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Development and Performance of A Temperature-Controlled Microwave Dryer

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ABSTRACT

The present study was conducted to dry apples in a Temperature-Controlled Microwave (TCM) drier under optimum conditions. Drying durations, drying curves, color changes and drying models were analyzed. Within the scope of this study, TCM drying, oven drying, shade and sun-drying methods were experimented. Apples were sliced into four and eight pieces and dried at 50, 60 and 70°C drying temperatures in three replicates. The shortest drying time (30 minutes) was achieved in temperature-controlled microwave drying and the longest drying time (287 hours) was observed in shade-drying method. TCM drying best preserved the color parameters. Lightness and redness values were best preserved with TCM drying at 70°C in four slices and yellowness value was best preserved with again TCM drying at 50 and 60°C temperatures in four slices. Chroma values were best preserved with temperature-controlled microwave drying at 50°C in eight slices. Considering the drying durations and color parameters, TCM drying was identified as the best method for drying apple.

Keywords: Apple dryer, Color preservation, Drying curves, Drying kinetics.

INTRODUCTION

Fresh vegetables and fruits generally have 80-90% moisture and they have quite short shelf life in fresh forms. Therefore, they can spoil easily in short time (Viboon, 2006). Drying is a preservation method used for several products since the ancient times. In essence, it is the removal of moisture from an agricultural commodity under controlled conditions (Tugrul *et al.,* 2001). There are many methods applied for drying agricultural products according to the type and application of heat. One of them is the microwave drying method. In microwave dryer, electromagnetic rays create heat by vibrating the water molecules in the product too much per unit time. The formation of heat in the product ensures higher moisture diffusion compared to other methods. This significantly reduces the drying time and energy consumption (Motevali *et al.,* 2011). High levels of temperature occur when drying the product with the microwave. The surface temperature values measured at 180, 540, 720 and 900 W power values of peach slices varied between 34.50-83.40 °C, 49.60-89.60 °C, 55.90-94.06 °C, and 68.20-145.20 °C, respectively. With this high temperature, the pulp of the fruit is carried to the surface of the material and it turns black and sometimes caramelized (Tasova *et al.,* 2020). To improve the performance and overcome these stated problems, microwave is generally combined with hot air drying, freeze-drying, vacuum drying, spouted bed drying and osmotic drying (Andres *et al.,* 2004; Kumar and Karim, 2019). Since all other hybrid dryers applied to microwave dryers are long in terms of drying time, the total drying time will be long. For this reason, it is thought that it would be more appropriate to control the drying temperature

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compared to the dried material with minimal changes in microwave dryers (temperature, power, time-controlled mw) (Bae *et al.,* 2017; Ambros *et al.,* 2018)

Apples were used in the present study as the drying material. Several researchers used microwave or hybrid dryers to dry apple. Polat *et al.* (2019) performed apple drying studies of 200 and 400 mmHg vacuum pressure values and 200 and 300 W microwave power values. They found the highest amount of potassium at 300W-200 mmHg drying conditions. Dai *et al.* (2019) investigated the effects of different microwave power densities (2.2, 3.5, 4.8, and 6.1 W g^{-1}), sample thicknesses (3, 5, 7, and 9 mm) on drying properties, and on visual and color quality values. They found that the appearance, texture, and general evaluation score of the process performed at 6.1 W g^{-1} power density was lower than the other methods. Li *et al.* (2019) carried out a coal drying study in the microwave oven by keeping it for 60, 120, 180, 240, 300 hours. Maximum temperature values occurring on the material surface was 101, 165, 203, 222 and 296ºC. The present literature review revealed that there are few studies in which the temperature is controlled in a microwave dryer and the dried product is compared with the other methods in terms of quality criteria.

In this study, we aimed to: (i) Determine drying kinetics of apples and color analyses on fresh and dried samples, (ii) Conduct drying experiments in a TCM drier designed within the scope of this study and observe samples dried naturally in shade and sun and in a drying oven, and (iii) Determine optimum drying conditions for apple drying in TCM drier and compare with the other methods.

MATERIALS AND METHODS

Drying Material

Apple samples to be used in drying experiments were supplied from a local supermarket in Tokat, and apples were preserved in a fridge at +4°C until the time of experiments.

