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SCIENTIFIC PAPER

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EFFECT OF HOT AIR AND HOT AIR-ASSISTED MICROWAVE DRYING ON DRYING KINETICS AND QUALITY OF RED AND WHITE PITAYA SLICES

Highlights

- D_{eff} value increased in both fruit types due to the increase in temperature and microwave power.
- The HAD method fitted to the parabolic model, HA-MWD to the page model.
- The increase in RR decreased SR in both fruits.
- The highest number of pores in the SEM monitoring of pitaya slices was observed in HA-MWD.
- The HA-MWD method is more advantageous in terms of energy consumption compared to the HAD.

Abstract

In this study, mathematical modeling, drying kinetics, rehydration ratio (RR), shrinkage ratio (SR), color change (ΔE), total phenolic content (TPC), antioxidant activity (AA), and microstructural examination of red and white pitaya fruits dried by hot air drying (HAD) and hot air assisted microwave drying (HA-MWD) methods were conducted. In the HAD and HA-MWD methods, the effective diffusion coefficient (D_{eff}) increased as the drying time shortened. While the Page model provides the best fit to HA-MWD curves, HAD curves are also appropriately defined by the Parabolic Model. The RR value was found to be higher in the HA-MWD method. TPC values of fresh red and white pitaya fruits were calculated as 389.7±0.8 and 310.1±0.4 mg GAE/100 g dry matter (DM), respectively. The highest TPC value in HAD was determined as 251.4±0.4 mg GAE/100 g DM at 70 °C. In the HA-MWD method, TPC and AA decreased due to an increase in microwave power. SEM monitoring showed that crack and pore sizes increased with the temperature increase in HAD for both fruit types. The increase in microwave power caused more damage to the structure in the HA-MWD method.

Keywords: Pitaya, drying, effective diffusion, mathematical modeling, microstructure.

INTRODUCTION

Pitaya or dragon fruit (*Hylocereus* spp.) is considered the fruit of species in the cactus family and is widely grown in tropical or subtropical regions around the world [1]. Pitaya is generally classified as white flesh/red shell, red flesh/red shell, and white flesh/yellow shell pitaya according to its flesh and shell appearance [2]. However, there are three main varieties grown commercially [3].

Dragon fruit generally has a taste resembling a mixture of pear and kiwi. The white-fleshed dragon fruit tastes like a cross between an unripe kiwi and a pear. The red-fleshed dragon fruit tastes like a mixture of pear, kiwi, and melon. The taste of the yellow-skinned, white-fleshed dragon fruit is more aromatic and sweeter than the other two species [4]. Pitaya fruit generally consists of 36-37% shell part, 47-49% flesh part (pulp), and 14% seeds [5].

Pitaya fruit, especially its pulp layer, contains vitamins, minerals, and nutritional components (group B vitamins, vitamins E and C, sodium, potassium, calcium, phosphorus, iron, fat, protein, carbohydrate, flavonoid, crude fiber, betacyanins, phenolics, essential fatty acids, carotenoids, and polyphenols) that are quite high. It exhibits relatively high antioxidant activity compared to other subtropical fruits [6].

Pitaya fruit has a short shelf life due to its rapid ripening, which limits storage time during transportation and marketing. Different preservation methods can be used to extend the shelf life of fresh pitaya fruit. Drying, an

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alternative process to food preservation, aims to reduce water activity, provide microbiological stability, extend shelf life, and prevent undesirable physical and chemical changes [7]. When drying foods, the method that will cause the least change in the structure should be preferred. HAD, one of these methods, is the most widely used method in the industry for the preservation and processing of fruits and vegetables. In the HAD method, food can be exposed to high temperatures for a long time to reach the final moisture content. For this reason, undesirable changes occur in the chemical, physical, and sensory properties of the food [8]. In recent research, the microwave-assisted hot air drying method has been developed to prevent these negative situations in the product and to obtain the desired higher quality products [9].

Quantitative understanding of the drying process is of great practical and economic importance in many areas such as process design, quality control, and energy saving. This understanding can be used in the industry to develop more effective and efficient drying processes. Especially in the drying of foods, correct management of the drying process ensures the preservation of product quality, prevention of microbial spoilage, and extension of the shelf life of the products. Additionally, optimizing energy consumption contributes to reducing environmental impacts by reducing operating costs [10]. Kinetic models are used to design a process that can carry out the drying process safely and keep the quality at the highest level. These models help ensure optimum conditions at every stage of the process by accurately predicting drying time, temperature profile, and moisture content. Quantitative analysis and kinetic modeling of the drying process significantly enhance process efficiency in industrial applications while also playing a crucial role in achieving energy savings and sustainability goals. The advantage of thin-layer drying models, in which foods are dried in a thin layer, is that the equations in this model require little data and are easy to use [11]. Thin-layer drying equations are equations that include the change of dimensionless moisture content against time [12].

There are a limited number of studies in the literature comparing HA-MWD with HAD in terms of drying properties, mathematical modeling, rehydration, and shrinkage properties of pitaya slices. In addition, the number of studies reporting the change in total phenolic substance and antioxidant activity content as a result of drying is very few. In this context, this study aims to determine the drying, rehydration, and shrinkage properties of pitaya slices dried by HA-MWD and HAD methods as well as to compare their microstructural investigations.

