Check for updates

Article

FOOD SCIENCE AND TECHNOLOGY INTERNATIONAL

Phenolic content and some physical properties of dried broccoli as affected by drying method

Merve Sılanur Yilmaz[1,2], Özge Şakiyan[1], Işıl Barutcu Mazi[3] and Bekir Gökçen Mazi[3]

Abstract

Broccoli samples (*Brassica oleracea*) with an initial moisture content of 82.87% (wb) were dried using microwave technology (18, 36, and 54 W/g). Convective drying was used as a control group. The dependent variables investigated in the study were phenolic content, color, rehydration capacity, and microstructure of broccoli samples. Moreover, the best fitting thin layer model to the experimental moisture ratio was determined. The phenolic contents were found as 892.4, 740.6, and 759.8 mg gallic acid/100 g dry matter for fresh, convective dried, and microwave (MW) dried at 54 W/g broccoli samples, respectively. The total phenolic content of samples dried at 54 W/g was closest to fresh samples compared to other MW power intensities and convective drying. A similar result was obtained for color values too. L*, a*, and b* of microwave-dried samples at 54 W/g were comparable to fresh broccoli. Another important result obtained from the study was the insignificant effect of drying conditions on rehydration capacity. In addition, it was found that microwave power had a positive effect on drying time; as the microwave powers applied were compared, the shortest drying time was reached at 54 W/g. When the process durations of microwave drying and convective drying were compared, it can be reported that a much lower process time for microwave drying was obtained with respect to convective drying. Drying in microwave oven has reduced the drying time by 49–52%. In the light of the results obtained, it may be declared that it is possible to produce high-quality dried broccoli samples in a very short time by using microwave drying at 54 W/g.

Keywords

Microwave, drying, total phenolic content, color, rehydration capacity, microstructure

Date received: 21 February 2017; accepted: 8 August 2018

INTRODUCTION

Broccoli (*Brassica oleracea* L. var. *italica Plenck*) is a favorite winter vegetable belonging to the Brassicaceae family. Its homeland is eastern Mediterranean basin and Italy (Ciancaleoni et al., 2014; Thapa et al., 2015). In recent years, the production and consumption of broccoli have increased considerably. It has been reported that 46,353 tons of broccoli was produced in Turkey in 2015 (TUIK, 2016). The interest upon broccoli increased due to its nutritive value and beneficial health effects. The high nutritional value of broccoli depends on its A, B1, B2, B5, B6, and E vitamins, Ca, Mg, Zn, and Fe minerals (Gad and Abd El-Moez, 2011; Icier et al., 2010). One other important feature of broccoli is its high amount of vitamin C with a concentration of 82–140 mg/100 g of broccoli (Sermenli et al., 2011). Consumption of broccoli influences the human health in a positive way thanks to its

Food Science and Technology International 25(1) 76–88
© The Author(s) 2018 Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/1082013218797527
journals.sagepub.com/home/fst
SAGE

[1]Department of Food Engineering, Ankara University, Ankara, Turkey
[2]Department of Food Engineering, Bitlis Eren University, Bitlis, Turkey
[3]Department of Food Engineering, Ordu University, Ordu, Turkey

Corresponding author:
Özge Şakıyan, Faculty of Engineering, Department of Food Engineering, Ankara University, Golbasi Campus, Ankara, Turkey.
Email: osakiyan@ankara.edu.tr

particular bioactive compounds. Glucosinolates, sulphoraphane, polyphenols, and some minerals such as selenium are among these compounds (Moreno et al., 2006). In addition to these, broccoli is rich in total phenolic content (TPC) and it varies from 412 to 987 mg/100 g fresh sample in terms of gallic acid (Dziki et al., 2012; Reis et al., 2015). Broccoli has a huge potential on preventing some kinds of cancer and some other cardiovascular illnesses (Abdulah et al., 2005; Mukherjee et al., 2008; Wang et al., 2004). In particular, the presence of high amounts of glucosinolates in broccoli appears to be related to its protective effect against cancer (Moreno et al., 2006). Similarly, selenium acts as a cellular antioxidant and the lack of this mineral is associated with the development of cardiovascular diseases and it also causes some kinds of cancer (Witte et al., 2001).

The metabolic reactions of fresh broccoli shortens its shelf life (Doymaz, 2013); therefore, in order to prolong its life after harvesting and to maintain its usage through the whole year, different preservation techniques such as cooling, freezing and drying have been applied (Mrkíc et al., 2006). Drying is a process of dewatering the food product. The method of protecting food products through drying has been applied since ancient times. The moisture content of 80–90% is expected to be reduced to around 10–20% by drying process. By reducing water content and thereby water activity of foods, it is aimed to reduce microbial activity and the rate of other reactions and thus to extend the durability of foods. The quality features of foods such as taste, smell, and nutritive value are also protected by lowering moisture content (Cemeroglu, 2004).

In traditional drying methods, heat comes to the surface of the food with conduction, convection, or radiation and then it is transmitted to the inner parts (Cemeroglu and Ozkan, 2004). Drying firstly begins on the surface of the product and depending on the initial drying temperature, this may lead to formation of an outer hard layer which decreases or prevents further moisture removal from the product (Karaaslan, 2012). Apart from that, in traditional drying method, the drying process is much longer, causing time and energy loss. The desire for solving the problems existing in the traditional drying process and obtaining higher quality dried products in a shorter time by consuming lower energy has led researchers to study the use of innovative approaches in the traditional drying methods or the use of new technologies. One of the alternative methods in the process of drying is microwave application which provides many advantages such as saving of time and energy; it also protects the nutritive value, process control and provides selective heating (Thostenson and Chou, 1999). The popularity of using microwaves in the heat treatment applications increases due to the fact that high-quality products which can be prepared in a short time with the help of technological innovations are preferred. Microwave provides benefits on different aspects like the process of tempering, drying, pre-heating, pasteurization/sterilization, and baking. The volumetric heating property of microwave drying provides a faster process compared to the traditional drying methods due to the homogeneity of the application (Vadivambal and Jayas, 2007). Besides, overheating on the surface, contraction and loss of nutrient problems may be partially solved (Soysal, 2004).

This study was conducted to dry broccoli (*Brassica oleracea* L. var. *italica Plenck*) by using microwave energy. The main objective of the study was to produce dried broccoli with better quality characteristics in a shorter processing time. It was also aimed to determine the effect of different microwave powers (18, 36, and 54 W/g) on some basic parameters (drying kinetics, color, rehydration capacity, phenolic content, and microstructure) of broccoli.

MATERIALS AND METHODS

Materials

Broccoli samples used in the study were purchased from a local market in Ankara, Turkey. They were cut into pieces with a length of 3–4 cm (one-third of its length was its flowery part and two-thirds of its length was the stalk section) and with a diameter of 1 cm (stalk) to 3 cm (flower). They were stored at +4 °C. All chemicals used for the analysis of phenolic compounds were of analytical grade. They were obtained from Sigma-Aldrich and Merck Chemicals and used as received without any further purification. The water used to prepare all solutions was deionized water.