Moisture Analyses

Before drying process, 55-60 g samples were taken in 4 replicates to determine initial moisture content of the samples. Samples were dried in an oven at 70ºC until a constant weight (Abuşka and Dogan, 2010) and then moisture contents were calculated by using fresh and dry weights of the samples.

Design of Temperature-Controlled Microwave Dryer

TCM dryer is composed of 3 main components (Figure 1). These are microwave oven, infrared temperature sensor, and microprocessor control board. Microwave oven was Kenwood brand with 800W output power. Infrared temperature sensor was Optris brand CT LT model non-contact temperature sensor with a measurement range of -50 and 975ºC. Microprocessor control board allows both temperature and time control. Some modifications were made in installation of the three main components. For sensor (3) and oven (4) installation, a metal (2) piece 5 cm high was placed over the microwave. Microwave oven on is a control panel (1) to control the drying temperature. Then, a hole was opened at the center of the metal piece until 1 mm to the base. A hole of 2.8 mm diameter was opened at the bottom of this metal and sensor reader head was fixed over the metal. In this way, the sensor with reading arrays was prevented from microwave rays. Sensor reading ray passes through the narrowest section at 5 cm distance and forms an array (Figure 2).

A control panel was installed to adjust microwave temperatures and microwave standing time. The microprocessor software was developed to operate temperature

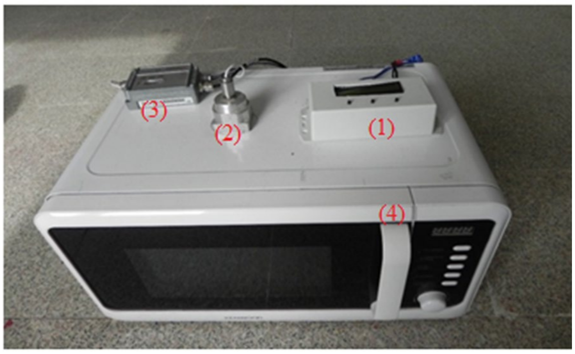


Figure 1. Temperature-controlled microwave drier: (1) Temperature control panel, (2) Non-contact infrared temperature sensor, (3) Temperature sensor display, (4) Microwave oven.

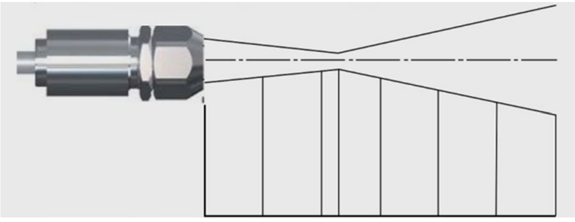


Figure 2. Fan reading pattern of non-contact infrared temperature sensor.

control panel. These temperature values would be achieved by the energy produced in the apple by the magnetron in the microwave oven. These determined drying temperatures would be controlled via the designed control panel.

There is an input and output point of the temperature sensor. Input point is the point where temperature-reading head is placed and output point is the place from where measured temperature value are transferred to the computer. Non-contact infrared temperature sensor has analog values selectable within the range of 0 4-20 mA^{-1}, 0-5, and 0-10V.

Temperature-Controlled Microwave Drying Method

About 60-70 g sample was used in TCM dryer. Drying was performed at 50, 60 and 70ºC temperatures. There was ±4.5ºC deviation from the targeted drying temperature. Standing time was specified as 10 seconds and this time indicates the period in which the microwave oven should be "off" when the product temperature reached the drying temperature. Temperature and standing periods were inputted into the control panel and drying process went on automatically.

Oven-Drying Process

About 50-60 g samples were dried at 50, 60 and 70ºC. Precise scale was used to determine the weight changes during the drying process.

Sun and Shaded-Open Atmosphere Drying Process

About 50-60 g samples were naturally dried in four replications. Drying materials were placed in paper plates and dried over folding wire shelves.

