effective method. The only disadvantages of drying under the sun in accordance with other processes are that the drying rate is slow and the time is prolonged [6].

Convective drying by hot air is a widely used drying method in the literature. In these kinds of dryers specifical, air speed is practiced by product, the product has a short drying time. Having a simple design, manufactured localy, having a small maintenance and operational cost, drying different

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products according to the season, are among the advantages of these drying systems [7, 8]. During both conventional drying processes, considerable loss in food content takes place. To reduce the food content losses, to preserve the quality of the dried food and to shorten the drying time at low temperatures, the vacuum drying process is successfully applied instead of the conventional methods [9].

Microwave and infrared technology, which has become common in recent years, takes its place in the food industry by shortening the drying time associated with providing quality food. Using microwave driers in combination with hot air live driers increases product quality and energy efficiency [10]. The fundamental principle of microwave heating is provided with the conversion of electromagnetic energy to thermal energy by affecting the polar molecules in the material [11]. Microwave heating systems are successfull drying systems for fruits, cereal crops and many food products which have a high moisture content. In brief, drying with microwaves has the characteristics of 4 important properties; fast processing, energy efficiency, low cost and a high quality of the dried product [12].

As stated in [13], various infrared heat sources could be used for drying applications. IR energy is a form of electromagnetic energy or heat energy. The penetration properties of IR radiation into a given material directly increases the energy flux without burning the material's surface and so the required heating time of the conventional heating method decreases. The advantages of infrared heating by conventional heating can be listed as follows: providing regular heating in a short time, decreasing deterioration and nutritional loss, the equipment has simple and flexible usage areas and considerably economizes the energy consumption.

Drying is also the most energy consuming process in the food industry. New drying methods and dryers must be designed and investigated to minimise the energy cost of the drying process [14].

Although there are some investigations focused on the drying characteristic of the pumpkin, there is too much information on the drying characteristics of the Cucurbita pepo L., which is a subgroup of pumpkin. The objectives of this study are to evaluate and compare the drying kinetics, product quality and specific energy consumption during the drying of pumpkin slices (Cucurbita pepo L.) by five drying methods: (1) hot-air convection drying, (2) open-sun drying (3) the vacuum drying process, (4) IR drying and (5) microwave drying. Two different drying conditions were applied for the microwave, IR and hot-air drying methods. In addition to this, to obtain the best model for the drying kinetics of pumpkin slices; Lewis, Henderson & Pabis, Page, Logarithmic, Aghbashlo et al., Verma et al. and Midilli et al. models were fitted to the experimental data. Also effective moisture diffusivity values were calculated.

MATERIALS AND METHODS

Material

Fresh pumpkin (Cucurbita pepo L.) samples were obtained from a local supermarket in İstanbul, Turkey and stored in a chamber at 15–20 ºC until processing. The initial moisture content of the fresh pumpkin samples was determined using the drying oven (Memmert UM-400, Germany) at 105 ºC for 24 h [15]. These experiments were run thrice to obtain a reasonable average. The average initial moisture content of the pumpkins was found to be 92 % w.b. Before the drying process the pumpkin samples were washed, their top and bottom parts were cut and then the pumpkin samples were cut into 0.5 ± 0.03 cm sized cylindrical slices using a knife.

Drying equipment and IR drying procedure

Drying experiments were carried out in a moisture analyzer with a 250 W halogen lamp (Snijders Moisture Balance, Snijders b.v., Tilburg, Holland). During the infrared drying process, a sample was separated over the entire pan evenly and homogeneously. The power level was set in the control unit of the equipment. The drying experiment was performed at the infrared power levels of 83 W and 125 W. The pumpkin samples (approximately 40 ± 0.2 g) were taken from the dryer at 30 min time intervals during the drying process and their weights were measured with a digital balance (Precisa, model XB220A, Precisa Instruments AG, Dietikon, Switzerland) with an accuracy of 0.001 g. When the samples' moisture content reached approximately 0.08 g water/g of dry matter (dry basis) the drying process was terminated.

MW

The drying experiments were carried out in a Robert Bosch Hausgerate GmbH (Germany) model microwave oven which has a maximum output power of 800 W at 2450 MHz. The microwave oven has the capability of operating at different microwave stages while its power range is 90 to 800 W. The area subjected to microwave drying is 530 mm x 500 mm x 322 mm in size and consists of a rotating glass plate which is 300 mm in diameter at the base of the oven.