Methods

Drying. Hot-air drying was performed in a tray drier (Eksis Industrial Drying Systems, Model TK-LAB, Turkey). The width, depth, and height of the drying chamber of the tray drier were 1 m, 1 m, and 1.5 m, respectively. The tray drier consists of 10 trays which were sorted bottom to top of the chamber. The length and the width of the trays can also be reported as 40 cm and 40 cm, respectively. Thirty samples were placed on the trays at a time. As a control, samples were dried at 60 °C with an air velocity of 1 m/s and tray velocity of 5 r/min for 300 min to the final moisture content of 8.79% (wb). The conditions of conventional drying were determined under the light of previous studies (Doymaz and Sahin, 2016; Mahn et al., 2016) and preliminary experiments. Experiments were repeated two times.

Samples were not suitable for a direct microwave drying, and hence a pre-drying treatment was applied to all samples to avoid cooking. Samples were pre-dried in the tray drier at 60 °C with an air velocity of 1 m/s and tray velocity of 5 r/min until reaching a certain moisture content (1 kg water/kg dry matter) and subsequently microwave dried to the final moisture content. The intermediate moisture content was determined by preliminary experiments to manage obtaining dried product without burned spots. The pre-drying duration was determined accordingly. Microwave drying was performed in a kitchen-type microwave oven (General Electric, GMOM 25 model, USA) at power intensity levels of 18 W/g, 36 W/g, and 54 W/g (Karaaslan, 2016; Ozkan et al., 2007). The levels were determined according to the preliminary experiments. Since higher microwave power intensities applied to broccoli samples caused burned points on the sample, the experimental design of the study was prepared with the highest value of 54 W/g. The dimensions of the drying chamber of the microwave oven were $20 \times 30 \times 40$ cm. One broccoli sample, the dimensions of which were reported in the Materials section, was placed at the center of the turning table with a diameter of 28 cm. Dried broccoli samples were stored in vacuum-packages at 4 °C.

To evaluate the drying kinetics of broccoli, dimensionless moisture ratio (MR) values were determined from the moisture content data (kg water/kg dry matter) obtained during drying from equation (1)

$$MR = (M(t) - M_e)/(M_o - M_e) \quad (1)$$

where M_o is the initial moisture content, M_e is the equilibrium moisture content, and M(t) is the moisture content at time t. Each drying experiment was repeated two times. The weights of the samples were measured at regular intervals of time using a digital balance with an accuracy of ±0.001 g during drying process. The weight loss measure during drying was co-related with moisture content of samples. Arithmetic mean of data was used for the estimation of MR values. The equilibrium moisture content (M_e) was neglected since the values of M_e are relatively small compared to M_t and M_o (Balbay and Şahin, 2012; Dadali et al., 2007; Midilli et al., 2002; Tulek, 2011). Eight different single-layer drying models (Newton (Lewis, 1921), Page (Sarsavadiva et al., 1999), Henderson and Pabis (Henderson and Pabis, 1961), Wang and Singh (Wang and Singh, 1978), Logarithmic (Yaldiz and Ertekin, 2001), Verma et al. (Verma et al., 1985), Two-term (Zielinska and Markowski, 2010), Midilli et al. (Midilli et al., 2002)) were applied to drying curves. The nonlinear least-squares procedure was used to estimate model parameters (Matlab R2009b). The model with the lowest sum of squared errors of prediction (SSE) and root-mean-square-error (RMSE) and the highest coefficient of determination (R^2) was defined as the best model describing the thin layer drying behavior of broccoli. RMSE, SSE, and R^2 values were determined by using equations (2), (3), and (4), respectively

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

$$SSE = \sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pred,i}\right)^2 \quad (3)$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pred,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{mean}\right)^2}\right] \quad (4)$$

where N is the number of observations, n is the number of constants, $MR_{exp,i}$ and $MR_{pred,i}$ are the ith experimental and predicted MR values, respectively.

Determination of moisture content. The moisture contents of the samples before and after drying were measured at 105 °C (MA-150, Sartorius, Germany) with an infrared moisture measurement device.

Determination of color values. The surface color of samples was measured by using Minolta Color Reader (CR-400, Japan) and expressed as the CIE L*, a*, and b* color scale. The average of five different readings from the same region was recorded (Akbulut and Coklar, 2008).

Determination of rehydration capacity. The rehydration capacity of dried broccoli samples was determined by immersing samples in distilled water at 24 ± 2 °C for 24 h. Then the samples were taken out, filtered to remove excess water and weighed. The rehydration ratio was calculated as grams of rehydrated sample per gram of dry sample (Quintero-Ramos et al., 1992).

Determination of shrinkage. Shrinkage represents the volume reduction or the change of selected dimensions occurring due to the moisture taken away from the sample structure in a drying process (Aral and Beşe, 2016). Shrinkage (S) is calculated by using equation (5)

$$S = (V_{fresh\ sample} - V_{dried\ sample})/V_{fresh\ sample} \quad (5)$$

where $V_{fresh\ sample}$ is the volume of fresh sample (mL) and $V_{dried\ sample}$ is the volume of dried sample (mL).

The volume of fresh sample and dried sample was determined by using the volume displacement method (Sablani et al., 2002).

Determination of total phenolic content by Folin–Ciocalteu reagent assay. TPC of each sample was determined by the Folin–Ciocalteu method (Slinkard and Singleton, 1977) with some modifications. About 3 g of sample were homogenized (WiseTis, HG-15 model) with methanol (60 mL). Then, it was filtered and centrifuged (Isolab, 02012 Plus gren Euro plug) at 2500*g* for 15 min. The extract solution (60 μL) was mixed with 3.48 mL distilled water and 300 μL of Folin–Ciocalteu reagent (2 N), followed by the addition of 900 μL of 20% Na_2CO_3 solution. Subsequently, the mixture was incubated in a shaking incubator at 40 °C for 30 min and its absorbance was measured at 760 nm. Gallic acid in methanol was used as a standard. Results were expressed as milligram gallic acid equivalents (mg GAE/100 g of dry matter).

Analysis of phenolic compounds. For extraction, ground sample (2 g) was mixed with 40 mL of water/methanol (40:60) solution. The resulting suspension was sonicated using an ultrasonic water bath (Bandelin, Germany) at 30 °C for 30 min. The supernatant was removed and the process was repeated again. The combined extract was evaporated in a rotary evaporator at 30 °C under the reduced pressure. After evaporation, volume of the concentrate was completed to 30 mL with water/methanol (40:60) solution and filtered (0.45 μm syringe filter). Chromatographic analysis was performed on this sample.

The Accela UPLC coupled with TSQ Quantum Access MAX Triple Quadrupole MS (Thermo Fisher Scientific Inc. Waltham, MA, USA) system was used for analysis of phenolic compounds. The data were acquired and processed using Xcalibur software. The mass spectrometer parameters were as follows: the flow rate of sheath gas and aux gas was kept at 50 and 20 arbitrary units, respectively. The temperature of the capillary was held at 270 °C and spray voltage was ± 3500 V. The compounds were separated at 40 °C on a Hypersil Gold RP C18 column (50 mm × 2.1 mm, 1.9 μm, Thermo Fisher Scientific Inc., Waltham, MA, USA). The sample injection volume was 10 μL. Gradient elution was applied using water/methanol (95:5) containing 0.1% HCOOH and 4 mM ammonium acetate (A) and methanol (B). The flow rate was 0.4 mL/min and the linear gradient was 0–100% B in 4 min and was held at 100% B for 3 min and then decreased to 0% B until 2 min.

