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Effects of oven, microwave and vacuum drying on drying characteristics, colour, total phenolic content and antioxidant capacity of celery slices

A. Özkan Karabacak, S. Suna*, C.E. Tamer and Ö.U. Çopur

Uludag University, Faculty of Agriculture, Department of Food Engineering, 16059 Gorukle, Bursa, Turkey; syonak@uludag.edu.tr

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RESEARCH ARTICLE

Abstract

In this research, the effects of microwave (190, 375, and 680 W) vacuum (500, 600, and 700 mbar) and oven (70, 85, and 100 °C) drying methods on the total phenolics, antioxidant capacity, colour and drying characteristics of celery slices were studied. For the selection of the most suitable thin layer drying model, five mathematical models (Page, Modified Page, Logarithmic, Lewis, and Henderson and Pabis) have been applied to the treatments. In light of the statistical tests, Page and Modified Page models were considered the best to describe drying characteristics. Regarding the colour value changes during drying, L^*, ΔE_{ab} and h° decreased, and a^* increased. Additionally, both b^* and C^*_{ab} increased with microwave and oven drying but decreased with vacuum drying. Dried celery had 38.51-75.34% less total phenolic content than fresh samples, while its antioxidant capacities was greater. The highest ferric-reducing ability of plasma (FRAP; 49.35±3.10 μmol TE/g dw) and cupric-reducing antioxidant capacity (CUPRAC; 33.29±1.02 μmol TE/g dw) resulted from microwave drying at 680 W, and the highest antioxidant capacity from the DPPH method (9.87±0.04 μmol TE/g dw) resulted from microwave drying at 375 W. In overall evaluation, microwave drying provided greater nutritional properties by increasing antioxidant capacity and gave the advantage of reduced drying times.

Keywords: celery, drying kinetics, colour, phenolics

1. Introduction

Celery (*Apium graveolens* L.), which is rich in a variety of phenolics, vitamins and minerals, has been used as a medicinal vegetable for a long time (Madamba and Liboon, 2001). The most abundant minerals in fresh celery are potassium (260 mg/100 g), sodium (80 mg/100 g), calcium (40 mg/100 g), phosphorus (24 mg/100 g) and magnesium (11 mg/ 100 g), while celery stalks include 3.1 mg/100 g ascorbic acid, 6 g/100 g dietary fiber, and 6.1 mg/100 g choline (USDA, 2001). Celery contains many different types of phenolics with antioxidative properties. Moreover, celery cell walls include pectic polysaccharides, which are well known to be components of dietary fibre and possess anti-inflammatory activity (Ovodova *et al.*, 2009; Popov *et al.*, 2005, 2006; Thimm *et al.,* 2000). Celery has recently received increased attention worldwide due to its beneficial health effects such as its role in reducing lipid levels in hypercholesterolemia (Manal and Sahar, 2012). Celery plant, seeds and seed extracts are also used against bronchitis, asthma, rheumatism and gout (Fazal and Singla, 2012). Additionally, dried celery is used as a flavouring agent due to its characteristic flavour and medicinal value (Madamba and Liboon, 2001).

Drying is one of the most common methods used to prolong the shelf life of foods (Dadali *et al.*, 2007a; Incedayi *et al.*, 2016). Together with being a preservation method, drying has advantages such as facilitating the storage and transportation conditions of foods as well as allowing them to be consumed in every season. Furthermore, foods become more resistant to microbiological, enzymatic and chemical degradations with drying (Kaya *et al.*, 2015). In this field, mathematical models are used for the development of the drying system performances, the preservation of the nutritional quality of foods and the decisions involving the most suitable food-specific techniques (Alibas, 2012; Babalis and Belessiotis, 2004). Thin layer drying models can be classified as theoretical, semi-theoretical (Page, Modified Page, Lewis, Henderson and Pabis, Logarithmic, Two term, Approximation of diffusion) and empirical (Wang and Singh, Thomson) (McMinn, 2006; Özdemir and Devres, 1999).