Color Measurements

Color measurements were performed on fresh and dried samples. Minolta brand CR300 model color-meter was used in color measurements. Hunter Lab Chroma-meter color values of L, a, b were measured. These values are: " L " indicates the Lightness of the material and ranges between 0-100 with 0 representing the darkest black (no reflection) and 100 representing the brightest white (full reflection). " a " indicates the colors of red-green and " b " indicates the colors of yellow-blue, and they respectively take (+, -) values. The color is indicated as grey when a= 0 and b= 0 (McGuire, 1992). Chroma is another color parameter and indicates the tone of the color. It gets lower values at pale colors and higher values at vivid colors. Chroma value (Kavdır *et al.,* 2007) and Hue angle (Agudo *et al.,* 2014) were calculated by using the following equations;

$$C = (a^2 + b^2)^{1/2} \tag{1}$$

$$h^\circ = \tan^{-1}\left(\frac{b}{a}\right) \tag{2}$$

Here; a: red/green of the product, b: yellow/blue, C: the color's chroma, hue: the color's equivalent in 360 degrees angle.

Browning Index (BI) and "x" values (Plou *et al.,* 1999) were calculated by using the following equations;

$$BI = \frac{[100(x - 0.31)]}{0.17} \tag{3}$$

x: It is a coefficient used in the calculation of the browning index.

$$x = \frac{a + (1.75\,xL)}{[(5.645\,xL) + (a - (3.012\,xb))]} \tag{4}$$

Drying Model

Time-dependent moisture release of dried apples was calculated by using the following equation;

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{5}$$

Where, MR: Released Moisture Ratio; M: Instantaneous Moisture of the material (g moisture g DM^{-1}, DM: Dry Matter), $M_{e:}$ Equilibrium Moisture of the material (g moisture g DM^{-1}), $M_{0:}$ Initial Moisture of the material (g moisture g DM^{-1}).

Pestano *et al.* (2018) and Darniadi *et al.* (2018) used Equation 5 to determine the receivable moisture content rate of the product. Yağcıoğlu (Polatcı and Taşova, 2017), Midilli-Küçük (Midilli *et al.,* 2002) and Page (Page, 1949) models were selected to model the moisture changes of the drying process. The model equations are presented below:

Yağcıoğlu, $MR = k.\exp(-h.t)+j$ (6)

Midilli-Küçük, $MR = h.\exp(-j.t^k)+(m.t)$ (7)

Page, $MR = \exp(-h.t^k)$ (8)

Over the drying curves, model coefficients, variance analysis p (0.05) values and R^2 values were determined. The k, h and t values in the model indicate the model coefficients.