MATERIALS AND METHODS

Material

Red pitaya (RP) and white pitaya (WP) (*Hylocereus polyrhizus* and *Hylocereus undatus*) fruits were obtained from the Erdemli district in Mersin, Turkey. Erdemli is located at 10 m above sea level with coordinates 36° 36' 17" north latitude and 34° 18' 30" east longitude. Pitaya fruits were sliced in 0.5 ± 0.1 cm thickness after peeling.

Drying Procedure

Hot air drying (HAD)

RP and WP fruits were sliced to a thickness of 0.5 ± 0.1 cm and weighed 250 g, placed on metal drying trays. Pitaya fruits were dried in a hot air drying oven to 14% moisture content (Arçelik, KMF 833 W, Turkey). The drying procedure was carried out at an air velocity of 1 $m \cdot s^{-1}$ at temperatures of 50, 60, and 70 °C. All drying processes were carried out in triplicate.

Hot air-assisted microwave drying (HA-MWD)

In the HA-MWD method, three temperatures (50, 60, and 70 °C) and two different microwave powers (100 W and 200 W) were determined. The drying process was carried out in six different parameters: 50 °C + 100 W, 50 °C + 200 W, 60 °C + 100 W, 60 °C + 200 W, 70 °C + 100 W and 70 °C + 200 W. RP and WP fruits, sliced to a thickness of 0.5±0.1 cm, were placed in a polypropylene drying tray at 250 g each and dried in a hot air assisted microwave (Arçelik, KMF 833 W, Turkey).

Drying Characteristics

Moisture content (M_t)

Eq. (1) was used to calculate the moisture content of RP and WP fruits during the drying process.

$$M_t = \frac{m - DM}{DM} \tag{1}$$

where M_t is the moisture content at any time, m is the weight of the sample (g), and DM is the amount of dry matter (g).

Moisture ratio (MR)

Eq. (2) was used to calculate the MR [13]. The M_t obtained by Eq. (1), was used to calculate the MR:

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{2}$$

At any time t, M_t and M_i (initial moisture content) are very small compared to M_e (equilibrium moisture) content. Therefore, M_i is ignored. The M_t is expressed in Eq. (1).

Effective moisture diffusivity (D_{eff})

Fick's diffusion equation, Eq. (3), is used to describe the drying process of agricultural products in the decreasing period of drying rate [14]:

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \nabla^2 M \tag{3}$$

This equation is simplified by Crank [14] for sliced products assuming that the moisture transfer occurs only by diffusion with a constant diffusion coefficient, with no shrinkage in the product, for a long drying time at a constant temperature. This model is valid for slab-shaped materials and assumes that moisture diffusion occurs over a flat surface:

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

D_{eff} was calculated by Eq. (4). In this formula, L is half the slice thickness of the sample before drying, and t is the drying time. For the long drying time, Eq. (4) is simplified in a straight line. Here, the value of n is accepted to be 1, and Eq. (5) is written as follows [15]:

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

The natural logarithm of the moisture content values is taken, and the graph of the drying time gives a linear curve; and the D_{eff} (Eq. 6) is calculated from the slope of this line [15]:

$$\text{Slope} = -\frac{\pi^2}{4L^2} D_{eff} \tag{6}$$

Mathematical modeling of drying curves

Correlation between the estimated and experimental data of pitaya slices dried with different drying methods, is explained by the coefficient of determination (R^2), chi-square ($\chi 2$), Root Mean Square Error (RMSE), Akaike Information Criteria (AIC) values. RMSE is a parameter that measures the deviation between the predicted and experimental data and determines the accuracy of the model. The RMSE value is calculated by taking the square root of the average of the squares of the differences between the values predicted by the model and the real values. A lower RMSE value indicates that the model performs better and its predictions are closer to the actual data. AIC is used to select the model that best fits the data set by establishing a balance between the accuracy and complexity of the model. To determine the model that best estimates the experimental data, the model with the lowest $\chi 2$, RMSE and AIC values and the highest R^2 value should be selected. RMSE (Eq. 7), chi-square ($\chi 2$) (Eq. 8) and R^2 values (Eq. 9) and AIC (Eq. 10) were calculated as follows [13]. The thin-layer drying models used in this study are given in Table 1. Calculations were made with the help of the MATLAB (R2022a, version 9.12) program using the trust-region algorithm and the non-linear curve fitting toolbox.

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=0}^{N}(MR_{\text{pre,i}} - MR_{\text{exp,i}})^2\right]^{\frac{1}{2}} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=0}^{N}(MR_{\text{pre,i}} - MR_{\text{exp,i}})^2}{N-n} \tag{8}$$

$$R^2 = \frac{\Sigma(MR_{pre} - MR_{exp})^2}{\Sigma(MR_{pre,av} - MR_{exp})^2} \tag{9}$$

$$AIC = -2\ln(L) + 2p \tag{10}$$

where L ismaximum likelihood value of the model,p is number of parameters in the model.