Scanning electron microscopy analysis. Scanning electron microscopy (SEM) analysis was performed to examine the microstructure of the fresh and dried samples. The samples were cut into slices and were coated with a very thin layer of gold. The SEM observations were taken at a magnification of 100 × and 500 × using an electron microscope (Hitachi SU1510, Tokyo, Japan) with an accelerating voltage of 15 kV.

Statistical analysis

Analysis of variance (ANOVA) was used to determine the significant differences. Minitab 16 software program (Minitab Inc., State College, PA, USA) was used to apply ANOVA. If significant differences were found, Tukey's Multiple Comparison Test was used for comparisons ($p \leq 0.05$).

RESULTS AND DISCUSSION

Drying kinetics

The initial moisture content of the broccoli was found to be around 4.838 kg water/kg dry matter and the drying process was continued until the final moisture content of samples reached 0.096 kg water/kg dry matter. Drying curve for hot-air drying method is shown in Figure 1. The total drying time required for broccoli samples using hot air drying was nearly 300 min. The moisture content of samples decreased gradually during this time. The variations of moisture content of broccoli samples with the microwave drying time at different power levels are given in Figure 2. For all levels of microwave power, the moisture contents of samples decreased sharply. The pre-drying time lasted for about 140–160 min. The microwave drying time was recorded as 16 min, 6.5 min, and 6 min at 18 W/g, 36 W/g, and 54 W/g power intensity levels, respectively. Microwave drying substantially reduced the total time of the drying process (49–52%). Similar results were reported by other researchers with different food materials like banana and kiwi fruit slices (Ozturk et al., 2016) and spinach leaves (Ozkan et al., 2007).

As seen from Figure 2, the microwave power level is an important factor on the drying rate of broccoli. The rate of moisture loss was higher at higher microwave power levels. This is an expected result since the energy absorbed by the sample increased as the microwave power level increased and it is known that higher amounts of volumetric heat generation inside the food material result in increased moisture vapor generation which creates significant internal pressure and concentration gradients (Datta, 1990). Therefore, the flow rate of the liquid through the food to the boundary is increased (Sumnu et al., 2005). Aydoğdu et al. (2015) observed a similar trend during microwave-infrared drying of eggplant and explained this by the fact that

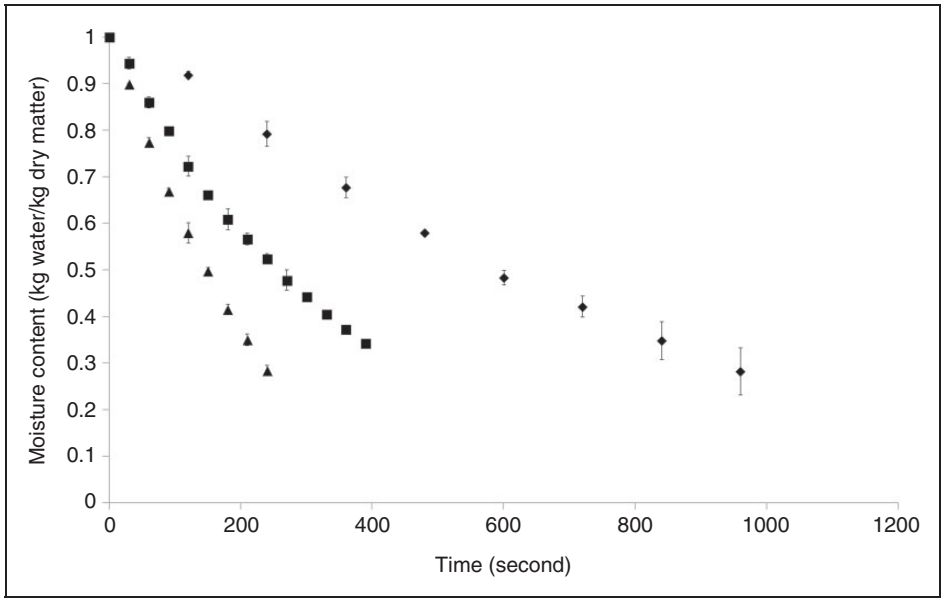


Figure 1. Variation of moisture content during conventional drying.

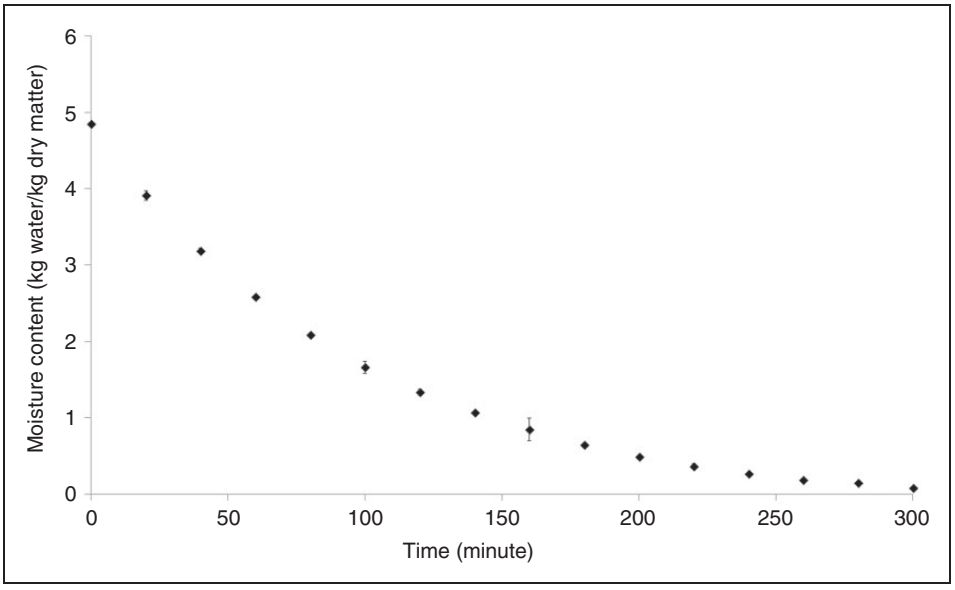


Figure 2. Variation of moisture content during microwave drying at different power intensity levels (18 W/g (•), 36 W/g (■), 54 W/g (▲)).

the rate of mass transfer was higher at higher microwave powers. Similarly, Béttega et al. (2014) reported that microwave power output has a significant effect on the drying rate of carrot.

The moisture content data were fitted to eight different single-layer drying models (Newton, Page, Midilli et al., Henderson and Pabis, Wang and Singh, Logarithmic, Verma et al., and Two-term), and the results of nonlinear regression analysis are presented in Table 1. As seen from Table 1, all correlation coefficients (R^2) were greater than 0.98, meaning that all of these models were notable in description of the thin layer drying characteristics of broccoli for both microwave drying and conventional drying. The RMSE and SSE values were within the range of 0.002709–0.029440 and 9.5×10^{-5}–0.0.456, respectively. In literature, the drying coefficient (k) was used as an approximation for characterizing the effect of temperature and it increases with increasing drying temperature (Oliveira et al., 2016; Rosa et al., 2015).

