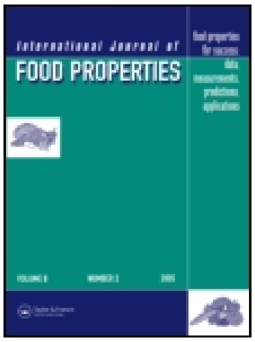

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Color and Microstructure Properties of Tomatoes Dried by Microwave, Convective, and Microwave-Convective Methods

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In this study, color and microstructure changes of tomato samples were investigated after microwave (90, 160, 350, and 500W), convective (50 and 75°C), and microwave-convective (90W-50°C, 90W-75°C, 160W-50°C, and 160W-75°C) drying treatments using a laboratory microwave-convective oven. The combined microwave-convective drying decreased the drying time required when compared to drying with either convective or microwave drying alone. The color of the samples dried at 50°C was closest to the fresh samples compared to other drying conditions. All color values of fresh tomato were affected by drying. Scanning electron microscopy images showed that disruption of the tomato samples significantly elevated with increasing drying temperature or microwave power level.

Keywords: Color, Drying, Structure, Scanning electron microscopy (SEM), Tomato.

INTRODUCTION

Worldwide, tomatoes are one of the most popular, versatile, and widely grown commercial annual crops.[1] Tomatoes, commonly consumed in daily diets, are a rich source of fiber, carotenes (lycopene, β-carotene), ascorbic acid, tocopherol, and phenolic compounds.[2] In recent years, the consumption of tomatoes has been associated with biologically active compounds that provide health benefits and reduce the risk of cancer and heart disease.[3]

Tomatoes are largely consumed fresh and are also used to manufacture a wide range of processed products, such as ketchup, sauces, pastes, and juice. However, tomatoes are a seasonal and perishable fruit and usually deteriorate within 2–3 weeks after harvest. Thus, to improve their shelf life and make the fruit available when not in season, tomatoes are often dried and sold in a dehydrated form. Dried tomato products are used as ingredients for pizza toppings, sauces, snacks, and other savory dishes.[4]

Drying is one of the oldest methods of food preservation, and drying is utilized to prolong storage periods, minimize packaging requirements, and reduce shipping weights.[5] However, in the particular case of dried foods, their process is associated with the loss of volatiles and flavors, changes in color and texture, and a decrease in nutritional value.[6] To eliminate such negative effects, it is

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extremely important to use the correct drying technique because these parameters can unfavorably affect the acceptability of dried products by consumers.

Different drying methods are used in the drying of fruits and vegetables. The most popular and efficient way to preserve food by reducing its moisture content is convective drying.[7] However, there are many problems associated with this drying method, such as the relatively long drying time, the high temperatures used, and the high velocities of the drying airflow.[8] Microwave drying is an alternative method that has various advantages, including energy savings and precise process control.[9] However, microwave drying is known to result in a poor-quality product when applied improperly.[10] To reduce these problems, microwave drying has been combined with existing drying techniques, which include convective air drying. Microwave-convective drying appears to be a promising possibility for producing dried fruits with a suitable shelf life and quality in a short time and with a reasonable energy consumption.[11] The aim of this study was to determine the thin-layer drying kinetics of tomato samples to evaluate the efficacy of convective, microwave, and microwave-convective drying techniques; to investigate the color differences between the fresh and dried products; and to analyze effects of drying treatments on the tomato structure using scanning electron microscopy (SEM).

MATERIALS AND METHODS

Drying Equipment and Drying Procedure

Fresh tomato samples were purchased from a local store in Bursa, Turkey, and stored at a temperature of 4 ± 0.5°C until dried. Whole tomatoes were sliced in half using a knife before the drying treatments.[12] The initial moisture content of the tomato samples was determined to be 11.2 ± 0.02 (g water/g dry matter) on a dry basis (d.b.) by drying at 105°C for 24 h in a forced-air convection oven. The drying rates of the tomato samples during the drying experiments were calculated as follows:[13]

$$Drying\ rate = \frac{M_{t+dt} - M_t}{dt}, \tag{1}$$

where M_t is the moisture content at a specific time (g water/g dry matter), M_{t+dt} is the moisture content at $t + dt$ (g water/g dry matter), and t is the drying time (min). The average drying rate was used in this study.