Determination of RR and SR

Rehydration analysis was performed according to the procedure recommended by Tepe and Tepe [13]. For this purpose, RP and WP fruits weighing 5 g were placed in a glass container. 400 ml of distilled water was placed on them and taken into a water bath at 40 °C. Temperature control was performed at regular intervals throughout the analysis. Rehydration analysis was completed after 24 hours, and pitaya slices were weighed. The rehydration rate was calculated by Eq. (11):

$$RR\% = \frac{W_r}{W_0} \tag{11}$$

where W_r is weight after rehydration (g), W_0 is the weight before rehydration (g).

SR values of dried red and white pitaya slices were expressed with bulk shrinkage. Liquid displacement technique was used to determine the bulk shrinkage [13]. In this method, hexane was used to measure the volume change. SR was calculated with the help of Eq (12).

Table 1. Some mathematical models used in modeling the drying process [16].

Model name	Model
Page	$MR = \exp(-kt^n)$
Henderson and Pabis	$MR = a\exp(-kt)$
Wang and Singh	$MR = 1 + at + bt^2$
Parabolic	$MR = a + bt + ct^2$
Logarithmic	$MR = a\exp(-kt) + c$
Lewis	$MR = \exp(-kt)$

$$SR\% = 100 - \frac{v_i - v_f}{v_i} \cdot 100 \tag{12}$$

where v_i: is the volume of fresh pitaya slice (cm^3), v_f: is the volume of dried pitaya slice (cm^3).

Determination of color

Hunter Lab Color Miniscan XE (Model No: 45/0-L, USA) was used for the color analysis of fresh and dried RP and WP fruits. First, pitaya slices were placed on a white surface and a transparent glass was placed over them. Then, color values were measured with the device away from light. Eq. (13) was used to calculate the total color change (ΔE):

$$\Delta E = \sqrt{\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2} \tag{13}$$

where $L^*_0$and $L^*$are lightness values before and after drying drying (0 = black, 100 = white).
where $a^*_0$and $a^*$are redness values before and after drying (a+ =red, a- =green).
where b^*_0 and b^* *are* yellowness values before and after drying drying (b+ =yellow, b- =blue).

Determination of TPC

Analysis of TPC was performed following the procedure recommended by Singleton and Rossi [17]. Methanol-water mixture was used as solvent in TPC extraction due to the polar structure of phenolic compounds. For this purpose, 1 g of pitaya fruit was taken and 25 mL of methanol-water solution (90:10) was added. Then, the samples became homogeneous with a homogenizer. Homogeneous samples were centrifuged at 9000 rpm at 4 °C. Centrifuged samples were filtered with a coarse filter. Next, 300 µL of the resulting filtrate was taken and mixed with 1500 µL of a solution (1:10 ratio of Folin-Ciocalteu reagent to ultrapure water) and kept in the dark for 5 minutes. Subsequently, 1200 µL of 7.5% $NaHCO_3$ solution was added and left at room temperature for 2 hours. After the incubation period, the absorbance values of the solutions were measured at 760 nm using a spectrophotometer (PG Instruments T80 UV/VIS, England). To calculate the results, the absorbance of gallic acid standard solutions prepared at concentrations of 25, 50, 62.5 and 100 ppm was measured. Measurement results were given in gallic acid equivalent (GAE 100 g^{-1} DM).

Determination of AA

Determination of AA was performed according to the DPPH (2,2-diphenyl-1-picrylhydrazyl) method [18]. For sample extraction, 25 mL of methanol: water (90:10) mixture was added to 1 g of pitaya fruits and homogenized in a homogenizer. It was centrifuged for phase separation. Centrifuged samples were filtered through filter paper to separate the clear phase. Next, 150 µL of the filtered samples was taken and 2850 µL DPPH was added. The mixture was incubated for 1 hour in a dark environment. After 1 hour, the absorbance of the samples was measured at 515 nm using a spectrophotometer. A trolox standard prepared at different concentrations was used to determine the values corresponding to the absorbances. Measurement results were given in mmol trolox equivalent (TE 100 g^{-1} DM).

Microstructural analysis (SEM)

The slice structure of pitaya fruits dried using different drying methods was observed using a scanning electron microscope (Zeiss-Supra 40VP 35 FESEM, Germany). Dried pitaya slices were coated with gold to provide a reflective surface for the electron beam during SEM monitoring. Photographs of the samples were taken at 15 kV voltage and 250x magnification [19].

Statistical analysis

Statistical analysis was performed using SPSS software (ver. 26, SPSS Inc., Chicago, IL, USA). One-way ANOVA and Tukey tests were applied to compare the mean values. Mean values were compared at a significance level of $p < 0.05$.