Table 1. Parameters of different single-layer drying models determined for broccoli samples dried by different drying methods

Model	Drying method	Constants and coefficients	RMSE	SSE	R^2
Newton	Hot air	$k = 0.0102$	0.012390	0.00230	0.9983
$MR = \exp(-kt)$	18 W/g	$k = 0.0711$	0.029440	0.00693	0.9865
	36 W/g	$k = 0.1628$	0.008393	0.00092	0.9985
	54 W/g	$k = 0.2935$	0.029260	0.00771	0.9878
Page	Hot air	$k = 0.0077$, $n = 1.061$	0.007940	0.00088	0.9993
$MR = \exp(-kt^n)$	18 W/g	$k = 0.0429$, $n = 1.218$	0.007663	0.00041	0.9992
	36 W/g	$k = 0.1536$, $n = 1.041$	0.006660	0.00053	0.9991
	54 W/g	$k = 0.2412$, $n = 1.195$	0.012200	0.00119	0.9981
Henderson and Pabis	Hot air	$a = 1.012$, $k = 0.0104$	0.012080	0.00204	0.9985
$MR = a\exp(-kt)$	18 W/g	$a = 1.039$, $k = 0.0754$	0.024230	0.00411	0.9919
	36 W/g	$a = 1.013$, $k = 0.1662$	0.006488	0.00050	0.9992
	54 W/g	$a = 1.034$, $k = 0.3074$	0.026280	0.00553	0.9913
Wang and Singh	Hot air	$a = -0.0075$, $b = 1.48 \times 10^{-5}$	0.032250	0.01456	0.9893
$MR = 1 + at + bt^2$	18 W/g	$a = -0.0582$, $b = 0.0008$	0.014550	0.00148	0.9971
	36 W/g	$a = -0.1510$, $b = 0.0078$	0.007035	0.00059	0.9990
	270 W	$a = -0.2355$, $b = 0.0137$	0.008018	0.00051	0.9992
Logarithmic	Hot air	$a = 1.037$, $k = 0.0094$, $c = -0.0386$	0.002739	9.8×10^{-5}	0.9999
$MR = a\exp(-kt) + c$	18 W/g	$a = 1.498$, $k = 0.0425$, $c = -0.4809$	0.014240	0.00122	0.9976
	36 W/g	$a = 1.025$, $k = 0.16280$, $c = -0.0133$	0.006739	0.00050	0.9992
	54 W/g	$a = 1.520$, $k = 0.16280$, $c = -0.5146$	0.007751	0.00042	0.9993
Verma et al.	Hot air	$a = 1.067$, $k = 0.00919$, $g = 0.0015$	0.002709	9.5×10^{-5}	0.9999
$MR = a\exp(-kt)+(1-a)\exp(-gt)$	18 W/g	$a = -0.145$, $k = 0.53160$, $g = 0.0854$	0.006841	0.00028	0.9995
	36 W/g	$a = 1.003$, $k = 0.16240$, $g = 0.0538$	0.009092	0.00091	0.9985
	54 W/g	$a = -6.773$, $k = 0.51430$, $g = 0.4767$	0.014156	0.00140	0.9978
Midilli et al.	Hot air	$a = 0.998$, $k = 0.00926$, $n = 1.011$, $b = -9.6 \times 10^{-5}$	0.003159	0.00012	0.9999
$MR = a\exp(-kt^n) + bt$	18 W/g	$a = 1.004$, $k = 0.04361$, $n = 1.241$, $b = 0.00194$	0.008255	0.00034	0.9993
	36 W/g	$a = 1.004$, $k = 0.16210$, $n = 1.083$, $b = 0.00823$	0.005767	0.00033	0.9994
	54 W/g	$a = 1.004$, $k = 0.21340$, $n = 1.035$, $b = -0.0329$	0.008065	0.00039	0.9994
Two-term	Hot air	$a = 1.094$, $k_0 = 0.0090$, $b = -0.0959$, $k_1 = 0.0023$	0.002725	8.9×10^{-5}	0.9999
$MR = a\exp(-k_0t)+b\exp(-k_1t)$	18 W/g	$a = -0.145$, $k_0 = 0.5258$, $b = 1.1460$, $k_1 = 0.0854$	0.007450	0.00028	0.9995
	36 W/g	$a = 1.019$, $k_0 = 0.1623$, $b = -0.0089$, $k_1 = -0.0534$	0.007110	0.00050	0.9992
	54 W/g	$a = 1.016$, $k_0 = 0.2361$, $b = -0.0389$, $k_1 = -0.3017$	0.008046	0.00039	0.9994

In this study, the drying coefficient (k) was higher in the case of microwave drying and also found to increase with increasing microwave power level for the models with exponential function except the Verma and Two-term exponential models. The Two-term model was found as the most appropriate model in defining the drying behavior of hot-air drying of broccoli (Figure 3). Similarly, the Two-term model showed a better fit to the experimental MR values obtained during microwave drying at 54 W/g. However, Verma and Midilli et al. models provided the lowest RMSE and the highest R^2 values for microwave drying at

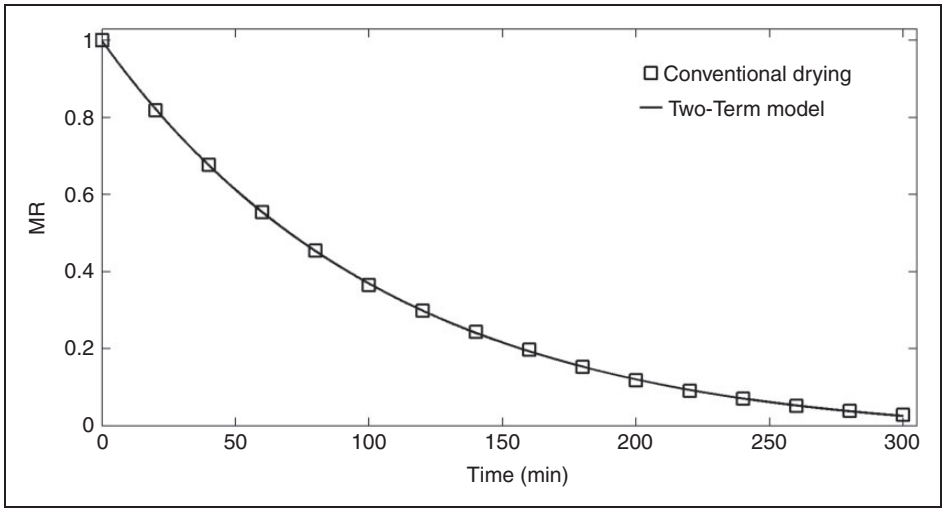


Figure 3. Experimental and predicted drying curves for conventionally dried broccoli.

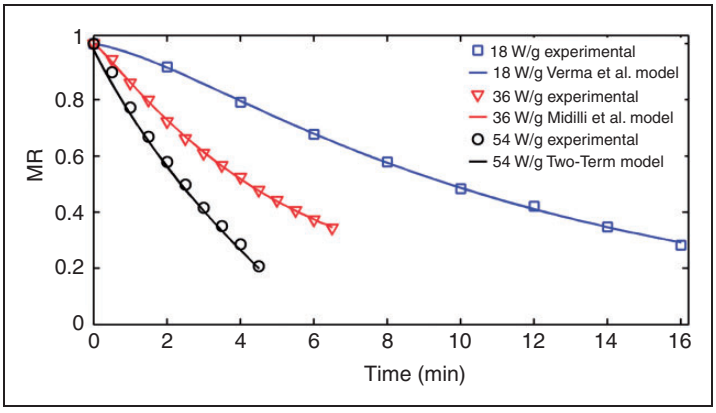


Figure 4. Experimental and predicted drying curves of broccoli during microwave drying at different power intensity levels.