The adjustment of the microwave output power and processing time was done with the aid of a digital control apparatus located on the microwave oven. The drying experiments were set at two different microwave power levels of 90 W and 125 W. During drying, the experiments were carried out using the sliced pumpkins known weight of approximately 34±2 g with the thin layer placed on the rotatable plate fitted inside the microwave oven cabin. The rotating glass plate was removed from the oven every 2 min during the drying period and the moisture loss was determined by weighing the plate using a digital balance. The microwave drying process continued until the moisture content reduced to approximately 0.09 g water/g of dry basis of the initial moisture content.

Cabinet dryer

The drying experiments were performed in a cabinet type dryer (APV & PASILAC Limited of Carlisle, Cumbria, UK). It was made up of stainless steel sheets and it consisted of a rectangular tunnel 0.54 m x 1.4 m x 1.02 m in size. The dryer consisted of a centrifugal fan to supply the air flow, an electrical heater and an air filter. The dryer is operated at dry bulb temperatures of 0–200 ºC. The desired drying air temperature was attained by electrical resistance and controlled by the heating control unit. The velocity of the air passed through the system was measured by an anemometer in the range of 0.4–30 ms^{-1} (model AM-4201, Lutron Electronic, Taipei, Taiwan). The air flow was measured directly in the drying chamber. The samples were dried in the perforated square chamber, which had a flow cross-section of 30 cm × 30 cm. Weight loss of the samples was recorded by using a digital balance (Mettler-Toledo AG, Grefensee, Switzerland, model BB3000) with a sensitivity of 0.01 g.

The pumpkin slices of about 100g were distributed uniformly as a single layer at the sample tray and then were dried in the hot air dryer. The hot air drying was carried out by drying the pumpkin samples at 50ºC and 70ºC air temperatures and with a constant air velocity of 1 m/s. Pumpkin samples' moisture loss was measured by a balance and recorded at 30 min intervals. The drying process was finished when the moisture content of the samples achieved approximately 0.07 g water/g of dry matter.

Open air-sun drying

To clean the samples from dust and foreign materials, the selected pumpkin samples were washed with tap water. Open air - sun drying experiments were carried out during the month of August 2014 (from 08.00 a.m. to 20.00 p.m.) in Greece. The pumpkin slices of about 50 g were distributed uniformly as a single layer on the sample tray and then were exposed to sunlight for 12 hours daily. Moisture loss and the ambient air's temperature was measured by a portable digital balance during the drying process at 30 min intervals (Alfais, I2000-1, which has 0–300 g measurement range with an accuracy of ± 0.1 g). When the drying time took more than 12 h to reduce the effect of the increase in moisture content, samples were packed overnight. The ambient air's temperature during the drying experiments was between 36 to 49 °C. The highest air temperature was reached between 10:30 a.m. and 14:30 p.m. The drying process continued until the sample reached the desired moisture level of 9 % (w.b.). The dried samples were packed in low density polyethylene bags.

Vacuum drying oven

Vacuum drying treatment was performed in the laboratory type vacuum oven (Nuve EV 0180, Turkey) with the technical features ~220 V, 50 Hz, 3.5 A and 800 W. The vacuum oven's temperature, which has a sensitivity of 1°C, is a maximum of 250°C. The area of vacuum drying was 30 cm x 20 cm x 25 cm in size. A laboratory type vacuum pump (Carpanelli MMDE80B4, Italy) was used in the vacuum drying operation. Its operating conditions were ~220/240 V, 50/60 Hz and 5.1/4.8 A. The adjustment of the vacuum value and processing temperature was done with the aid of a digital control facility located on the vacuum drying oven. In the drying experiments pumpkin slices' with a weight approximately of 30 ± 2 g and a constant temperature of 50 °C and pressure of 0.1 kPa were used in the vacuum oven dryer. The moisture loss in the pumpkin slices was measured with a balance and it was recorded at 30 min intervals. Good results as a consequence of drying of the pumpkin slices by vacuum drying were not achieved.

Mathematical modelling

Moisture ratio

The moisture ratio (*MR*) and drying rate were calculated using the following equations:

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

where *MR* is the moisture ratio, M_t, M_o and M_e are the moisture content (g water/g dry matter) on a dry basis at any time, initial and equilibrium, respectively. The equilibrium moisture content (*Me*) was assumed to be zero for microwave, infrared drying etc. and the *MR* equation (Equation 1) was simplified as Equation 2 [16]:

$$MR = \frac{M_t}{M_o} \quad , (2)$$

Drying Rate

The drying rate during the experiments was calculated using the following formula:

$$\frac{dM}{dt} = \frac{M_{t+dt} - M_t}{dt} \quad , (3)$$

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

Effective moisture diffusivity

The effective moisture diffusivity is therefore calculated by the following equation [17]:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2.\pi^2.D_{eff}}{4L^2}.t\right] (4)$$

where, D_{eff} is the effective moisture diffusivity (m^2/s); L is the half-thickness of the slab in the samples (m); and n is a positive integer. In practice, only the first term of Eq. (4) is used to yield [18]:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff}\, t}{4L^2}\right] \quad (5),$$

The effective moisture diffusivity (D_{eff}) was also typically calculated by using the slope of Eq. (5). A straight line with a slope of k_o was obtained when ln(MR) was plotted versus the time:

$$k_o = \frac{\pi^2 D_{eff}}{4L^2} \quad (6),$$

Using the slope value of (Eq. 6), the effective moisture diffusivity could be determined.