RESULTS AND DISCUSSION

Drying of pitaya fruit

MR graphics of drying of RP and WP fruits by HAD and HA-MWD methods are shown in Fig. 1, and images of dried pitaya slices are shown in Fig. S1. Drying times and Deff (m2 s-1) values are given in Table 2. When comparing the drying times of RP and WP fruits dried using HAD at 50 °C, 60 °C, and 70 °C, WP fruit dried faster. The reason for this is thought to be due to the high number of seeds in the WP fruit. Çetin *et al.* [20] reported that white dragon fruit dried in a shorter time than red dragon fruit. In the HA-MWD method, the drying time was considerably shorter than the HAD method. RP fruit dried in 840 minutes at 50 °C, while at 50 °C + 100 W and 50 °C + 200 W, drying times were 315 and 60 minutes, respectively. For both fruit types, drying time was shortened due to the increase in drying temperature and microwave power. Raj and Dash [8] reported that white-fleshed pitaya fruit dried in 510 minutes at 60 °C. Nordin *et al.* [21] reported that red pitaya dried in 27 hours in hot air drying at 55 °C and in 6 hours in hot air assisted microwave drying. Deff increased due to temperature increase in both fruits in HAD. Deff values of white pitaya fruit were higher. In HA-MWD, as microwave power increased, Deff increased. The highest Deff was observed for WP at 70 °C + 200 W. Ayala Aponte *et al.* [22] reported an increase in Deff as drying time decreased. As the permeability of the cell wall increases at high temperatures, the diffusion of water molecules increases, resulting in an increase in Deff [23]. In one study, white pitaya fruits sliced 3 and 5 mm thick were dried at 60, 70 and 80 °C.As a result of the study, the highest Deff was measured in fruits dried at 80 °C with a slice thickness of 5 mm with 9.21×10^{-10} (m^2 s^{-1}) [24].

Mathematical modeling of pitaya fruits

Statistical parameters (χ^2, RMSE, AIC, R^2) of the thin layer modeling used in this study are given in Tables S3-S6 (Supplementary material). As a result of drying RP fruits with HAD, the drying curves were explained with the parabolic model, which had the highest R^2 and lowest χ^2, RMSE, and AIC. The AIC value was considered as an additional parameter to select the best model. The experimental values and those predicted by the model showed a strong correspondence, as confirmed by the AIC. Recently, AIC has been used to more accurately select the best mathematical model representing the drying curves in different agricultural products [25].

Similar results were observed for WP fruit dried using HAD. The model that best explains the drying curves was chosen as a parabolic model. The parabolic model assumes that the rate of water loss is high at the beginning of the drying process and decreases as time progresses. This modeling can be used to predict the change in moisture content of food over the drying period. Drying curves of HA-MWD as a result of drying at different temperatures and microwave powers were described by the page model. The result was the same for RP and WP fruits. The highest R^2 and lowest χ^2, RMSE, and AIC values were detected in the page model. Whereas the Page model is based on the understanding that the rate of water loss decreases with time and is dependent on humidity, the parabolic model assumes that the rate of water loss decreases with time and is independent of moisture [13]. Ayala-Aponte *et al.* [22] applied Newton, Handerson-Pabis, Peleg, and Weibull mathematical models to the data obtained from pitaya fruits dried at 50, 60, and 70 °C. The study found that the Peleg model (R^2 = 0.990) and Weibull model (R^2 = 0.996) best fit the experimental data. Drying of white pitaya fruit at 200, 400, and 600 W and 60 °C was reported to fit the Weibull kinetic model [8]. In a study of *Hylocereus undatus* shells drying at 50, 60, and 70 °C, it was determined that the drying kinetics fit the page model [26]. The drying kinetics of white pitaya fruits dried with a heat pump at different slice thicknesses and temperatures were best described by the Avhad and Marchetti model [27]. Newton, Page, Lewis, Henderson, logarithmic, and Midilli models were applied to the data obtained from drying king oyster mushrooms with four different methods. As a result of the study, it was seen that Midilli and Page models were more suitable for simulating the drying process [28]. In a different study, it was reported that the lotus root dried with different methods was fit to the modified page model (R2> 0.99) [29]. The reason for the difference in kinetic models may be due to the difference in fruit type, structure of the food matrix, moisture content of the product and drying conditions.

Table 2. Drying time, effective moisture diffusivity, and rehydration ratio of dried pitaya fruits.

Drying Method	Drying time (min)		D_{eff}(m^2s^{-1})		RR % (40 °C)		SR %	
	RP	WP	RP	WP	RP	WP	RP	WP
50 °C	1480	840	$1.18x10^{-10}$	$2.03x10^{-10}$	2.71±0.014^{e}	2.48±0.014^{e}	85.21±0.18^{a}	84.98±0.32^{a}
60 °C	750	570	$2.36x10^{-10}$	$3.04x10^{-10}$	2.97±0.028^{c}	2.70±0.024^{b}	83.87±0.17^{b}	81.78±0.24^{c}
70 °C	540	315	$3.38x10^{-10}$	$5.75x10^{-10}$	3.20±0.007^{b}	2.73±0.012^{ab}	82.34±0.32^{c}	80,34±0.14^{d}
50 °C + 100W	435	315	$3.72\ x10^{-10}$	$5.41\ x10^{-10}$	3.20±0.014^{b}	2.57±0.010^{cd}	81.79±0.14^{c}	83,61±0.24
50 °C + 200W	75	60	$2.43\ x10^{-9}$	$2.87\ x10^{-9}$	2.65±0.022^{e}	2.50±0.010^{de}	86.13±0.39^{a}	84,48±0.31^{ab}
60 °C + 100W	415	270	$4.23\ x10^{-10}$	$6.42\ x10^{-10}$	3.13±0.035^{b}	2.65±0.034^{bc}	81.11±0.41^{c}	82.12±0.16^{c}
60 °C + 200W	70	50	$2.52\ x10^{-9}$	$3.28\ x10^{-9}$	2.86±0.020^{d}	2.56±0.036^{de}	82.01±0.15^{c}	83.55±0.18^{b}
70 °C + 100W	345	195	$4.90\ x10^{-10}$	$8.79\ x10^{-10}$	3.35±0.010^{a}	2.80±0.022^{a}	80.09±0.18^{d}	79.13±0.21^{e}
70 °C + 200W	67	47	$2.60\ x10^{-9}$	$3.60\ x10^{-9}$	2.89±0.016^{d}	2.71±0.018^{b}	81.92±0.14^{c}	81.44±0.34^{c}