Evaluation of these drying methods shows that oven drying is the most popular and effective method. Although oven drying has some drawbacks such as the drying time duration and low energy efficiency, it is widely used due to its low cost (Arslan and Ozcan, 2010; Soysal and Oztekin, 2001). As an alternative method, vacuum drying is used at reduced pressures, which enables food to be dried at lower temperatures. With this method, fewer oxidation reactions occur due to the absence of air, while the flavour, colour and texture of the dried foods are maintained (Geankoplis, 2011; Gunasekaran, 1999; Zielinska *et al.*, 2013). Microwave drying is another alternative with various advantages such as a higher drying rate, homogeneous energy delivery on the material and better process control (Arslan and Ozcan, 2010; Demiray *et al.*, 2016; Incedayi *et al.*, 2016; Maskan, 2000). Several researchers have recently studied the drying kinetics of okra (Dadali *et al.*, 2007b), peach (Zhu and Shen, 2014), avocado (Avhad and Marchetti, 2016), garlic (Demiray and Tulek, 2014), kiwi (Kaya *et al.*, 2010), spinach (Dadali *et al.*, 2007a), onion (Arslan and Ozcan, 2010) and potato (Celen *et al.*, 2016). There are also some studies focused on the drying of stalks (Sareban and Souraki, 2016) and leaves (Demirhan and Ozbek, 2011; Roman and Hensel, 2011) of celery. Additionally, different parts of celery roots were dried by Bialobrzewski (2006), Jezec *et al.* (2008), Priecina and Karlina (2013). However, a very limited amount of literature describes the drying of slices of celery, and this report was the first study in which the drying kinetics of celery slices dried with different methods (microwave, vacuum and oven) were studied with thin layer models. Furthermore, the aims of this research were to ascertain the thin layer drying kinetics of celery slices, to choose the most appropriate mathematical models and to identify the differences in total phenolics, antioxidant capacity and colour between fresh and dried samples.

2. Material and methods

Chemicals

All chemicals used were of analytical quality. TPTZ (2,4,6-tris(2-pyridyl)-s-triazine) was obtained from Fluka (Buchs, Switzerland). Neocuproine (2,9-dimethyl-1,10-phenanthroline), DPPH (2,2-diphenyl-2-picrylhydrazyl), methanol, sodium carbonate, gallic acid, Trolox ((±)-6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) were supplied by Sigma Aldrich (Darmstadt, Germany). Iron (III) chloride hexahydrate, Folin-Ciocalteu reagent, copper (II) chloride, ammonium acetate and hydrochloric acid were purchased from Merck (Darmstadt, Germany).

Materials

Fresh celery was supplied from a local market in Bursa, Turkey and stored at 4±0.5 °C until the drying processes were performed. Afterward, the celery was washed, wiped, pared and sliced with a food slicer (Nicer Dicer, Zhe Jiang, China). The average length, width and thickness of slices were 7.0±0.05, 2.4±0.05 and 0.3±0.05 cm, respectively. The moisture of the samples was analysed with a moisture analyser (MA150; Sartorius, Göttingen, Germany), and the primary moisture of the celery slices was 8.23 g water/g dry base.

Drying procedure

Three different methods (oven, vacuum and microwave drying) were applied to celery slices. All experiments were carried out in triplicate.

A universal oven (UN55; Memmert, Schwabach, Germany; 53 l volume) was used for oven drying treatments. A total of 50 g of celery slices was placed uniformly as a thin layer on an aluminium plate with a 300 mm diameter. Drying treatments were carried out at 70, 85 and 100 °C. Samples were weighed at 30 min intervals for 2.5 h and then every 15 min during drying. The loss of moisture was determined by weighing the plate using a digital balance (MS3002S; Mettler Toledo, Greifensee, Switzerland) with an accuracy of 0.01 g. Drying experiments lasted between 155 and 270 min, depending on the oven temperature.

The vacuum drying experiments were performed in a vacuum dryer (VO400; Memmert, 49 l volume) at 70 °C and 500, 600 and 700 mbar. A temperature of 70 °C was used according to the report by Madamba and Liboon (2001), who studied the optimization of vacuum drying of celery in the temperature range from 65-75 °C. Then, 50 g of samples was put uniformly in the same aluminium plate used in oven drying. The moisture loss during drying was determined at each 30 min for 3 h and then every 15 min. The duration of the drying process was between 210 and 285 min, depending on the vacuum pressure.

A digital microwave oven (MWHA 2824 B; Hotpoint Ariston, Fabriano, Italy, 28 l volume) with electrical characteristics of 230 V at ~50 Hz and a maximum output of 900 W was used for microwave drying. The size of the microwave cavity was 520×479×341 cm, and a rotating glass plate of 315 mm diameter was at the base of the oven. Drying treatments were performed at 190, 375 and 680 W microwave power levels. In total, 50 g of celery slices were put in a thin layer on a glass plate in the microwave oven.

Drying was applied for a period from 7 to 33 min, which was related to the microwave power. During the drying process, the rotating glass plate was removed from the microwave oven at 3, 2, and 1 min intervals (at 190, 375 and 680 W, respectively), and its weight was measured with a digital balance (MS3002S; Mettler Toledo) with a precision of 0.01 g.