The statistical modelling procedure

In order to determine the moisture ratio as a function of drying time, seven different thin-layer drying models, namely Lewis, Henderson & Pabis, Page, Logarithmic, Aghbashlo et al., Verma et al. and Midilli et al. models were used (Table 1).

Statistical analysis

The statistical analysis of the experimental data was determined using the STATISTICA computer program. Three criteria of statistical analysis were used to evaluate the adjustment of the experimental data to the different models; the coefficient of determination (R^2), reduced chi-square (χ^2) and root – mean-square error (RMSE). The parameters can be calculated as follow:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - z} \quad , (7)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \quad , (8)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted dimensionless MR, respectively, N is the number of the data values and z is the number of constants of the models. Higher R^2, smaller $\chi 2$ and RMSE values indicated a better fit of the experimental data to the model [26].

Table 1. List of models.

Model name	Model	Reference
Lewis	$MR = \exp(-kt)$	[19]
Henderson and Pabis	$MR = a\exp(-kt)$	[20]
Page	$MR = exp(-kt^n)$	[21]
Logarithmic	$MR = a\exp(-kt) + c$	[22]
Aghbashlo et al.	$MR = exp\left(-\frac{k_1 t}{1+k_2 t}\right)$	[23]
Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	[24]
Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	[25]

Colour measurement

The sample colour before and after the drying process was measured using a Chromameter CR - 400 (Minolta, Japan). For the dried samples three parameters L, a and b, which indicate the brightness (on a lightness–darkness scale), greenness-redness and blueness-yellowness respectively, were used to study the changes in colour. The Chroma was determined using the following equation [27].

$$C^* = \sqrt{a^2 + b^2} \quad , (9)$$

Energy consumption

Energy consumption in the infrared

In the IR dryer, sum of the energy was consumed by the IR lamp to dry the pumpkin samples.

E_t is the total energy consumption during the infrared drying that is calculated using the following equation (10).

$$E_t = P * t \quad , (10)$$

where E_t is the total energy consumption (kWh), P is the infrared power level (kW), t is the drying time (h).

Energy consumption in the microwaves

The energy consumption value required for drying pumpkin slices in the microwaves was calculated with Equation (11) [28].

$$E_t = P * t \quad , (11)$$

where E_t is the total energy consumption (kWh), P is the microwave power output (kW), t is the drying time (h).

Energy consumption in the hot air

In hot air drying, the total energy consumption was due to the drying and blowing of air by an electric heater and fan, respectively. The total energy consumption value was calculated from Equation (12) [29]:

$$E_t = \rho_a A v c_p \Delta T * D_t \quad , (12)$$

where E_t is the total energy consumption (kWh), ρ_a is the air density (kg/m^3), A is the cross sectional area of the container (m^2), herein a sample is placed, υ is the air velocity (m/sec), c_p is the specific heat (kJ/kg °C), ΔT is a temperature difference between the air inlet and outlet of the dryer (°C), D_t is the total drying time of each sample (h).

Calculation of the specific energy consumption

The total energy consumption of the drying process was evaluated through the Specific Energy Consumption (SEC). Electrical energy was consumed during the drying process. The specific energy consumption, which is a measure of the energy needed to evaporate a unit mass of water from the product, was calculated using the following equation [30]:

$$Q_s = \frac{Q_t}{m_w} \quad , (13)$$

where Q_s is the specific energy consumption in kWh *kg^{-1}[H_2O], Q_t is the consumed energy in kWh, m_w is the mass of vaporized water in kg [H_2O].

RESULTS AND DISCUSSION

Drying curves

Figure 1 shows the moisture ratio as a function of drying time for the different drying methods and conditions.