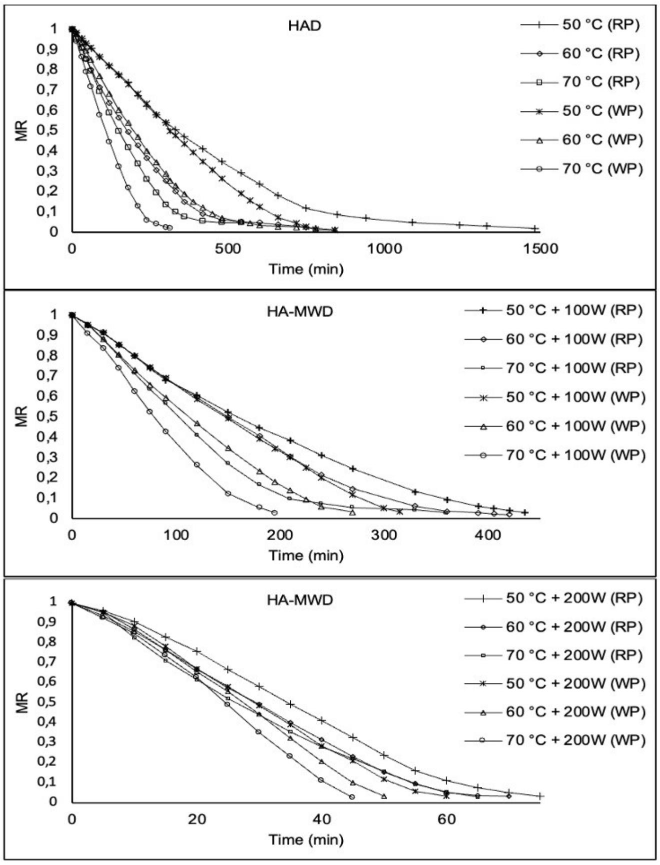

Figure 1. *MR changes of red and white pitaya fruits dried in HAD and MA-MWD*

RR and SR of dried pitaya fruits

The rehydration rate of a dried food is often used as an index of quality. It shows the physical injuries and chemical changes caused by the removal of water from the cellular structure during the drying process [30]. RR and SR of dried RP and WP fruits are shown in Table 1. In the HAD method, RR increased in both fruit types due to the increase in temperature. The increase of RR decreased the shrinkage of pitaya slices. Doymaz [31] explains the low RR at low temperature due to lower diffusion of water across the surface and cellular structure damage during the rehydration process. The RR of dried RP fruit was higher than that of WP fruit ($p<0.05$). This is because the flesh of the RP fruit was more than the WP fruit. Therefore, it attached more water to its structure. Accordingly, shrinkage was observed less in RP fruits. At the same drying temperature, increasing microwave power decreased RR. The highest RR was determined as 3.35±0.010 and 2.80±0.022 in RP and WP fruits at 70 °C + 100W drying, respectively ($p<0.05$). The lowest SR was detected in the 70 °C + 100W drying method ($p<0.05$). Since the pore structure of the products dried in microwave drying is greater, it allows more water to be absorbed, so the rehydration rate is higher [32]. In a study by Raj and Dash [8], hot air and intermittent microwave methods were used to dry pitaya fruits. As a result of the study, it was found that the lowest RR was 1.667 in hot air drying, and the highest rehydration rate was found in the intermittent microwave drying method at 600 W. In a study in which pitaya fruits were dried by hot air and freeze-dried, the RR of freeze-dried fruit chips was found to be higher. They reported that the reason for this was the homogeneous cell structure that served as capillary pathways [33]. Similarly, it has been reported that the RR of apple slices dried in microwave is higher than that of apple slices dried in hot air [34].