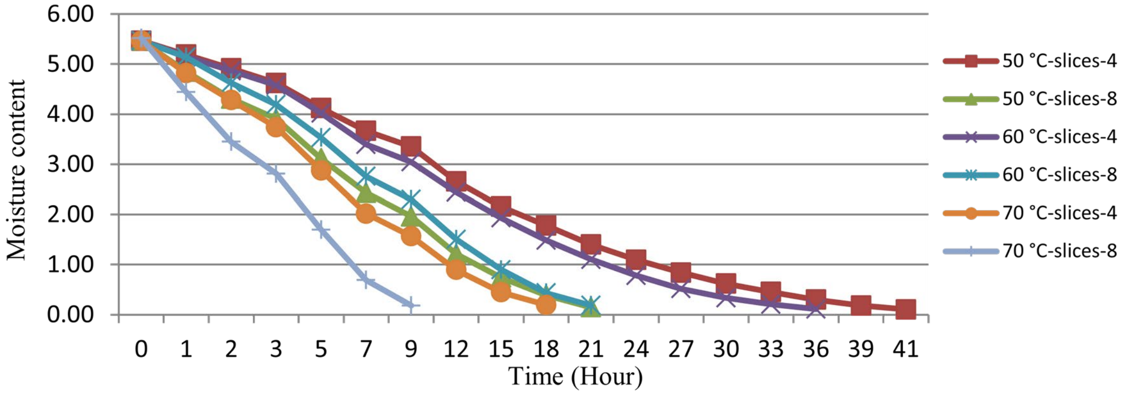
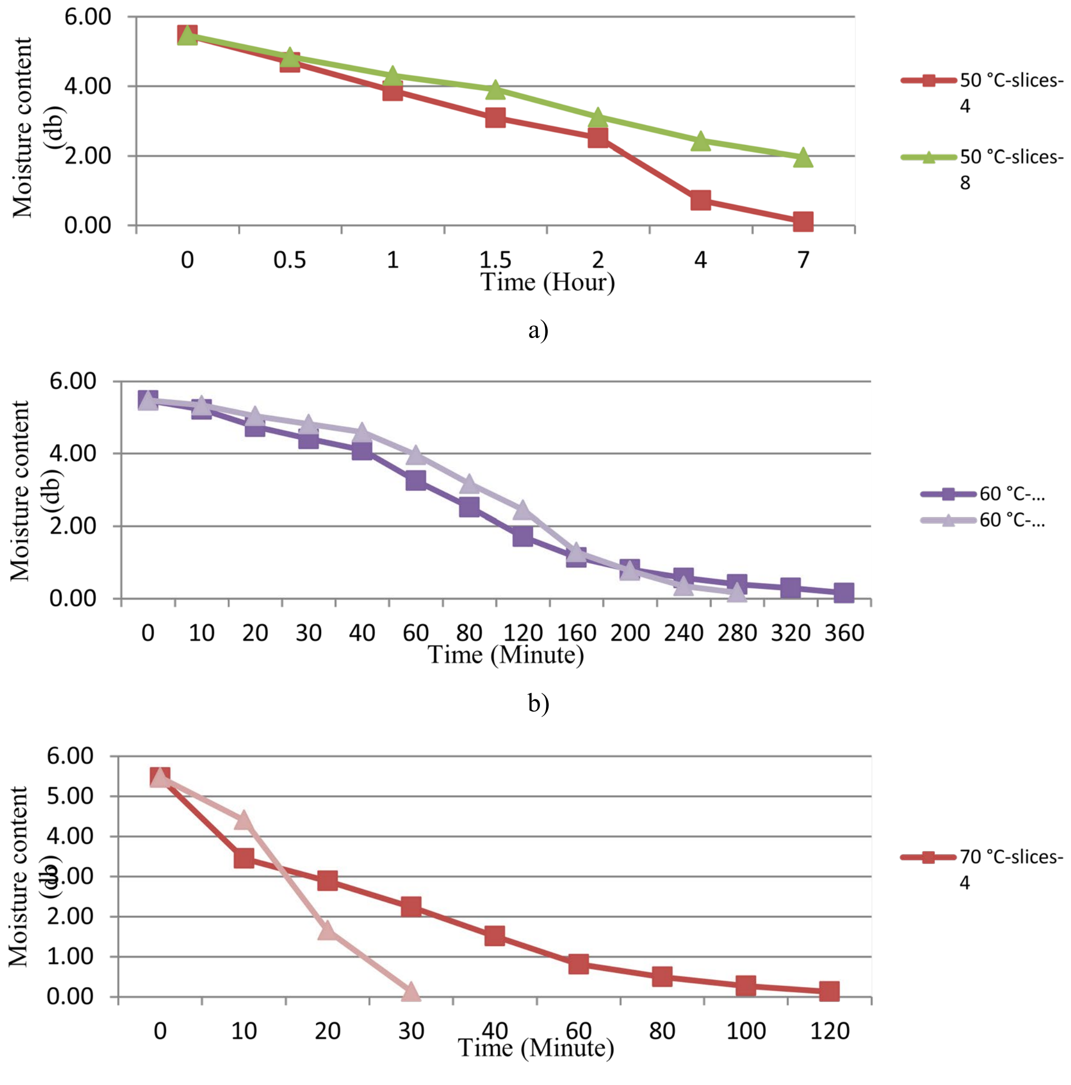


Figure 3. Moisture rate values of dried apple slices depending on the time.



a)

b)

c)

Figure 4. Change in moisture content (d.b.) of dried apple slices depending on the time: (a) 50ºC drying temperature, (b) 60ºC drying temperature, (c) 70ºC drying temperature.

Statistical Analysis

Experimental data on fresh and dried samples were subjected to variance analysis with the use of SPSS20 software and significant means were compared with the use of Duncan's multiple range test. Statistical analysis of the data R^2 of the drying curves ($P< 0.05$) was determined by processing in SigmaPlot10.

RESULTS AND DISCUSSION

Drying Performance Values

With drying processes, moisture level of the apple samples was reduced to 10-13% levels in fresh basis. Total drying time and average final moisture levels of the four drying methods are provided in Table 1. In the review study on the drying of seedless raisins,

Table 1. Final moisture content of dried apples (% wb) and drying time.