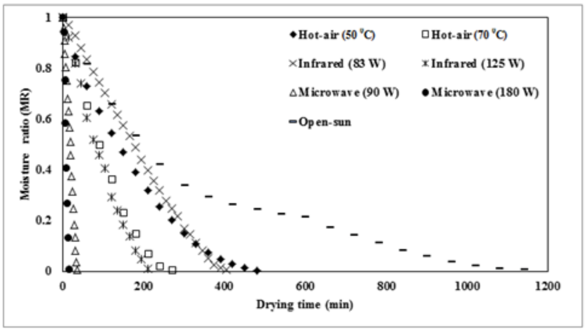

Fig. 1. Drying curves of pumpkin slices at different drying methods and conditions.

As seen from Figure 1, the drying time was quite different for four drying methods to reach the final moisture ratio. The drying time of the dried pumpkin slices with different drying methods ranged from 14 to 1140 minutes. The drying curves are typical and similar to fruits and vegetables. In Fig. 1 it is discerned that the increase in the microwave power level [31, 32], air temperature [33, 34] and infrared power level [35] shortened the drying period in microwave drying, air-drying and infrared drying, respectively. The moisture ratio decreases gradually with the increases in drying time, exhibiting a downward curve. The figure also indicates that the drying time for microwave drying is much shorter than the hot air, infrared and open-sun drying. The time required to reduce the moisture ratio from 1 to 0.006 ranged between 14 and 36 min at two power levels with microwave drying, while it ranged between 270 and 480 min at two temperatures with hot air drying, while it ranged between 210 and 405 min at two power levels with infrared drying. To reach the desired final moisture content, 14 minutes drying time indicated the high efficiency of the microwave drying method (180 W), which was about 82 times faster than open-sun drying. The drying time of pumpkin slices dried under the sun was determined as 19 h.

The drying time was much faster than for the other drying methods as compared to the conditions by microwave drying of pumpkin slices. For this reason, the drying rate (g water)/(g dry matter*min) curves are shown in the two different figures as Figure 1 and 2 in order to clearly see the drying rate curves.

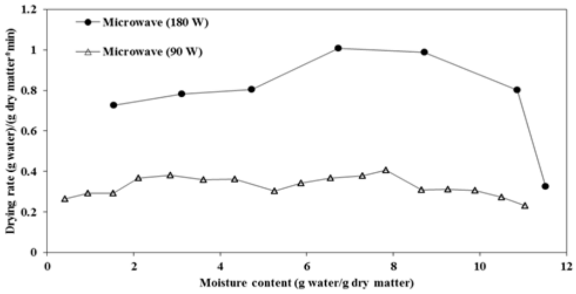

Fig. 2. Drying rate versus moisture content of pumpkin slices at two different microwave power levels.

Since the initial moisture content of the pumpkin slices was relatively constant (11.5 g water/g dry matter), the difference in the drying time requirements was considered mainly due to the difference in the drying rates. The drying rate curves for pumpkin slices dried at two microwave output power levels (90 to 180 W) are given in Figure 2. Depending on the drying conditions, the average drying rates of pumpkin slices ranged from 0.407 to 1.008 (g water)/(g dry matter*min) for the output power between 90 and 180 W, respectively. The moisture content of the pumpkin (92% w.b.) 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 time progressed, the moisture loss in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. Higher drying rates were determined at higher microwave output power levels. Thus, the microwave output power level had a crucial effect on the drying rate.

The variation of drying rate with moisture content for the different drying conditions of hot air, infrared and open-sun drying are shown in Figure 3.

As expected, the drying rate would decrease as the moisture content decreases. As can be seen from these figures, no constant rate period exists. All the drying processes occurred in the falling rate period. In the infrared drying experiments (83 and 125 W) initially rising but after a while falling the drying rate period is present. The experiment, in which the infrared power level is 125 W, the rising drying rate period is clear by far. During the falling drying rate period, the predominant mechanism is the internal mass transfer. The open sun drying experiment lasted for approximately 19 h. Consequently, a small rising drying rate period formed in the figure that originated as a result of the drying process continued the next day. Similar results were reported by [36, 14, 37].

Mathematical Modelling of Drying Data

The values of R^2, $\chi 2$ and RMSE were calculated and given in Table 2.