Color of dried pitaya fruits

*L**, *a** and *b** values of fresh and dried RP and WP slices are shown in Table 3. *L** value increases in both fruit types depending on the temperature increase in HAD. The *L** value is an important quality parameter that expresses the lightness and darkness of the color. In RP fruit, an increase in *a** value, which expresses the redness of the color, was observed due to the increase in temperature in HAD. The highest *a** value was at 70 °C (p<0.05). It was observed that the color values were less preserved in the long-term drying method at low temperature. Therefore, the highest ΔE values was calculated for both fruit types at 50 °C in HAD (p<0.05). For RP fruit, *L** and a value decreased due to the increase in power at the same drying temperature in HA-MWD. The highest ΔE changes occurred during drying at 50 °C + 200W (p<0.05). Results were similar for WP fruit. The increase in microwave power resulted in increased ΔE values. Asthiani *et al.* [35] reported that the ΔE values of peach slices dried by hot air and hybrid hot air-microwave method increased due to the increase in microwave power. Raj and Dash [17] reported that the color change of *Hylocereus undatus* fruit dried by intermittent microwave drying was in the range of 18.643-24.847. It was reported that the *L**, *a** and *b** values of white dragon fruit dried by hot airdrying method at 60 °C were 16.28 ± 1.25, 7.91±00 and 6.08 ± 0.97, respectively [36]. Horuz and Maskan [30] reported that the color change caused by the microwave drying method was greater than the hot air drying method. This indicates that the color is better preserved at low microwave power in HA-MWD in both fruit types. The color of dried fruit is affected by the degradation of some pigments, non-enzymatic browning, and oxidation of phenolic compounds, which contribute to changes in color hue and intensity.

TPC of dried pitaya fruits

TPC values of fresh and dried pitaya fruits were shown in Table 4. TPC value of RP fruit was higher than WP fruit. TPC values of fresh RP and WP fruits were calculated as 389.71±0.80 and 310.11±0.42 mg GAE 100 g^{-1} DM, respectively (p<0.05). Angonese *et al.* [37] found the TPC value of fresh white and red dragon fruit to be 75.6 ± 14.4 and 107.4 ± 10.8 mg GAE/100g DM, respectively. In both fruit types, there was an increase in TPC values due to the increase in temperature during HAD (p<0.05). It is reported that this is due to the shortening of the drying time. Most phenolic compounds are highly sensitive to heat and easily oxidized. The decrease in total phenolic substance content with drying is explained by irreversible oxidation and thermal degradation of phenolic components due to long-term temperature exposure. The highest TPC value in HAD was determined as 251.35±0.35 mg GAE 100 g^{-1} DM at 70 °C (p<0.05). A decrease in the TPC was observed in RP fruits dried by the HA-MWD method, depending on the increase in microwave power at the same temperature. The highest TPC value was calculated as 250.95±0.71 mg GAE 100 g^{-1} DM at 70 °C + 100W (p<0.05). Raj and Dash [8] reported that microwave power decreased the TPC of pitaya fruit. Şahin *et al.* [38] explained that the decrease in TPC with higher power levels in microwave drying may be due to the temperature increase due to internal heating and the degradation of polyphenols.

AA of dried pitaya fruits

AA values of fresh RP and WP fruits were found to be 82.89±0.33 and 54.21±0.74, respectively (p<0.05). The AA value of RP fruit was higher than that of WP fruit (Table 4). Al-Mekhlafi *et al.* [39], in a study on seven different pitaya samples, found that the antioxidant activities of red-fleshed fruits were higher than white-fleshed fruits. In a study, the antioxidant activities of fresh white and red pitaya fruits were found to be 17.56 and 22.65 µg GA/g, respectively. It was stated that the antioxidant properties of red dragon fruit are twice the amount due to betacyanin pigment compared to white pitaya fruit [7]. In HAD carried out at 50, 60 and 70 °C, it was observed that AA increased as the drying temperature increased. Liatrakoon *et al.* [40] reported that when they applied heat treatment to white-fleshed and red-fleshed dragon fruit purees between 50 and 90 °C for 0-60 minutes, the antioxidant activity of both fruit types increased due to the increase in temperature. A shorter drying time increased the AA value. In HA-MWD, AA decreased as microwave power increased at the same temperature (p<0.05). Increasing microwave power increased the internal temperature of the product; therefore, more loss was observed. In HA-MWD, the highest AA was observed at 60 °C + 100W in both fruit types (p<0.05). AA values were better preserved in RP fruit than in WP fruit. Similarly, Lee *et al.* [41] found that the AA value of red dragon fruit dried by spray drying was higher than that of white fruits.

Microstructural analysis of dried pitaya fruits

SEM monitoring of RP and WP fruits dried by HAD and HA-MWD methods is shown in Fig. S2. When the SEM monitoring of RP fruits dried by HA drying method was examined, the formation of pores and cracks increased due to the increase in temperature. In SEM monitoring of WP fruits dried at 50, 60, and 70 °C, crack and pore sizes increased due to the temperature increase. These structural changes increased the porosity of the fruit slices and contributed to the increase in RR. The highest RR in the HAD method was determined at 70 °C in both fruit types. This increase in RR prevents excessive collapse of cellular structures and reduces the SR value. The drying process applied at high temperatures causes the water to evaporate quickly. This may cause various deformations and breaks on the fruit surface in SEM monitoring. Cracks and pores formed during drying increase the permeability of the fruit tissue and directly affect the movement and distribution of moisture. Bassey *et al.* [7] report that drying the pitaya fruit at high temperatures will cause the formation of microchannels and pores that will help remove moisture. When microstructural analysis of RP fruits dried by HA-MWD were examined; At the same temperature, more porous growth and crack formation were observed due to the increase in microwave power. It is thought that the reason for the formation of the porous structure is due to the high volumetric heating. Determination in the pore structure was observed more due to the increase in temperature and microwave power due to drying of RP fruit with the HA-MWD method. The largest pore structures and cracks occurred in the 70 °C + 200W drying method.