18 W/g and 36 W/g power intensity levels, respectively. Experimental MR data and the predicted values of the MR calculated by using the most appropriate models at each microwave drying condition are shown in Figure 4.

Color values

It is generally known that vegetables are a vital source of many bioactive compounds, such as vitamins, minerals, pigments, and volatile compounds. Some process parameters such as temperature, microwave power, light, exposure time, and oxygen are responsible for the degradation of these compounds during drying process. Since color can be considered as the indicator of pigment retention, it can be offered to be used for the optimization of drying process. For this reason, in this study, the effects of different MW powers on dried broccoli color were studied. For this purpose, L* (lightness), a*(greens), and b*(yellowness) values were observed and compared with the control group (Table 2). The results showed that there was no significant effect of microwave power on lightness of samples. This can be explained by the short processing times of microwave application. Aydoğdu et al. (2015) also showed that microwave heating did not result in any significant color change in microwave-dried eggplants. Similarly, there was no significant difference between microwave-dried samples and the control group, but both were found to have less lightness values than fresh samples (Table 2). This result showed that microwave drying was a promising technique for broccoli drying in terms of color characteristics of the product. Although the difference was not significant, the L* value of the sample dried at 54 W/g had the highest value and was closer to fresh samples. This is due to

Table 2. Color values of broccoli samples

Samples	L*	a*	b*
Fresh broccoli	50.30a ± 2.09	−14.19b ± 1.01	26.39ab ± 3.37
Control	39.33b ± 3.12	−6.61a ± 1.67	24.08b ± 1.92
18 W/g	37.33b ± 3.59	−5.95a ± 1.87	23.71b ± 3.29
36 W/g	39.34b ± 3.12	−4.91a ± 1.80	27.73ab ± 1.42
54 W/g	42.07b ± 2.12	−7.87a ± 2.03	29.63a ± 1.99

L*: lightness; a*: greens, and b*: yellowness.
Note: Mean values in a column with different letters are significantly different at $p < 0.05$.

Table 3. Rehydration capacity and shrinkage of broccoli samples

Samples	Rehydration capacity	Shrinkage (%)
Fresh	–	–
Control	6.42a ± 0.32	60.44b ± 8.11
18 W/g	5.56b ± 0.34	83.31a ± 4.63
36 W/g	5.42b ± 0.19	75.88a ± 6.04
54 W/g	5.59b ± 0.24	78.93a ± 6.22

Note: Mean values in a column with different letters are significantly different at $p < 0.05$.

the short period of drying which causes less damage to color pigments and more preserved color can be obtained. In literature, there were some similar results reported. Alibas (2007a) dried nettle leaves with microwave, hot air, and under vacuum. He found that L* value of dried samples at 850 W microwave power, which was the highest microwave power applied, was closer to fresh samples. Similarly, Alibas and Koksal (2014) dried mallow leaves using three different techniques (convective, vacuum, and microwave drying). The results of this study showed that microwave-dried samples had the most similar color values to fresh samples. Valadez-Carmona et al. (2016) examined the effect of microwave drying and oven drying on color of coconut husk. They found that microwave-dried samples had closer lightness values to fresh coconut husks than the oven-dried ones. Negative a* value is the indicator for the presence of green color. As this value approaches zero, the green color in the samples decreases. In Table 2, it is given that there was a significant difference between processed samples and fresh ones ($p < 0.05$). But it can also be seen that the type of application did not affect the a* values of the samples significantly. Despite the fact that no significant difference between application types and microwave powers was detected, the a* value of samples dried at 270 W was closer to that of fresh samples.

Alibas (2007b) reported a similar result. He dried pumpkin slices by using microwave, hot air, and microwave–hot air combination. Pumpkin slices, dried with microwave (160 W and 350 W) had close a* values to fresh samples. Similarly, Mujaffar and Loy (2016) dried vegetable amaranth leaves with microwave at different powers (200, 500, 700, and 1000 W), but they reported that a* values of samples dried at low powers (200 and 500 W) were similar to fresh samples. The final color value to be discussed is b* value, which indicates yellow color when positive. It can be seen from Table 2 that both microwave power and application type were effective on b* values ($p < 0.05$). This variation in b* value can be due to the appearance of yellow color in the samples due to chlorophyll degradation.

Shrinkage and rehydration capacity

Another important parameter to be considered in the quality of the dried material is the rehydration capacity. It generally gives information about the physical and chemical changes in the material during drying. The rehydration capacity of dried samples is shown in Table 3. The results showed that although there was a significant difference between conventional drying and microwave drying, no significant effect of microwave power was detected. This can be explained by the shrinkage results of the study (Table 3). Since the shrinkage values of microwave-dried samples were too high, it resulted in low rehydration capacity. In literature, some researchers reported similar results but some announced quite the opposite. Kutlu and İşçi (2016) dried tomatoes by using hot air and microwave and observed rehydration capacity. The results showed that tomato samples dried with hot air had a higher rehydration capacity. On the contrary, Maskan (2000) dried banana slices using different drying methods: convection, microwave, and convection followed by MW finish drying and the result of this study showed that MW finish-dried banana had the highest rehydration capacity. This can be explained by the differences between the microstructures and porosities of different materials.

Microstructure

SEM micrographs of fresh, control and microwave-dried (54 W/g) samples are shown in Figure 5. Fresh broccoli tissue is composed of uniformly distributed oval cells as seen in Figure 5(a) (Xin et al., 2014). A high degree of cell disruption was obtained in both dried samples as compared to the fresh broccoli sample. The structural damage is higher in the sample dried by hot air–microwave combination drying method. Microwave drying led to the formation of large gaps