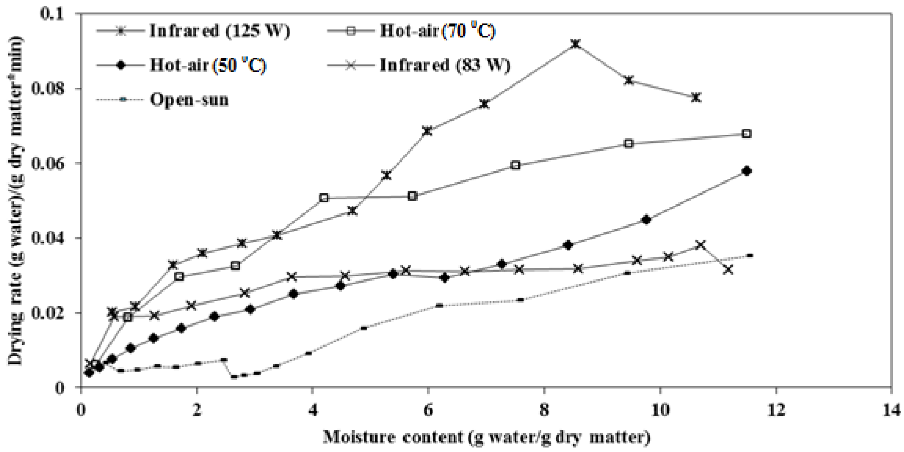

Fig. 3. Drying rate versus moisture content of pumpkin slices at different drying methods and conditions.

Table 2. Statistical results obtained from the selected models.

Models	Drying methods	Drying conditions	R^2	χ^2	RMSE
Lewis	Infrared	83 W	0.9304	0.007238	0.083527
	Infrared	125 W	0.9563	0.004683	0.066081
	Microwave	90 W	0.8991	0.010951	0.101825
	Microwave	180 W	0.8982	0.013873	0.110176
	Sun	36 to 49 °C	0.9864	0.001048	0.031551
	Hot - air	50 ºC	0.9826	0.001724	0.040277
	Hot - air	70 ºC	0.9673	0.004022	0.060163
Henderson & Pabis	Infrared	83 W	0.9803	0.005327	0.070318
	Infrared	125 W	0.9676	0.003731	0.056838
	Microwave	90 W	0.9247	0.008652	0.087956
	Microwave	180 W	0.9211	0.012548	0.097011
	Sun	36 to 49 °C	0.9876	0.001007	0.030106
	Hot - air	50 ºC	0.9846	0.001626	0.037867
	Hot - air	70 ºC	0.9728	0.003757	0.054825
Page	Infrared	83 W	0.9912	0.000947	0.029651
	Infrared	125 W	0.9937	0.000719	0.024955
	Microwave	90 W	0.9907	0.000754	0.025974
	Microwave	180 W	0.9946	0.000854	0.025309
	Sun	36 to 49 °C	0.9904	0.000780	0.026491
	Hot - air	50 ºC	0.9937	0.000664	0.024207
	Hot - air	70 ºC	0.9959	0.000562	0.021209
Logarithmic	Infrared	83 W	0.9982	0.000193	0.013117
	Infrared	125 W	0.9974	0.000318	0.015943
	Microwave	90 W	0.9973	0.000324	0.016517
	Microwave	180 W	0.9932	0.001284	0.028329
	Sun	36 to 49 °C	0.9878	0.001048	0.029848
	Hot - air	50 ºC	0.9989	0.000118	0.009865
	Hot - air	70 ºC	0.9970	0.000474	0.018212
Aghbashlo et al.	Infrared	83 W	0.9304	0.007516	0.083527
	Infrared	125 W	0.9563	0.005044	0.066081
	Microwave	90 W	0.8991	0.011595	0.101825
	Microwave	180 W	0.8982	0.016185	0.110176
	Sun	36 to 49 °C	0.9903	0.000785	0.026586
	Hot - air	50 ºC	0.9825	0.001839	0.040277
	Hot - air	70 ºC	0.9673	0.004524	0.060163
Verma et al.	Infrared	83 W	0.9583	0.004685	0.064667
	Infrared	125 W	0.9780	0.002743	0.046818
	Microwave	90 W	0.9758	0.002956	0.049879
	Microwave	180 W	0.9868	0.002509	0.039598
	Sun	36 to 49 °C	0.9890	0.000944	0.028327
	Hot - air	50 ºC	0.9866	0.001510	0.035258
	Hot - air	70 ºC	0.9847	0.002419	0.041154
Midilli at al.	Infrared	83 W	0.9994	0.000070	0.00775
	Infrared	125 W	0.9984	0.000216	0.012588
	Microwave	90 W	0.9991	0.000113	0.009452
	Microwave	180 W	0.9986	0.000315	0.012555
	Sun	36 to 49 °C	0.9924	0.000692	0.023526
	Hot - air	50 ºC	0.9987	0.000151	0.010758
	Hot - air	70 ºC	0.9990	0.000170	0.010089

Table 3. Colour parameters of fresh and dried pumpkin slices.