A laboratory microwave-convective oven (Whirlpool AMW 545, Turkey) with the technical features of ~230 V, 50 Hz, and a frequency of 2450 MHz, was used for the drying experiments. This oven was operated in the convective mode at an air velocity of 1 m/s, with air temperatures of 50 and 75°C, in the microwave mode at output power levels of 90, 160, 350, and 500W, and in the microwave-convective mode at four different combinations of power level and temperature (90W-50°C, 90W-75°C, 160W-50°C, and 160W-75°C). The air flow rate was measured by a digital anemometer (Thies Clima, Germany) having a least count of 0.1 m/s. The microwave, convective, and combined microwave-convective drying experiments were performed in an area of 210 × 450 × 420 mm, consisting of a rotating glass plate (400 mm in diameter) at the base of the oven. In the experiments, 500 ± 0.02 g samples of tomato halves were placed on the glass plate in a thin layer and dried. For mass determination, a digital balance (Baster, Istanbul, Turkey), with a 0.01 g precision, was placed under the oven.[14] The drying process continued until the moisture content of the tomatoes decreased to 0.14 ± 0.03 (g water/g dry matter) on a dry basis. The moisture losses were recorded in 10-min intervals during the drying process. Energy consumption of the microwave-convective oven was determined using a digital electric counter (Kaan, Type 101, Turkey) with 0.01 kW h precision. All experiments were performed in triplicate.

Color Measurement

A colorimeter (MSEZ-4500 L, HunterLab, Virginia, USA) was used to measure the color parameters of the fresh and dried tomato samples. The Hunter L^*, a^*, and b^* values correspond to lightness, greenness ($-a$) or redness ($+a$), and blueness ($-b$) or yellowness ($+b$), respectively. The instrument was calibrated using standard white and black plates before each color measurement. The reading was performed on the external surface of the sample, and the mean of three readings at random locations on the sample was used. A black plastic cell, with a diameter similar to the nose cone of the colorimeter, containing the sample was placed above the light source, and the L^*, a^*, and b^* color values were recorded.[15] Using the following equations, the a^* and b^* values were used to calculate Chroma (C) (Eq. 2), which indicates the color saturation and is proportional to its intensity, and the Hue angle (α) (Eq. 3), which characterizes the color of food products to aid in describing color changes during drying.[16]

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

$$\alpha = \tan^{-1}\left(\frac{b}{a}\right). \tag{3}$$

Structural Analysis

The microstructure of the dried tomato samples was investigated using a scanning electron microscope (Carl Zeiss/EVO 40, Oberkochen, Germany). The samples were subsequently coated with gold to provide a reflective surface for the electron beam. The gold coating was performed using a sputter coater (BALTEC SCD-005, Wetzlar, Germany) under a low vacuum (20 kV) in the presence of the inert gas argon.[14] The external surfaces of the samples were analyzed for the effects of different drying conditions on the tomato samples.

Statistical Analysis

The results were analyzed using the MINITAB 14 software package.[17] The research was conducted using a randomized plot factorial experimental design. The mean differences were tested for significance with a least significant difference (LSD) test at a 1% level of significance.

RESULTS AND DISCUSSION

Drying Kinetics of Dried Tomatoes

Figure 1 shows the moisture content versus drying time curves of tomato samples under all drying conditions. According to the experimental results obtained from all the experiments, increases in the temperature and microwave power level caused a decrease in the drying time. These results are similar to those reported by Sacilik[18] and Taheri-Garavanda et al.[19] for the convective drying of tomatoes and by Soysal et al.[20] and Inchuen et al.[21] for the microwave drying of different food materials. The microwave drying alone was more efficient than the convective method on drying time and energy consumption (Table 1). The shortest drying time and lowest energy consumption were obtained at a microwave level of 500W. In this way, the short drying time at 500W would save energy