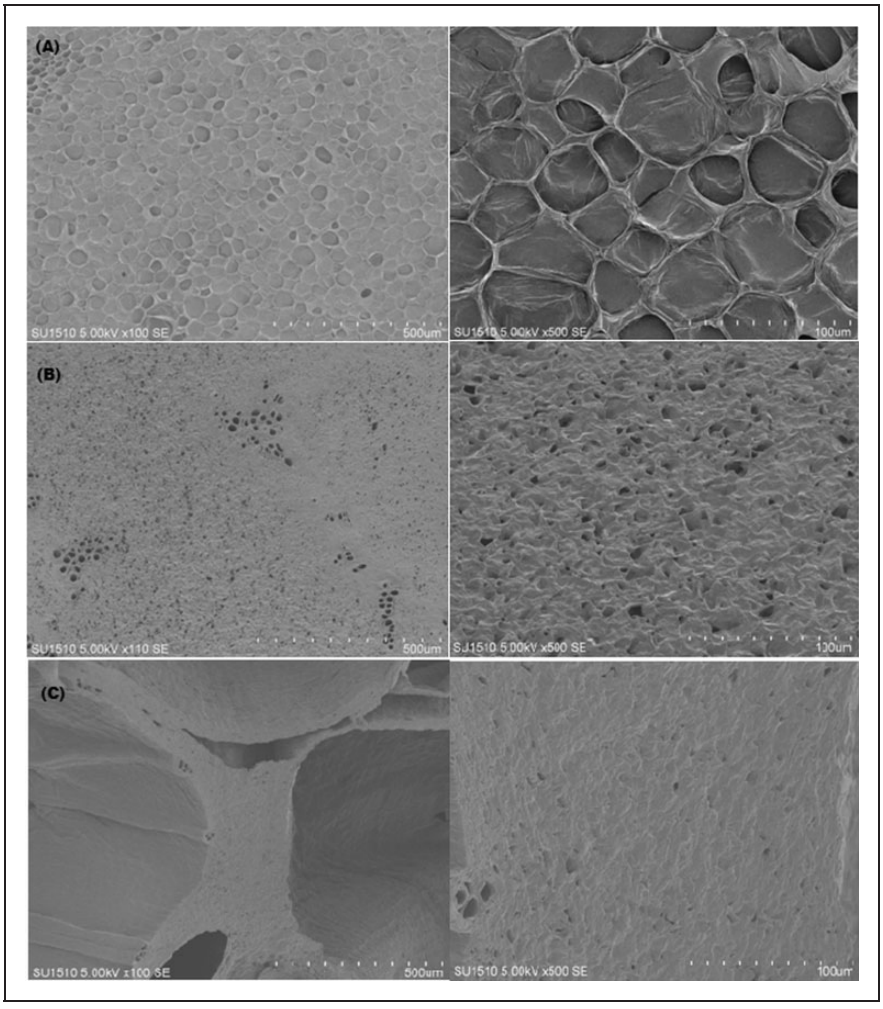


Figure 5. SEM microphotographs (100 × and 500 × magnification) of the surface of the (a) fresh broccoli, (b) control, and (c) hot air-microwave-dried broccoli samples.

that can be macroscopically observed within the broccoli tissue (Figure 5(c)) which is thought to be caused by rapid removal of water due to internal heat generation. The tissue between these gaps appears to be more compact and less porous as compared to control (Figure 5(b) and (c)). This may explain the lower rehydration ratio of microwave-dried sample as compared to the control sample. It is widely known that the food microstructure formed during drying process is highly related to the rehydration capacity of the dried product (Giri and Prasad, 2007; Vega-Gálvez et al., 2015; Xie et al., 2017). Krokida and Philippopoulos (2005) stated that cellular and structural disruption during drying causes lower rehydration capacity. Many researchers have similarly attributed the low-water absorption capacity of dried products to higher cell disruption and tissue damage (Ciurzyńska, 2013; Doymaz, 2015; Ricce et al., 2006; Vega-Gálvez et al., 2008).

Total phenolic content

The TPC of fresh broccoli was found as 892.4 mg gallic acid/100 g dry matter. After conventional and microwave drying, the TPC of the sample was reduced due to the temperature increase of the material. It can be seen from Table 4 that there was a significant effect of drying process on TPC of the broccoli samples. Besides, the microwave power was found to be significantly effective too. The samples which were exposed to 54 W/g microwave power intensity had comparable TPC results to fresh samples. This could be due to the short processing time. Since the sample was exposed to microwaves for a shorter duration, the phenolic compounds were less affected. Likewise, Turkmen et al. (2005) studied the effects of microwave and convectional cooking methods on total phenolics of broccoli and they reached the highest content of total phenolics with microwave cooking. In a study of LC

Reis dos Ramos et al. (2015), cauliflower was processed by using different cooking methods (boiling, steam, and microwave). They reported that MW cooked samples had the highest TPC and it was also declared that microwave cooked samples were comparable to fresh samples in terms of phenolic content. As a final example from literature, Sun et al. (2014) studied the effect of different cooking methods on phenolic contents of *Boletus* mushrooms. For this aim, steaming, pressure-cooking, microwave heating, frying, and boiling methods were used and it was stated that microwave heating established the best results in terms of phenolic content.

Identification of phenolic compounds

In order to determine the effect of microwave drying on some phenolic compounds (luteolin, apigenin, quercetin, isorhamnetin, caffeic acid, syringic acid, rosmarinic acid, trans-ferulic acid, p-coumaric acid, and chlorogenic acid) of broccoli (*Brassica oleracea*), Liquid Chromatograph Triple Quadrupole Mass Spectrometer (LC-MS/MS) chromatography was performed. The phenolic compounds of luteolin, apigenin, caffeic acid, syringic acid, and rosmarinic acid were not detected in the analyzed samples (Table 5). The trans-ferulic acid and p-coumaric acid content of control and MW dried samples was much higher than the respective contents in the fresh broccoli. These results may be explained by an increment of the accessibility of phenolic compounds by the drying treatments (Wojdyło et al., 2014). The analysis of the content of phenolic compound in the dried broccoli samples showed that phenolic acids were more stable during drying than the flavonoid. The content of chlorogenic acid in the dried samples ranged from 38.4% to 89.1% of the initial value. The highest content was determined in the samples of broccoli dried by MW at 54 W/g power intensity.

Table 4. Total phenolic content of broccoli samples

Samples	Total phenolic content (mg gallic acid/100 g dry matter)
Fresh	892.4a ± 25.7
Control	740.6bc ± 48.70
18 W/g	507.1 d ± 29.40
36 W/g	606.9cd ± 71.20
54 W/g	759.8ab ± 115.20

Note: Mean values in a column with different letters are significantly different at $p < 0.05$.

CONCLUSION

In the current study, it was aimed to dry broccoli (*Brassica oleracea* L. var. *italica Plenck*) by using microwave energy. In addition, the effects of different drying methods and different microwave power intensities on the quality characteristics (color, rehydration capacity, microstructure, shrinkage, total phenolic content, drying rate) of broccoli were investigated. It was also aimed to produce dried broccoli with better quality characteristics in a shorter processing time. In this

Table 5. Phenolic compounds in broccoli methanolic extracts from different samples.

	Broccoli (*Brassica oleracea*)		
Phenolic compounds (μg/g dry matter)	Fresh	Control	Microwave dried (54 W/g)
Flavonoid			
Luteolin	ND	ND	ND
Apigenin	ND	ND	ND
Quercetin	1.845 ± 0.078	0.032 ± 0.001	0.173 ± 0.021
Isorhamnetin	1.230 ± 0.009	0.029 ± 0.012	0.474 ± 0.035
Phenolic acid			
Caffeic acid	ND	ND	ND
Syringic acid	ND	ND	ND
Rosmarinic acid	ND	ND	ND
trans-Ferulic acid	4.976 ± 0.140	3.098 ± 0.164	7.252 ± 0.098
p-Coumaric acid	0.262 ± 0.004	0.495 ± 0.026	1.258 ± 0.062
Chlorogenic acid	52.158 ± 1.290	20.023 ± 0.163	46.489 ± 1.783
Total	60.470	23.676	55.646

ND: Not detected. Note: Values are presented in mean ± standard error of the mean, n = 2.

present study, experimental data for broccoli samples were used to evaluate several thin layer drying models available in the literature. All of these models were notable in description of the thin layer drying characteristics of broccoli for both microwave drying and conventional drying. The cell disruption of dried samples as compared to the fresh broccoli sample was noticeable and it was more clear in microwave drying. The phenolic contents of fresh, convective dried, and MW dried at 54 W/g broccoli samples were found as 892.4, 740.6, and 759.8 mg gallic acid/100 g dry matter, respectively. The results showed that microwave dried samples with a microwave power intensity of 54 W/g were found to have comparable phenolic content results with respect to fresh broccoli. Similar trend was observed in the case of color values; the L* value of the sample dried at 54 W/g had the highest value and was closer to fresh samples. Another important finding of the study was the positive effect of microwave power on drying time. A threefold increment of microwave power (from 18 W/g to 54 W/g) decreased the drying time from 156 minute to 144 minute. Moreover, the shortest drying time was achieved by using microwave when compared to conventional method. Microwave drying was found to be the fastest heating method (49–52% reduction) with better quality characteristics. Thus, it can be recommended to be used for drying broccoli samples.