Dryer type		Slices	Moisture content (% wb)	Drying time (h)
Oven	50°C	8	12.86±0.81	21
		4	9.41±0.70	41
	60°C	8	15.68±0.66	21
		4	10.16±0.33	36
	70°C	8	14.71±0.28	9
		4	16.24±0.19	18
Temperature-Controlled microwave dryer	50°C	8	15.00±0.09	6
		4	9.74±0.98	7
	60°C	8	14.41±0.21	4.5
		4	13.35±0.33	6
	70°C	8	11.61±1.02	0.5
		4	11.23±1.10	2
Sun drying		8	17.48±0.23	72
		4	16.87±0.18	168
Shaded-open atmosphere drying		8	8.13±1.26	216
		4	9.40±1.14	287

Akdeniz (2011) stated that the range of 14-15% of the final moisture level of the product may be appropriate. The longest drying time (287 hours) was observed in drying 4 slices at shade and the shortest drying time was achieved in TCM drying of 8 slices at 70 °C temperature. This situation accelerates the moisture diffusion and decreases the drying time as the surface area increases when the apple is sliced in 8. The longest drying time in oven drying (41 hours) was observed at 50°C in 4 slices, and the shortest drying time was achieved in TCM drying of 8 slices at 70°C. The drying data of the drying processes in hot air and microwave ovens are given in Figures 3 and 4.

Horuz *et al.* (2018) used a hybrid dryer with increasing oven temperatures and decreasing microwave power levels to dry apples and reported average drying times of 330-800 minutes. Akoy and Hörösten (2015) carried out a drying experiment for drying mango slices in a TCM dryer and reported quite shortened drying times as compared to convective drier. In TCM drier, the longest drying time was observed at 50°C in 4 slices and the shortest drying time (30 minutes) was achieved at 70°C for 8 slices. Cucurullo *et al.* (2012) dried cylindrical apple slices in a TCM drier and reported significant decreases in drying time with increasing temperatures. In natural drying methods at shade and sun, the shortest drying time (72 hours) was achieved at sun-drying for 8 slices and the longest drying time (287 hours) was observed at shade-drying for 4 slices. Winiczenko *et al.* (2018) experimentally studied the effect of drying temperature and air velocity on apple quality parameters such as Color Difference (CD), Volume Ratio (VR), and Water Absorption Capacity (WAC) in convective drying. Optimization of drying conditions was carried out in the range of air temperatures from 50 to 70°C and air velocity from 0.01 to 6 m s^{-1}. A novel algorithm of multi-objective optimization, based on Artificial Neural Network (ANN), Genetic Algorithm (GA) and Pareto optimization was developed. Unique Pareto optimal solution within specified constraints was found at air temperature 65°C and 1 m s^{-1} velocity.

Values of Drying Models

To model change in moisture while drying agricultural products, various models are used to identify the relationships between actual and estimated values. The coefficients of drying curves ($P < 0.05$), " R^2 ", and " P " values are presented in the Tables 2 and 4. Among the models obtained according to Table 2-4, the mathematical model that best predicted the drying data was determined as Page and Mıdıllı-Kucuk. These models were chosen because they are widely used in the literature.

Color Values

L, a, and b values of fresh and dried apples were measured and secondary color parameters of chroma and hue angle values were calculated. The L, a, and b values of fresh and dried samples were also subjected to Duncan's test ($P < 0.05$). L, a, b, chroma and hue angle values and Duncan's test results ($P < 0.05$) are provided in Tables 5 and 6. The greatest L (lightness) value was observed on fresh apples, the lowest value was seen at 70ºC in 8 slices in TCM drying. TCM drying at 70ºC in 4 slices best preserved the brightness of fresh apples ($P < 0.05$) (Table 5). In the apple drying studies, Martins *et al.* (2018) observed that the b value remained stable with the increase in the drying temperature, while the L value increased with the temperature. In a similar study, Polat *et al.* (2019) determined that the L values of the samples increased with the increase of vacuum pressure at constant power value, and the L value decreased

Table 2. Numerical values for the parameters of Yağcıoğlu Equation and Model " R^2 " and "P" values.