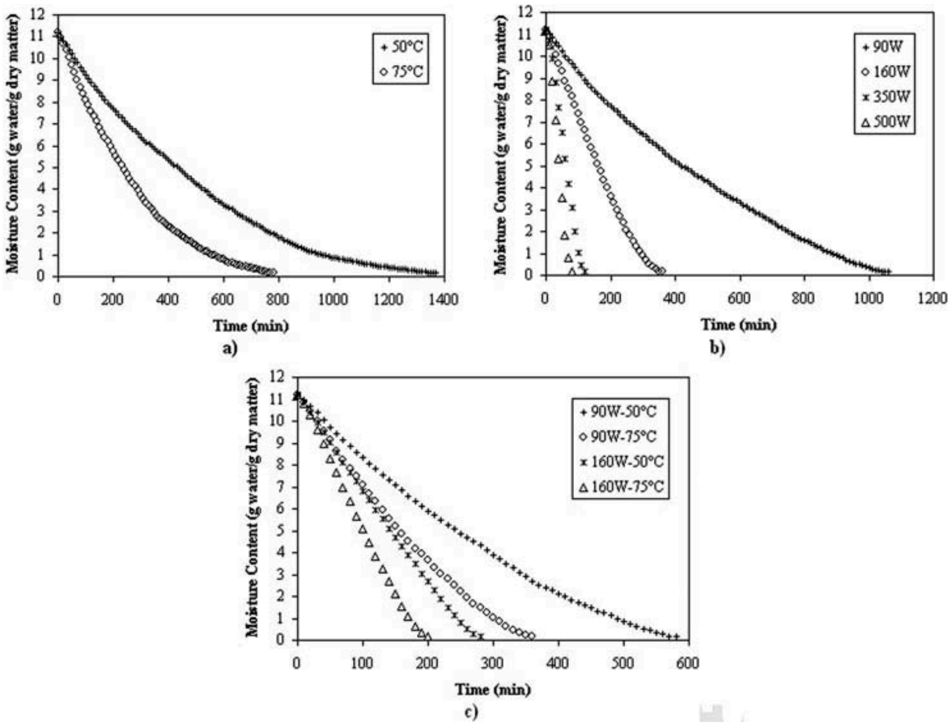

FIGURE 1 Drying curves of tomato samples at (A) different convective temperatures, (B) microwave power levels, and (C) microwave-convective combinations.

TABLE 1
The effects of drying treatments on the drying parameters of tomato samples

Drying method	*Drying time (min)*	*Average drying rate (g water/g dry matter/min)*	*Energy consumption (kWh)*	*Percent improvement in drying time (compared with 50°C)*
Convective drying				
50°C	1370 a	0.01 f	3.44 a	—
75°C	780 c	0.02 e	3.00 b	43.07
Microwave drying				
90W	1060 b	0.02 e	2.61 c	22.63
160W	360 e	0.04 d	1.83 e	73.72
350W	120 h	0.09 a	1.07 g	91.24
500W	80 h	0.13 b	0.94 g	94.16
Microwave-convective drying				
90W-50°C	580 d	0.02 e	2.19 d	57.66
90W-75°C	360 e	0.04 d	1.94 e	73.72
160W-50°C	280 f	0.04 d	1.42 e	79.56
160W-75°C	200 g	0.06 c	1.36 f	85.40

Different letters of the alphabet in the same column differ significantly ($P \leq 0.01$).

consumption by about 73% compared with convective drying at 50°C. There was a marked reduction in the drying time with the microwave-convective combination compared to the microwave or air-drying treatment alone. This result is in good agreement with previous studies.[9,22] As expected, higher average drying rates were obtained with higher temperatures and at higher microwave power levels, thus the air temperature and microwave power have an important effect on the average drying rate of tomatoes. Similar results were obtained by Doymaz[23] for the convective drying of tomatoes and by Inchuen et al.[21] and Özbek and Dadalı[24] for the microwave drying of different products.