Drying methods	Drying conditions	Colour parameters			C^*
		L	**a**	**b**	
	Fresh	67.75	11.06	21.77	24.41
İnfrared	83 W	49.73	12.80	10.66	16.65
	125 W	47.75	14.42	10.74	17.98
Microwave	90 W	67.19	0.59	27.28	27.28
	180 W	57.11	3.89	26.31	26.59
Hot - air	50 ºC	68.95	11.91	25.65	28.28
	70 ºC	68.68	11.58	26.75	29.15
0pen - sun	31 - 46 ºC	70.63	11.12	24.2	26.63

Table 4. Effective moisture diffusivity values for the various drying methods.

Drying methods	Drying conditions	D_{eff} ($m^2 s^{-1}$)
İnfrared	83 W	3.24×10^{-10}
	125 W	6.09×10^{-10}
Microwave	90 W	0.85×10^{-7}
	180 W	2.48×10^{-7}
Hot - air	50 ºC	2.78×10^{-10}
	70 ºC	9.38×10^{-10}
0pen - sun	31 – 46 ºC	2.96×10^{-11}

Thin-layer drying models, in other words the Lewis, Henderson and Pabis, Page, Logarithmic, Aghbashlo et al., Verma et al. and Midilli et al. were used to describe the drying process during the drying of pumpkin slices.

In order to describe the moisture ratio as a function of drying time with different drying methods, 7 different drying models were fitted to the experimental data and their coefficient of determination (R^2), reduced chi-square (χ^2) and root–mean-square error (*RMSE*) were calculated. R^2, RMSE and $\chi 2$ statistical data with respect to 7 different drying models are given in the Table 2. The grade of fitting was determined by the lowest χ^2 and *RMSE* and the highest R^2 values.

From Table 2, the statistical data with respect to 7 different drying models used for explaining the drying circumstance occurred in the falling rate drying period was examined individually and using the Midilli et al. model and provided the minimum error for a separable moisture rate. At drying the process of pumpkin slices' standard error (*RMSE*) of prediction conducted by this model ranged from 0.00775 to 0.023526. In addition to this as seen from the table, the chi-square (χ^2) values ranged from 0.000070 to 0.000692 which are close to zero. Adequacy of modelling ranged from 0.9994 to 0.9924.

Effect of drying methods and conditions on the colour of pumpkin slices

Before and after the drying process, the L (lightness), a (greenness), b (yellowness) and C* (Chroma) values of pumpkin slices were measured and these results are given in Table 3.

One of the quality of the parameters of food and agricultural product is the colour parameter. Too much colour changes influence the marketing negatively by affecting the quality of the product. It is an index of the inherent good qualities of a food and the association of colour with the acceptability of a food is universal. Among the several basic quality characteristics of dried pumpkin slices the colour is an important one which indicates the effect levels of different drying methods or conditions. As stated previously, the L term stands for brightness, the a term is for a green-red balance, the b term is for a blue-yellow balance, the Hunter colour ratio and the chroma are measures for the colour purity. Values for the L, a, b and chroma (C*) coordinates of the fresh pumpkin slices were 67.75, 11.06, 21.77 and 24.41, respectively.

In general, the infrared drying at 83 and 125 W produced no remarkable changes in the colour parameters of the pumpkin slices as compared with the fresh pumpkin. However, the increase of power level from 83 W to 125 W caused an increase of the a and b values and a decrease of the L value. The microwave irradiation drying at 90 W allowed the obtaining of a product which was more similar to the fresh sample when the lightness was considered since the L value varied only from 67.75 to 67.19. When comparing the values obtained for the opposing colour parameters between the fresh sample and the pumpkin slices dried at 90 W, the a decreased from 11.06 to 0.59, showing that the red colour decreased with the drying process. As for the b, it increased slightly from 21.77 to 27.28, the dried samples were more yellow. These observations are corroborated with the increase from 24.41 to 27.28 in the value of the chroma. The dried pumpkin at 180 W turns into the final product as much lighter, much less red and more yellow with L, a and b values for which the values are 57.11, 3.89 and 26.31, respectively. The colour criteria obtained from the air drying experiments using 50 and 70 °C temperatures are given in Table 3. According to this the colour is closest to the fresh product when the air drying process's temperature is 50°C and 75°C. When the drying air temperature increased from 50 to 75 °C; the L, a values decreased and b values increased. These results were consistent with the observations made by different authors on the drying of pumpkin (Cucurbita pepo L.) slices [38, 39]. As seen from Table 3, the best colour values were achieved during the open sun drying and these values are the closest to the fresh material. This is followed by hot air-drying, microwave drying and infrared drying successively. Similar findings are also available in the literature [40, 41].

Determination of Effective Moisture Diffusivity

The effective moisture diffusivity was calculated using the method of slopes. Effective diffusivities are typically determined by plotting the experimental drying data in terms of ln (MR) versus time. From the Eq. (6), a plot of ln (MR) versus time gives a straight line with a slope (k_o). This slope is the measure of the diffusivity. The effective diffusivity values for various drying methods and conditions are presented in Table 4.