Table 3. Color of dried pitaya fruits.

Drying Method	RP				WP			
	L^*	a^*	b^*	ΔE	L^*	a^*	b^*	ΔE
Fresh	19.72±0.89^{de}	38.19±0.63^{a}	-8.10±0.78^{d}	0.00	58.96±0.25^{a}	-0.79±0.02^{be}	4.12±0.66^{cd}	0.00
50 °C	18.90±0.51^{e}	8.96±0.73^{de}	-1.29±0.23^{bc}	30.02±0.18^{a}	31.44±1.56^{f}	-0.61±0.06^{bd}	5.89±0.12^{bc}	27.61±0.12^{c}
60 °C	23.74±0.33^{ab}	17.80±0.38^{b}	-1.84±0.26^{c}	20.72±0.24^{c}	38.97±0.88^{d}	0.28±0.18^{a}	4.34±0.68^{cd}	19.99±0.21^{e}
70 °C	25.53±0.35^{a}	20.01±0.87^{b}	-1.72±0.35^{c}	20.06±0.32^{c}	51.17±0.74^{b}	-1.17±0.15^{de}	7.58±0.24^{ab}	8.74±0.14^{g}
50 °C + 100W	22.47±0.21^{bc}	8.41±0.33^{df}	-1.62±0.52^{bc}	30.11±0.17^{a}	40.23±0.86^{d}	-1.43±0.09^{e}	5.95±0.21^{bc}	18.94±0.18^{ef}
50 °C + 200W	16.00±1.07^{f}	6.10±0.62^{f}	-1.95±0.15^{c}	32.88±0.14^{a}	20.64±0.78^{h}	-0.10 ±0.10^{bc}	1.98±0.53^{e}	38.39±0.32^{a}
60 °C + 100W	21.33±0.15^{cd}	12.31±0.22^{c}	-1.66±0.15^{bc}	26.71±0.20^{b}	44.59±1.35^{c}	-1.05±0.9^{ce}	5.53±0.20^{bc}	14.55±0.26^{f}
60 °C + 200W	19.72±0.52^{de}	6.93±0.52^{ef}	-1.67±0.16^{bc}	31.91±0.22^{a}	24.36±0.85^{g}	-0.05±0.10^{ab}	2.19±0.28^{de}	34.66±0.25^{b}
70 °C + 100W	21.21±0.42^{ce}	13.05±0.71^{c}	0.60±0.41^{a}	26.64±0.28^{b}	45.72±0.31^{c}	-1.39±0.09^{e}	9.45±0.18^{a}	14.43±0.24^{f}
70 °C + 200W	10.47±0.10^{g}	10.79±0.61^{cd}	-0.24±0.40^{ab}	29.96±0.24^{a}	35.68±0.73^{e}	-0.55±0.06^{bc}	2.41±0.19^{de}	23.38±0.12^{c}

*Different letters in the same column indicate significant differences with a confidence of 95%.

Table 4. Total phenolic matter and antioxidant activity of dried pitaya fruits.

Drying Method	TPC (mg GAE/100 g DM)		AA (mmol TE/100 g DM)	
	RP	WP	RP	WP
Fresh	389.71±0.80^{a}	310.11±0.42^{a}	82.89±0.33^{a}	54.21±0.74^{a}
50 °C	197.17±0.73^{h}	162.97±0.88^{i}	38.075±0.52^{g}	34.82±0.45^{de}
60 °C	227.62±0.62^{e}	174.45±0.40^{h}	47.42±0.45^{de}	43.11±0.32^{bc}
70 °C	251.35±0.35^{b}	197,3±0.34^{e}	49.35±0.61^{d}	46.70±0.98^{b}
50 °C + 100W	240.35±1.06^{c}	207.12±0.34^{d}	52.32±0.72^{c}	36.52±0.23^{de}
50 °C + 200W	201.6±0.53^{g}	192.90±0.72^{f}	41.62±0.50^{f}	34.82±0.75^{de}
60 °C + 100W	211.25±0.99^{f}	228.22±0.40^{b}	60.22±0.70^{b}	39.18±0.28^{cd}
60 °C + 200W	205.07±0.57^{g}	213.52±1.06^{c}	53.22±0.32^{c}	29.07±0.66^{f}
70 °C + 100W	250.95±0.71^{b}	209.85±0.92^{d}	54.25±0.42^{c}	34.35±0.32^{e}
70 °C + 200W	232.35±0.98^{d}	187.52±0.28^{g}	46.22±0.66^{e}	26.57±0.55^{f}

*Different letters in the same column indicate significant differences with a confidence of 95%.