Color Analysis

The color of a dried product is a critical quality parameter to the acceptance of the final product by consumers. The results of the changes in L^* (brightness), a^* (redness/greenness), b^* (yellowness/blueness), C (Chroma), and α (Hue angle) values caused by the different drying methods of tomato samples is presented in Fig. 1.

L* *value*

Figure 1a shows the trends of drying treatments on the lightness of the dried tomato samples compared with a fresh sample. There was a significant decrease ($P \leq 0.01$) in the lightness of all the dried samples from 36.70 in the fresh tomato to 23.88 after drying at 500W. The L^* value of the sample dried at 50°C (32.34) was the highest among the other dried samples, which was closer to the L^* value of the fresh sample. Microwave and microwave-convective combination dried tomato samples were significantly darker in color when compared to convective dried samples and increasing of the microwave level and temperature decreased L^* value. Dried tomato samples at 90W (26.21) and 90W-75°C (26.38) showed no statistical difference ($P > 0.01$) with respect to drying treatments. Similarly, there was not a significant ($P > 0.01$) difference between the 160W (25.51) and 160W-75°C (25.35) dried tomatoes. On the other hand, a combination of 50°C with a microwave level at 90 and 160W yielded higher lightness than the tomato samples dried at 90 and 160W.

a* *value*

As can be seen from Fig. 1b, redness of the fresh sample decreased significantly ($P \leq 0.01$) under all of the drying conditions. The a^* value of the samples changed between 27.49 to 31.38 for convective, 20.39 to 27.37 for microwave, and 23.34 to 27.53 for microwave-convective drying. Redness of samples was more influenced by microwave drying and the lowest a^* value was obtained with the dried tomato at 500W (20.39). The least decreased was observed at 50°C (31.38).

b* *value*

The b^* values of fresh and dried samples that were dried with different drying methods are presented in Fig. 1c. There was a significant decrease ($P \leq 0.01$) in the yellowness of all the dried tomato samples from 32.20 in the fresh sample to 13.12. The tomato dried at the 50°C (25.76) was the yellowest whereas samples dried at 500W (13.12) had the least yellow color.

C *and* α *values*

The analysis of the L^*, a^*, and b^* parameters is not sufficient to evaluate changes in food color during processing. According to Abers and Wrolstad,[25] the α value has the most significant correlation with visual scores, and the *C* value is a good indicator of the amount of color. The results of *C* and α values for the fresh and dried samples are presented in Figs. 1d and 1e. The α values of the dried tomato samples were significantly ($P \leq 0.01$) decreased compared to those of the fresh samples. The sample dried at 50°C (39.41°) was closer to α value of the fresh tomato (42.07°). The lower α values recorded by all dried samples compared with the fresh tomato clearly indicate that more browning occurred. The decrease in α value is an indication of more brown pigment formation and shifting away from yellowness.[26] The *C* value of the fresh sample decreased under all the drying conditions in the same way as in α values. Higher *C* values of convective dried samples and lower *C* values of microwave dried tomatoes support the high L^* values of convective dried samples and low L^* values of microwave dried samples. The higher the *C* value, the higher is the color intensity of dried samples perceived by consumers.[27]

It has been previously reported that the color parameters of dried tomato samples compared with a fresh sample decreased significantly with increasing temperature[28] and microwave power.[29] The decrease in color parameters as a result of drying treatments may be strongly related to degradation of lycopene and non-enzymatic reaction (Maillard reaction).[12] Lycopene is responsible for the characteristic red color of tomato fruits and tomato products and can be degraded by the thermal processing.[30] The main causes of tomato lycopene degradation during processing are isomerization and oxidation.[31] Lycopene of the fresh tomato can isomerize from its *trans*-form into the colorless form the *cis*-lycopene as a result of thermal treatment.[32]