Dryer type		Slices	k	h	j	R^2	P
Oven	50 °C	8	1.1183	0.0960	-0.1255	0.9997	< 0.0001
		4	1.1357	0.0509	-0.1285	0.9996	< 0.0001
	60 °C	8	1.2915	0.0700	-0.2777	0.9990	< 0.0001
		4	1.1557	0.0563	-0.1468	0.9994	< 0.0001
	70 °C	8	1.2347	0.1697	-0.2391	0.9989	< 0.0001
		4	1.1177	0.1153	-0.1122	0.9994	< 0.0001
Temperature -Controlled microwave dryer	50°C	8	1.3549	0.2331	-0.3253	0.9896	<0.0001
		4	1.1183	0.3550	-0.0952	0.9955	<0.0001
	60°C	8	1.4527	0.2779	-0.4063	0.9927	<0.0001
		4	1.0493	0.5644	-0.0087	0.9969	<0.0001
	70°C	8	14.2950	0.1485	-13.2428	0.9682	<0.0001
		4	0.9549	1.9393	0.0133	0.9914	<0.0001

Table 3. Numerical values for the parameters of Midilli-Küçük Equation and Model " R^2 " and " P " values.

Dryer type		Slices	k	h	j	m	R^2	P
Oven	50 ºC	8	0.9880	0.9964	0.1081	-0.0044	0.9996	< 0.0001
		4	1.0838	0.9953	0.0457	-0.0015	0.9997	< 0.0001
	60 ºC	8	1.1120	1.0014	0.0693	-0.0050	0.9993	< 0.0001
		4	1.0924	0.9961	0.0508	-0.0019	0.9996	< 0.0001
	70 ºC	8	0.9682	0.9997	0.2033	-0.0174	0.9990	< 0.0001
		4	1.0733	0.9967	0.1124	-0.0027	0.9996	< 0.0001
Temperature-Controlled microwave dryer	50 ºC	8	1.4258	0.9932	0.2430	-0.0017	0.9960	< 0.0001
		4	1.2556	0.9952	0.3358	-0.0007	0.9994	< 0.0001
	60 ºC	8	1.4371	0.9970	0.3177	-0.0068	0.9979	< 0.0001
		4	1.1579	1.0113	0.5336	0.0051	0.9987	< 0.0001
	70 ºC	8	2.5817	1.0001	20.6315	-0.0157	0.9999	< 0.0001
		4	0.7972	0.9940	1.6287	-0.0229	0.9954	< 0.0001

Table 4. Numerical values for the parameters of Page Equation and Model " R² " and " P " values.

Dryer Type		Slices	k	h	R²	P
Oven	50 ºC	8	0.0080	1.1048	0.9970	< 0.0001
		4	0.0402	1.1674	0.9982	< 0.0001
	60 ºC	8	0.0595	1.2573	0.9968	< 0.0001
		4	0.0446	1.1845	0.9979	< 0.0001
	70 ºC	8	0.1949	1.1862	0.9941	< 0.0001
		4	0.1074	1.1386	0.9986	< 0.0001
Temperature-Controlled microwave dryer	50 ºC	8	0.2499	1.4276	0.9958	< 0.0001
		4	0.3410	1.2534	0.9993	< 0.0001
	60 ºC	8	0.3284	1.4777	0.9975	< 0.0001
		4	0.5093	1.1278	0.9977	< 0.0001
	70 ºC	8	21.5904	2.6044	0.9999	< 0.0001
		4	1.8081	0.8678	0.9940	< 0.0001

Table 5. Laboratory color values determined by measuring apple slices.

Dryer type		Slices	L	a	b
Fresh			73.57^{a}	-1.38^{h}	17.38^{d}
Oven	50°C	4	66.55^{b}	7.75^{cde}	20.09^{bc}
		8	66.82^{b}	6.95^{ef}	21.39^{ab}
	60°C	4	67.42^{b}	8.46^{cd}	19.73^{bc}
		8	68.16^{b}	6.60^{f}	21.11^{abc}
	70°C	4	65.00^{b}	7.86^{cde}	19.83^{bc}
		8	67.33^{b}	8.10^{cde}	22.09^{a}
Temperature-Controlled microwave dryer	50°C	4	58.15^{c}	8.07^{cde}	17.52^{d}
		8	51.75^{de}	8.50^{cd}	15.46^{e}
	60°C	4	64.74^{b}	7.21^{ef}	17.24^{d}
		8	49.91^{e}	7.46^{def}	12.80^{f}
	70°C	4	69.57^{ab}	4.01^{g}	15.94^{de}
		8	44.62^{f}	7.26^{ef}	9.54^{g}
Sun drying		4	56.69^{c}	16.10^{a}	20.16^{bc}
		8	58.77^{c}	15.48^{a}	19.84^{bc}
Shaded-open atmosphere drying		4	55.75^{cd}	9.96^{b}	19.36^{c}
		8	64.51^{b}	8.75^{c}	22.15^{a}

when the power value increased at constant vacuum value. The calculated values from measured L, a and b values are provided in Table 6.