Among the four drying methods, microwave drying offered the highest values of D_{eff} for microwave power levels of 90 and 180 W. In microwave drying, the D_{eff} values increased with the increasing drying microwave power. If samples were dried at higher microwave power, increased heating energy would increase the activity of the water molecules leading to a higher moisture diffusivity. The value of D_{eff} for infrared and hot-air drying was slightly higher than the open sun drying. In drying pumpkin slices by the infrared and hot-air drying methods, the effective moisture diffusivity value increases with increasing power and temperature. In foods the effective moisture diffusivity values are in the range of 10^{-12} to 10^{-6} m^2/s and the accumulation of values is in the region 10^{-10} to 10^{-8} m^2/s (75%) [42, 43]. In the literature there is no study associated with the drying of pumpkin slices (Cucurbita pepo L.) with infrared and open sun drying. Some studies dealing with the drying of pumpkin slices with microwaves are available in the literature but data about the effectiveness of moisture diffusivity does not exist.

The D_{eff} value of pumpkin slices (Cucurbita pepo L.) [8] undergoing hot-air drying at 50 and 60 ºC was in the range of 3.38×10^{-10} to $9.38 \times 10^{-10} m^2/s$, respectively.

Energy consumption

The energy consumption values obtained in the drying trials carried out with three different drying methods are given in Figure 4.

When three different drying methods were compared with the energy consumption values, the lowest energy consumption occurred in the microwave drying method and this was followed by the infrared and hot-air drying methods. Energy consumption is zero for the open sun drying so this drying method isn't accounted for in Figure 4. As seen in Figure 4, the total energy consumption decreases with the increasing air temperature and power level. The best result with regard to energy consumption was obtained for microwave drying at the 180 W power level. The energy consumption at this level was 0.042 kWh. Among all the drying methods the highest value with respect to the energy consumption was obtained for the hot-air drying process at a temperature of 50ºC and 1.35 kWh. Th energy consumption was 0.042–0.054, 0.44–0.56 and 0.75–1.35 kWh for microwave, infrared and hot-air drying, respectively. As a result, the energy consumption in the drying processes carried out at low temperature and power levels which yielded a longer drying period was determined to be at higher rates. These results agree with the observations of previous researchers [44, 45].

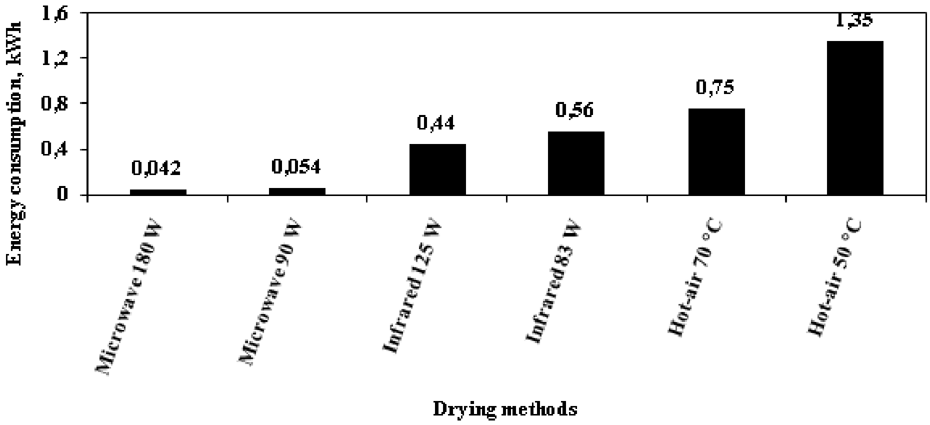

Fig. 4. Energy consumption versus different drying methods of pumpkin slices during the drying process.

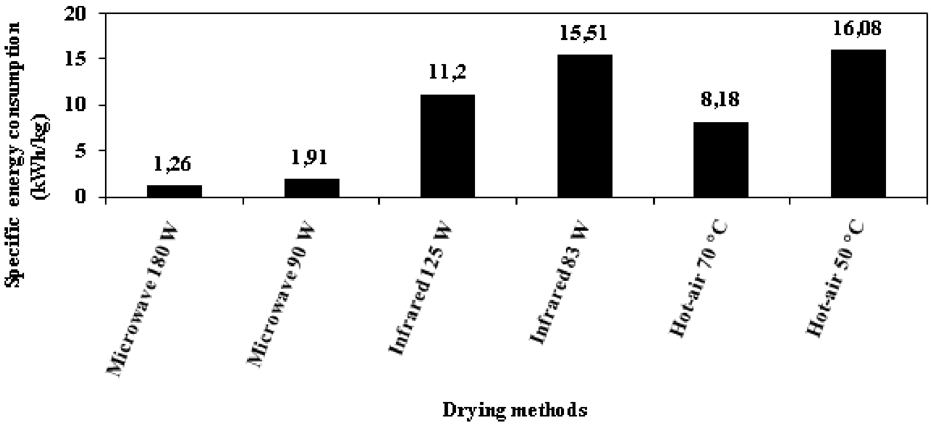

Fig. 5. Specific energy consumption versus different drying methods and conditions for drying of 1 kg wet product.