Microstructural Changes

Figure 2 shows the SEM images of the dried tomatoes after the different drying methods. The difference in microstructure after convective drying at 50 and 75°C was clearly visible, with the samples dried at 75°C exhibiting a collapsed structure compared to the samples dried at 50°C. For the microwave drying at 350 and 500W, structural deformation was higher than the samples exposed to 90 and 160W, which may be due to the higher diffusion rate generated by the greater microwave power.[33] With regard to the microwave-convective drying conditions, a high temperature and microwave power level during the drying process caused structural damage, destroying the external surfaces of the samples. Similar results were reported by Askari et al.[34] for tomato samples and by Witrowa-Rajcherta and Rzaca,[35] Thuwapanichayanan et al.,[36] and Vega-Gálvez et al.[37] for different food materials and were in accord with the effect of the high temperatures on the structure of the dried products. Drying at 500W resulted in the complete destruction of the samples' external structure, which may be due to the higher microwave power levels causing more intense evaporation of water.

CONCLUSIONS

In the present study, the effect of different drying treatments on the drying kinetics, color, and structural properties of tomato samples were investigated. The highest energy saving and the shortest drying time was provided with a 500W microwave application. Also, the results verified that the drying time was reduced by combining microwave treatment with conventional drying. It was found that higher average drying rates were obtained with a higher microwave power and at higher temperatures. The Hunter L^*, a^*, and b^* values for dried tomatoes decreased with the drying treatments. Convective drying at 50°C yielded the best product color values, which were closest to the L^*, a^*, and b^* values of the fresh sample. In addition, the *C* and α values of the dried tomato samples were