Tonin *et al.* (2018) investigated chroma and total color change criteria as color values. With regard to chroma values, it was observed that TCM drying at 50ºC in 8 slices best preserved the chroma values of fresh apples. Sun-drying of 8 slices worst preserved the chroma values of fresh apples ($P< 0.05$). The greatest spoilage (browning) values at the end of drying were observed in natural drying methods.

CONCLUSIONS

Significant changes were observed in color parameters of all drying methods. Chroma values of fresh products were best preserved with TCM drying of 8 slices at 50°C. Chroma values were better preserved at lower temperatures. Lightness

Table 6. Color values determined by calculation of apple slices.

Dryer Type		Slices	C (Chroma)	h° (Hue angle)	BI
Fresh			17.44	-85.46	24.86
Oven	50°C	4	21.54	68.92	43.93
		8	22.48	70.01	45.56
	60°C	4	21.47	66.79	43.30
		8	22.12	72.63	43.55
	70°C	4	21.33	68.37	44.71
		8	23.53	69.89	47.95
Temperature-Controlled microwave dryer	50°C	4	19.29	65.26	45.49
		8	17.64	61.20	47.00
	60°C	4	18.69	67.31	38.66
		8	14.81	59.75	40.13
	70°C	4	16.44	75.89	29.78
		8	11.99	52.71	35.53
Sun drying		4	25.81	51.39	63.96
		8	25.16	52.03	59.76
Shaded-open atmosphere drying		4	21.77	62.77	55.11
		8	23.81	68.45	51.34

and redness of fresh apples were best preserved with TCM drying of 4 slices at 70°C. TCM drying at 50 and 60°C in 4 slices also best preserved the yellowness values of fresh apples. Considering the drying time, TCM drying of 8 slices at 70ºC yielded the shortest drying time. On the other hand, shade-drying of 4 slices yielded the longest drying time with 287 hours. However, Mıdıllı-Kucuk and Page models were the models that best predicted the data of the drying in the study. Considering the entire results obtained from different drying methods, it was concluded that TCM drying method yielding the best results with regard to color parameters and the shortest drying time could reliably be used in apple drying.

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ساخت و عملکرد خشک‌کن مایکروویوی کنترل شده با دما

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چکیده

این پژوهش برای خشک کردن سیب در خشک‌کن مایکروویوی با دمای کنترل شده (TCM) در شرایط بهینه انجام شد. مدت زمان خشک شدن، منحنی های خشک شدن، تغییرات رنگ و مدل‌های خشک شدن مورد تجزیه و تحلیل قرارگرفت. در محدوده این پژوهش، روش‌های خشک‌کردن با TCM، خشک کردن در کوره، و خشک‌کردن در سایه و آفتاب آزمایش شدند. سیب ها به چهار و هشت تکه بریده شده و در دماهای خشک شدن ۵۰، ۶۰ و ۷۰ درجه سانتی گراد در سه تکرار خشک شدند. کمترین زمان خشک کردن (۳۰ دقیقه) در خشک کردن مایکروویوی با دمای کنترل شده و بیشترین زمان خشک کردن (۲۸۷ ساعت) در روش خشک کردن سایه به دست آمد. خشک کردن با TCM پارامترهای رنگ را به بهترین صورت حفظ

کرد. مقادیر روشنی و قرمزی در خشک کردن با TCM در دمای ۷۰ درجه سانتیگراد در چهار تکه سیب به بهترین وجه حفظ شد و مقدار زردی در خشک کردن با TCM در دمای ۵۰ و ۶۰ درجه سانتیگراد در چهار تکه به بهترین وجه حفظ شد. مقادیر کروما با خشک کردن با مایکروویو با دمای کنترل شده در ۵۰ درجه سانتیگراد در هشت تکه به بهترین وجه باقی ماند. با در نظر گرفتن مدت زمان خشک کردن و پارامترهای رنگ، خشک کردن با TCM به عنوان بهترین روش برای خشک کردن سیب شناسایی شد.