PRACTICAL APPLICATIONS

The most important drawback of conventional drying such as hot-air drying is the long processing time at high temperatures which results in a decrement of the dried product quality. To overcome such a problem, as well as to obtain a product with better nutritional and sensory properties, the process could be speeded up by the application of microwave energy. In this study, the effect of microwave drying especially on phenolic content of broccoli samples was investigated.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID ID

Özge Şakiyan http://orcid.org/0000-0002-0778-8211

REFERENCES

Abdulah R, Miyazaki K, Nakazawa M and Koyama H. (2005). Chemical forms of selenium for cancer prevention. *Journal of Trace Elements in Medicine and Biology* 19: 141–150.

Akbulut M and Coklar H. (2008). Physicochemical and rheological properties of sesame pastes (Tahin) processed from hulled and unhulled roasted sesame seeds and their blends at various levels. *Journal of Food Process Engineering* 31: 488–502.

Alibas I. (2007a). Energy consumption and colour characteristics of nettle leaves during microwave vacuum and convective drying. *Biosystems Engineering* 96(4): 495–502.

Alibas I. (2007b). Microwave, air and combined microwave-air drying parameters of pumkin slices. *Science Direct* 40: 1445–1451.

Alibas I and Koksal N. (2014). Convective, vacuum and microwave drying kinetics of mallow leaves and comparison of color and ascorbic acid values of three drying methods. *Food Science and Technology* 34(2): 358–364.

Aral S and Beşe AV. (2016). Convective drying of hawthorn fruit (*Crataegus* spp.): Effect of experimental parameters on drying kinetics, color, shrinkage, and rehydration capacity. *Food Chemistry* 210: 577–584.

Aydoğdu A, Sumnu G and Sahin S. (2015). Effects of microwave infrared combination drying on quality of eggplants. *Food and Bioprocess Technology* 8: 1198–1210.

Balbay A and Şahin O. (2012). Microwave drying kinetics of a thin-layer liquorice root. *Drying Technology* 30: 859–864.

Béttega R, Rosa JG, Corrêa RG and Freire JT. (2014). Comparison of carrot (*Daucus carota*) drying in microwave and in vacuum microwave. *Brazilian Journal of Chemical Engineering* 31(2): 403–412.

Cemeroglu B. (2004). *Fruit and Vegetable Processing Technology*, 2nd ed. Ankara, Turkey: Bizim Büro Publisher.

Cemeroglu B and Ozkan M. (2004). *Drying Technology, Fruit and Vegetable Processing Technology*, 2nd ed. Ankara, Turkey: Bizim Büro Publisher, pp. 479–613.

Ciancaleoni S, Chiarenza GL, Raggi L, Branca F and Negri V. (2014). Diversity characterisation of broccoli (*Brassica oleracea* L. var. *italica Plenck*) landraces for their on-farm (in situ) safeguard and use in breeding programs. *Genetic Resources and Crop Evolution* 61: 451–464.

Ciurzyńska A, Lenart A and Kawka P. (2013). Influence of chemical composition and structure on sorption properties of freeze-dried pumpkin. *Drying Technology* 31: 655–665.

Dadali G, Apar DK and Ozbek B. (2007). Microwave drying kinetics of okra. *Drying Technology* 25: 917–924.

Datta AK. (1990). Heat and mass transfer in the microwave processing of food. *Chemical Engineering Progress* 86: 47–53.

Doymaz I. (2013). Effect of blanching temperature and dipping time on drying time of broccoli. *Food Science and Technology International* 20(2): 149–157.

Doymaz I. (2015). Infrared drying kinetics and quality characteristics of carrot slices. *Journal of Food Processing and Preservation* 39: 2738–2745.

Doymaz I and Sahin M. (2016). Effect of temperature and pre-treatment on drying and rehydration characteristics of broccoli slices. *Journal of Food Measurement and Characterization* 10(2): 364–373.

Dziki UG, Jeyna M, Swieca M, Dziki D, Baraniak B and Czyz J. (2012). Effect of bioaccessibility of phenolic compounds on in vitro anticancer activity of broccoli sprouts. *Food Research International* 49: 469–476.

Gad N and Abd El-Moez MR. (2011). Broccoli growth, yield quantity and quality as affected by cobalt nutrition. *Agriculture and Biology Journal of North America* 2: 226–231.

Giri SK and Prasad S. (2007). Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. *Journal of Food Engineering* 78(2): 512–521.

Henderson SM and Pabis S. (1961). Grain drying theory I: Temperature effect on drying coefficient. *Journal of Agriculture Research Engineering* 6: 169–174.

Icier F, Colak N, Erbay Z, Kuzgunkaya EH and Hepbasli AA. (2010). Comparative study on exergetic performance assessment for drying of broccoli florets in three different drying systems. *Drying Technology* 28: 193–204.

Karaaslan S. (2012). Microwave-related drying of fruits and vegetales. *Süleyman Demirel Universitesi Ziraat Fakultesi Dergisi* 7(2): 123–129.

Karaaslan S. (2016). Investigation of drying parameters of broccoli during fan-assisted microwave, air and a combined microwave/air drying. *The Journal of Animal and Plant Sciences* 26(1): 123–130.

Krokida MK and Philippopoulos C. (2005). Rehydration of dehydrated foods. *Drying Technology* 23: 799–830.

Kutlu N and İşçi A. (2016). Effect of drying methods on characteristics of cherry tomato and mathematical modeling. *GIDA: Journal of Food* 41(4): 197–204.

Lewis WK. (1921). The rate of drying of solid materials. *Industrial Engineering Chemistry* 13: 427–443.

Mahn A, Martin C, Reyes and Saavedra A. (2016). Evolution of sulforaphane content in sulforaphane-enriched broccoli during tray drying. *Journal of Food Engineering* 186: 27–33.

Maskan M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food Engineering* 44: 71–78.

Midilli A, Kucuk H and Yapar Z. (2002). A new model for single-layer drying. *Drying Technology* 20: 1503–1513.

Moreno DA, Carvajal M, López-Berenguer C and García-Viguera C. (2006). Chemical and biological characterization of nutraceutical compounds of broccoli. *Journal of Pharmaceutical and Biomedical Analysis* 41: 1508–1522.

Mrkíc V, Cocci E, Rosa MD and Sacchetti G. (2006). Effect of drying conditions on bioactive compounds and antioxidant activity of broccoli (*Brassica oleracea* L.). *Journal of the Science of Food and Agriculture* 86: 1559–1561.

Mujaffar S and Loy LL. (2016). Drying kinetics of microwave-dried vegetable amaranth (*Amaranthus dubius*) leaves. *Canadian Center of Science and Education* 5: 6.