The RR value similarly decreased with the increase in microwave power at the same temperature. Increasing temperature and microwave power caused further expansion of the internal structure. The results are similar for WP fruit. At the same temperature, more collapse and shrinkage were observed in the structure with increasing microwave power. Therefore, the lowest SR rates were calculated in the methods using 200 W microwave power. It has been revealed that increasing microwave power disrupts the cellular structure of the samples. It has been reported that this may be due to the high diffusion rate caused by temperature and microwave power [42]. Therefore, the optimum selection of temperature and microwave power in drying processes is critical to maintain the rehydration capacity and shrinkage rate of the product. Raj *et al.* [8] stated that as a result of drying, white-fleshed dragon fruit with the microwave vacuum drying (200 W, 400 W, 600 W) method, the pore diameter increased due to the increase in microwave power. In a study, when the SEM images of tomatoes dried with HAD, MW and HA-MWD methods were examined, it was revealed that the highest deformation occurred in tomatoes dried with MW and HA-MWD methods [43]. When the HAD method is compared with the HA-MWD method, it is seen that structural defects are more common in the HA-MWD method. Microwave energy causes water molecules to move rapidly, accelerating evaporation. However, while the inner surface of the fruit heats up faster, evaporation may occur slower on the outer surface. In this case, it may cause more cracks and pores in the fruit structure. Apart from this, high microwave powers and long-term processing may cause overheating and deterioration of the fruit structure.

CONCLUSIONS

In this study, drying properties, mathematical modelling, rehydration ability, TPC and AA values and tissue damage caused by the drying process were examined as a result of drying RP and WP fruits with HAD and HA-MWD. As a result of the research, the HAD and HA-MWD methods applied were effective in drying pitaya slices. As a result, although the high temperatures applied provided a short drying time, they caused structural defects. The HA-MWD method is a more efficient method in terms of energy consumption since it is completed in a shorter time than HAD. Although the HAD method can be widely used with low energy costs, it is disadvantageous in terms of energy efficiency due to long drying times. The HA-MWD method minimizes nutritional value loss by preserving the bioavailable components of the fruit. The HA-MWD method stands out as a faster and more efficient method. However, some promising drying methods need to be evaluated. Therefore, in future studies, it may be recommended to dry pitaya slices using with different pre-treatments and different drying methods. In this way, the most suitable conditions and methods can be optimized by observing textural properties and nutrient loss.

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NOMENCLATURE

AA - Antioxidant activity
DPPH - 2,2-diphenyl-1-picrylhydrazyl
Deff - Effective moisture diffusivity
DM - Dry matter
GAE - Gallic acid equivalent
HAD - Hot air drying
HA-MWD - Hot air-assisted microwave drying
MR - Moisture ratio
RMSE - Root mean square error
RP - Red pitaya
RR - Rehydration ratio
SR - Shrinkage ratio
TE - Trolox equivalent
TPC - Total phenolic content
WP - White pitaya

Latin Symbols
L: Half the slice thickness of the sample
M_e: Equilibrium moisture
M_i: Initial moisture content
M_t: Moisture content
R^2: Coefficient of determination

Greek Symbols
$\chi 2$: Chi-square.

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NAUČNI RAD
UDC

UTICAJ SUŠENJA VRUĆIM VAZDUHOM I MIKROTALASNIM SUŠENJEM POMOĆU VRUĆEG VAZDUHA NA KINETIKU SUŠENJA I KVALITET KRIŠKI CRVENE I BELE PITAJE

U ovoj studiji sprovedeno je matematičko modelovanje i kinetika sušenja plodova crvene i bele pitaje vrućim vazduhom (HAD) i sušenja mikrotalasima uz pomoć vrućeg vazduha (HA-MWD). Istraženi su, takođe, odnos rehidratacije (RR), odnos skupljanja (SR), promena boje (ΔE), ukupni sadržaj fenola (TPC), antioksidativna aktivnost (AA) i mikrostrukture. Kod obe metode, efektivni koeficijent difuzije (D_{eff}*) se povećava sa skraćivanjem vremena sušenja. Dok Pejdžov model najbolje odgovara HA-MWD krivama, HAD krive su definisane modelom parabole. Utvrđeno je da je vrednost RR veća kod HA-MWD metode. Vrednosti TPC svežih plodova crvene i bele pitaje su kao 389,7±0,8 i 310,1±0,4 mg GAE/100 g suve materije (DM), redom. Najviša vrednost TPC plodova sušenih HAD metodom iznosila je 251,4±0,4 mg GAE/100 g DM na 70 °C. Kod plodova sušenih HA-MWD metodom, TPC i AA su se smanjili zbog povećanja snage mikrotalasa. SEM je pokazalo da se veličina pukotina i pora povećava sa povećanjem temperature kod obe vrste voća sušenih HAD metodom. Povećanje snage mikrotalasa je izazvalo veće oštećenje strukture kod HA-MWD metode.*

Ključne reči: Pitaja, sušenje, efektivna difuzija, matematičko modeliranje, mikrostruktura.