Specific energy consumption

The specific energy consumption was determined by considering the total energy supplied to dry pumpkin samples from an initial moisture content of about 11.5 g water/g dry matter to a final moisture content of approximately 0.05 to 0.10 g water/g dry matter in all three dryers.

The specific energy consumption of the drying process under the different drying methods and conditions was calculated by Equation (13) and this graph is given in Figure 5.

As can be understood from Figure 5, a minimum heat energy (1.26 kWh/kg) is needed by the microwave drying method to dry 1 kg of pumpkin slices. The maximum energy (16.08 kWh/kg) is needed for the hot-air drying method. Because of a minimum of heat energy consumption (1.26 kWh/kg) and less drying time (14 min) it can be said from Figure 5 that the microwave drying method must be selected for drying the fresh pumpkin samples. Again as seen from Figure 5, reducing the specific energy consumption was observed by the increase in power level and temperature. These results are similar to those reported by the researchers for the other products [46, 47, 28, 48].

CONCLUSION

The pumpkin (Cucurbita pepo L.) has an important place for our country's vegetable production. Obtaining new products by drying pumpkin slices will increase the income gained from pumpkin production/processing and this situation will allow for the consumption of pumpkin all the year round. Researchers were motivated to prospect using different combinations of drying technologies because of the increasing trends in energy cost, product quality and product quantity.

Based on the conducted experiments, we can draw the following conclusions. The vacuum drying process is not suitable for the drying of pumpkin slices. The best result based on the drying period, coefficient of diffusion and specific energy consumption was obtained by the microwave drying method at the 180 W output power level.

In drying pumpkin slices by this method, the drying period was found to be 14 min, the coefficient of diffusion was 2.48 x 10^{-7} m^2s^{-1}, the energy consumption was found to be 0.042 kWh and the specific energy consumption was found to be 1.26 kWh/kg.

For the foodstuffs high "L", "b" and low "a" values are important parameters.

The measured colour parameters of the dried samples compared to fresh, the best colour quality was obtained in the pumpkin slices dried by the hot-air and open-sun drying methods.

The experimental data was obtained as a consequence of drying pumpkin slices by five different drying methods and the conditions were modelled with seven different thin layer drying models available in the literature. The Midilli et al. model, which will be used for determining the changing of the product's moisture content, has a high modelling efficiency. Therefore it is possible to obtain results very close to the experimental values.

The opinion is that the microwave drying method can be easily applied industrially and offers uniform high quality products to the consumer.

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ОЦЕНЯВАНЕ НА МЕТОДИТЕ И УСЛОВИЯТА НА СУШЕНЕ СПОРЕД КИНЕТИКАТА, КАЧЕСТВАТА НА ЦВЕТОВЕТЕ И СПЕЦИФИЧНАТА ЕНЕРГИЯ НА СУШЕНЕ НА ТЪНКИ СЛОЕВЕ ОТ ТИКВА

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(Резюме)

В тази работа са изследвани експериментално температурата на сушене на резени от тиква (Cucurbita pepo L.) и нивата на мощността. Образците са дехидратирани по пет различни метода: на открито, под вакуум, микровълни, инфрачервени лъчи и горещ въздух. Две нива на мощността са изпитани както следва: микровълни (90 и 180 W), инфрачервени лъчи (83 и 125 W) и горещ въздух (50 и 70 ºC), за да се изследва ефекта на тези методи. Вакуумното сушене е изследвано при постоянна температура от 50 °C и налягане от 0.1 kPa. Опитните данни за влагата са обработени по различни модели, известни в литературата (на Lewis, Henderson§Pabis, Page, логаритмичен, Aghbashlo и др., Verma и др. и Midilli и др.). Според тези резултати моделът на Midilli и др. превъзхожда останалите в хода на сушенето на образците. Енергийната ефективност и дифузионните коефициенти нарастват с нарастване на мощността на микровълните. От цветова гледна точка най-добри резултати се получават при сушене с горещ въздух и на открито.