Mukherjee S, Gangopadhyay H and Das DK. (2008). Broccoli: A unique vegetable that protects mammalian hearts through the redox cycling of the thioredoxin superfamily. *Journal of Agriculture and Food Chemistry* 56: 609–617.

Oliveira GHH, Costa MR, Botelho FM, Viana JL and Garcia TRB. (2016). Thermodynamic properties and kinetics of drying process of chia seeds (*Salvia hispanica* L.). *Research Journal of Seed Science* 9(2): 36–41.

Ozkan AI, Akbudak B and Akbudak N. (2007). Microwave drying characteristics of spinach. *Journal of Food Engineering* 78: 577–583.

Ozturk S, Sakiyan O and Alifaki YO. (2017). Dielectric properties and microwave and infrared-microwave combination drying characteristics of banana and kiwifruit. *Journal of Food Process Engineering* 40(3): 944–953.

Quintero-Ramos A, Borne MC and Anzaldua-Morales A. (1992). Texture and rehydration of dehydrated carrot as affected by low temperature blanching. *Journal of Food Science* 57(5): 1127–1128.

Reis dos Ramos LC, Ruffo de Oliveira V, Hagen MEK, Jablonski A, Flores SH and Rios AO. (2015). Carotenoids, flavonoids, chlorophylls, phenolic compounds and antioxidant activity in fresh and cooked broccoli (*Brassica oleracea* var. Avenger) and cauliflower (*Brassica oleracea* var. Alphina F1). *Food Science and Technology* 63: 177–183.

Ricce C, Rojas ML, Miano AC, Siche R and Duarte Augusto PE. (2016). Ultrasound pre-treatment enhances the carrot drying and rehydration. *Food Research International* 89: 701–708.

Rosa DP, Cantu-Lozano D, Luna-Solano G, Polachini TC and Telis-Romero J. (2015). Mathematical modeling of orange seed drying kinetics. *Ciência e Agrotecnologia, Lavras* 39(3): 291–300.

Sablani S, Rahman MS and Al-Sadeiri DS. (2002). Equilibrium distribution data for osmotic drying of apple cubes in sugar-water solution. *Journal of Food Engineering* 52: 193–199.

Sarsavadiva P, Sawhney R, Pangavhane DR and Sing I. (1999). Drying behaviour of brined onion slices. *Journal of Food Engineering* 40: 219–226.

Sermenli T, Mavi K and Yilmaz S. (2011). Determination of transplanting dates of broccoli (*Brassica oleracea* L. var *italica Plenck*) under Antakya conditions. *The Journal of Animal and Plant Sciences* 21(4): 638–641.

Slinkard K and Singleton VL. (1977). Total phenol analysis: Automation and comparison with manual methods. *American Journal of Enology and Viticulture* 28: 49–55.

Soysal Y. (2004). Microwave drying characteristics of parsley. *Biosystems Engineering* 89(2): 167–173.

Sumnu G, Sahin S and Sevimli M. (2005). Microwave, infrared and infrared-microwave combination baking of cakes. *Journal of Food Engineering* 71: 150–155.

Sun L, Bai X and Zhuang Y. (2014). Effect of different cooking methods on total phenolic contents and antioxidant activities of four Boletus mushrooms. *Journal of Food Science and Technology* 51: 3362–3368.

Thapa U, Prasad PH and Rai R. (2016). Studies on growth, yield and quality of broccoli (*Brassica oleracea italica Plenck*) as influenced by boron and molybdenum. *Journal of Plant Nutrition* 39(2): 261–267.

Thostenson ET and Chou TW. (1999). Microwave processing: Fundamentals and applications. *Composites Part A: Applied Science and Manufacturing* 30: 1055–1071.

TUIK. (2016). Turkish Statistical Institute, Ankara, Turkey. Available at: www.tuik.gov.tr (accessed 12 December 2016).

Tulek Y. (2011). Drying kinetics of oyster mushroom (*Pleurotus ostreatus*) in a convective hot air dryer. *Journal of Agricultural Science and Technology* 13: 655–664.

Turkmen N, Sarı F and Velioglu S. (2005). The effect of cooking methods on total phenolics and antioxidant activity of selected green vegetables. *Food Chemistry* 93: 713–718.

Vadivambal R and Jayas DS. (2007). Changes in quality of microwave-treated agricultural products – A review. *Biyosystems Engineeering* 98: 1–6.

Valadez-Carmona L, Cortez-Garcia RM, Plazola-Jacinto CP, Necoechea-Mondragon H and Ortiz-Moreno A. (2016). Effect of microwave drying and oven drying on the water activity, color, phenolic compounds content and antioxidant activity of coconut husk (*Cocos nucifera* L.). *Journal of Food Science Technology* 53(9): 3495–3501.

Vega-Gálveza A, Lemus-Mondacaa R, Bilbao-Sáinzb C, Fitoc P and Andrés A. (2008). Effect of air drying temperature on the quality of rehydrated dried red bell pepper (var. Lamuyo). *Journal of Food Engineering* 85(1): 42–50.

Vega-Gálvez A, Zura-Bravo L, Lemus-Mondaca R, Martinez-Monzo J, Quispe-Fuentes I, Puente L, et al. (2015). Influence of drying temperature on dietary fibre, rehydration properties, texture and microstructure of Cape gooseberry (*Physalis peruviana* L.). *Journal of Food Science and Technology-Mysore* 52(4): 2304–2311.

Verma LR, Bucklin JB, Endan F and Wratten T. (1985). Effects of drying air parameters on rice drying models. *Transactions of the ASAE* 28: 296–301.

Wang CY and Sing RP. (1978). A single layer drying equation for rough rice. ASAE paper 78, 3001.

Wang LI, Giovannucci EL, Hunter D, Neuberg D, Su L and Christiani DC. (2004). Dietary intake of cruciferous vegetables, glutathione S-transferase (GST) polymorphisms and lung cancer risk in a Caucasian population. *Cancer Causes and Control* 15: 977–985.

Witte KK, Clark AL and Cleland JG. (2001). Chronic heart failure and micronutrients. *Journal of the American College of Cardiology* 37: 1765–1774.

Wojdyło A, Figiel A, Lech K, Nowicka P and Oszmiański J. (2014). Effect of convective and vacuum-microwave drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. *Food and Bioprocess Technology* 7: 829–841.

Xie L, Mujumdar AS, Fang XM, Wang J, Dai JW, Du ZL, et al. (2017). Far-infrared radiation heating assisted pulsed vacuum drying (FIR-PVD) of wolfberry (*Lycium barbarum* L.): Effects on drying kinetics and quality attributes. *Food and Bioproducts Processing* 102: 320–331.

Xin Y, Zhang M and Adhikari B. (2014). The effects of ultrasound-assisted freezing on the freezing time and quality of broccoli (*Brassica oleracea* L. var. botrytis L.) during immersion freezing. *International Journal of Refrigeration* 41: 82–91.

Yaldiz O and Ertekin C. (2001). Thin layer solar drying of some vegetables. *Drying Technology* 19: 583–597.

Zielinska M and Markowski M. (2010). Air drying characteristics and moisture diffusivity of carrots. *Chemical Engineering and Processing* 49: 212–218.