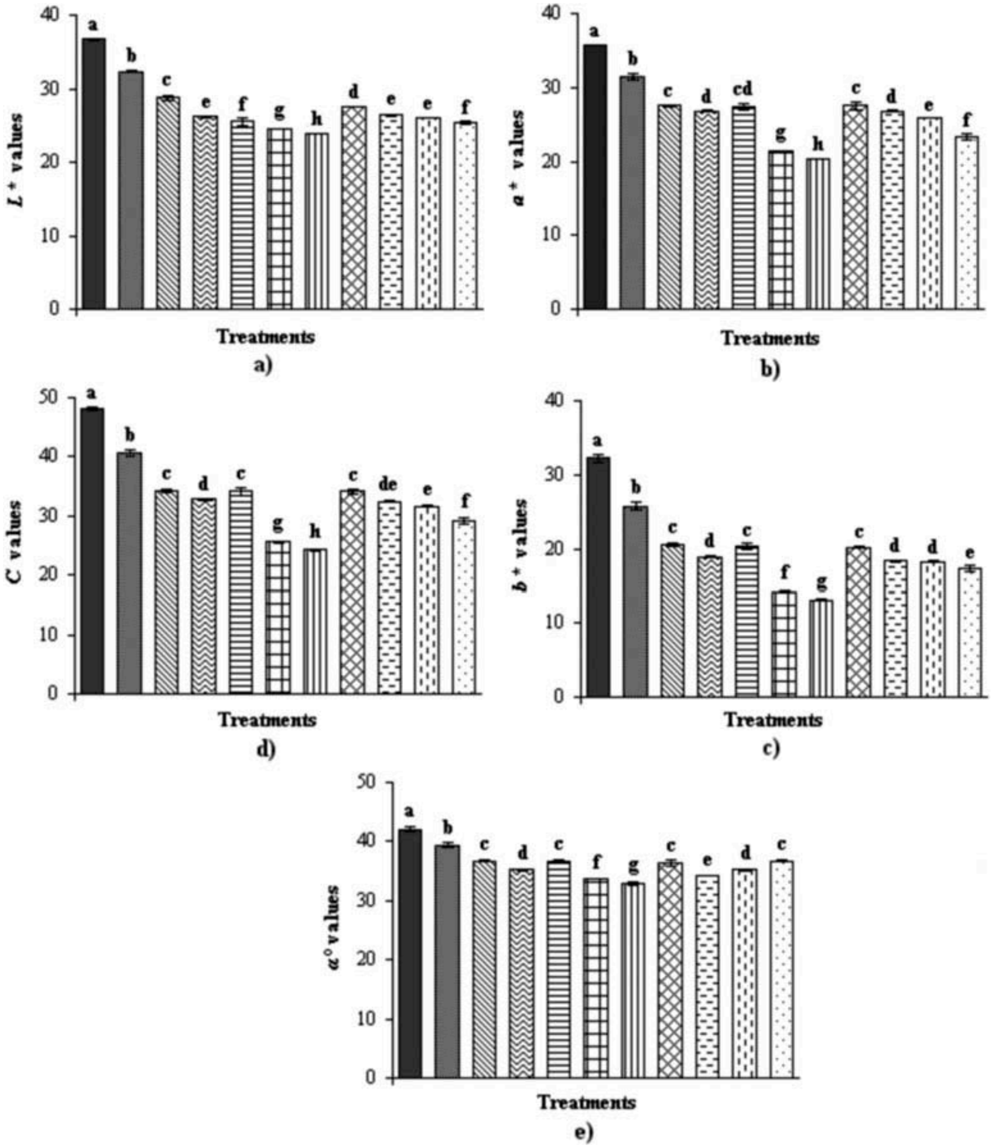

FIGURE 2 The effects of different drying methods (■ Fresh, ▩ 50°C, ▧ 75°C, ▨ 90W, ⊟ 160W, ⊞ 350W, ◫ 500W, ◫ 90W-50°C, ⊠ 90W-75°C, ▭ 160W-50°C, and ⬚ 160W-75°C) on color values (L^* (A), a^* (B), b^* (C), C (D), and α (E)) of tomatoes. Bars with different letters are significantly different ($P \leq 0.01$).

significantly reduced compared to those of the fresh samples. The SEM images revealed that a higher temperature and microwave power caused greater damage to the microstructure of the tomato samples (Fig. 3). The results of this study demonstrated that the microwave-convective drying method is suitable for tomato drying, which not only extensively reduces the drying time but also can decrease the color and microstructural changes compared to the convective or microwave drying alone.

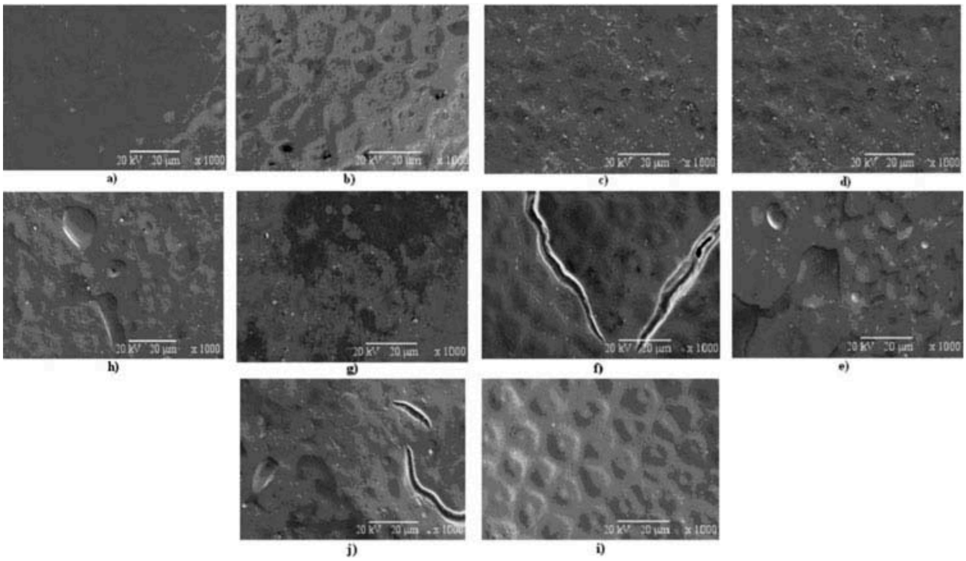

FIGURE 3 Scanning electron micrographs of fresh and dried tomato samples: convective drying at (A) 50°C and (B) 75°C; (C) microwave drying at 90W, (D) 160W, (E) 350W, and (F) 500W; and microwave-convective drying at (G) 90W-50°C, (H) 90W-75°C, (I) 160W-50°C, and (J) 160W-75°C.

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