Drying experiments were continued until the moisture content decreased to almost 0.12 g water/g dry base, and all of the samples were weighed for a maximum duration of 10 s.

Mathematical modelling of drying curves

Five different thin-layer drying models were used for the evaluation of the best model that reproduces the drying curve of celery slices (Table 1). The following equations were used to determine the moisture ratio (MR) and drying rate in celery slices during drying:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (1)$$

where MR is moisture ratio, M is the moisture content at a certain time (g water/g dry base), M_i is the primary moisture content (g water/g dry base) and M_e is the equilibrium moisture content (g water/g dry base) (Arslan and Ozcan, 2010).

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

where M_t and M_{t+dt} are the moisture content at t and t+dt (g water/g dry base), respectively, and t is drying time (min) (Dadali *et al.*, 2007b).

The root mean square error (RMSE) gives the deviation between the estimated and experimental values for the models. Higher correlation coefficients (R^2) and lower RMSE and Chi-square (χ^2) values were used to identify the excellence of the fit of the model to the oven, vacuum and microwave drying curves of celery slices. These parameters were calculated using the following equations:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2\right]^{1/2} \quad (3)$$

$$x2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (4)$$

Table 1. Mathematical models used in the drying of celery slices.

Model name	Model	References
Page	MR = exp(-kt^n)	Sarsavadiva *et al.* (1999)
Modified Page	MR = exp[(-kt)^n]	Overhults *et al.* (1973)
Logarithmic	MR = a exp(-kt) + c	Yagcioglu (1999)
Lewis	MR = exp(-kt)	Doymaz (2006)
Henderson and Pabis	MR = a exp(-kt)	Westerman *et al.* (1973)

where $MR_{exp,i}$ is the empirically dimensionless moisture ratio for test i, $MR_{est,i}$ is the estimated dimensionless moisture ratio for test i, N is the number of observations and n is the number of constants in the model (Avhad and Marchetti, 2016).

Colour analysis

The colour of fresh and dried celery samples was detected by using a Hunter Lab MiniScan EZ4500L (Reston, VA, USA) colorimeter. The device was calibrated with a standard black and white ceramic plate before the experiments. Approximately 5 g of the samples dried to the same moisture content (0.12 g water/g dry base) were analysed immediately after the drying procedure. The surface colour was measured at different locations on the celery slices. L^*, a^*, b^* values were displayed as lightness/darkness, redness/greenness and yellowness/blueness respectively. To describe colour changes during drying, chroma (C^*_{ab}), hue angle (h°) and total colour difference (ΔE_{ab}^*) were obtained from L^*, a^*, b^* values using equations 5, 6 and 7, respectively. The L^*, a^*, b^* values were used to calculate total the colour difference (ΔE_{ab}^*), chroma (C^*_{ab}) and hue angle (h°) in order to describe colour changes during drying (Dadali *et al.*, 2007c; Suna *et al.*, 2014). Chroma changed from 0 (dull) to 60 (vivid) and was calculated by using the following equation:

$$\text{Chroma } (C^*_{ab}) = \sqrt{(a^*)^2 + (b^*)^2} \quad (5)$$

The colour of food samples is generally characterized by calculating the hue angle (h°) value as shown in the following equation. This value is described by angles of 0, 90, 180 and 270°, which represent the colour of red, yellow, green and blue, respectively (Karaaslan and Tuncer, 2008).

$$h° = \arctan\left(\frac{b^*}{a^*}\right) \quad (6)$$

The total colour difference (ΔE_{ab}^*) indicates the colour saturation and was evaluated using Equation 7 (Šumić *et al.*, 2013).

$$\Delta E^*_{ab} = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^\circ - b^*_0)^2} \quad (7)$$

where L_0^*, a_0^*, b_0^* indicate the values of the fresh celery colour and L^*, a^*, b^* are the individual readings at each processing time.

Extraction of the samples

Extracts of fresh and dried celery were prepared according to Vitali et al. (2009) with slight modifications. In total, 2 g of homogenized celery was added to 20 ml of a $HCl_{conc/methanol/water}$ (1:80:10, v/v) mixture and shaken by a rotary shaker (JB50-D; Shanghai Shengke Instruments, Shanghai, China) at 250 rpm for 2 h at 20 °C, and the mixture was then centrifuged (3K 30; Sigma Aldrich) at 3,500 rpm for 10 min at 20 °C. The supernatants were stored at -20 °C until analysed.

Determination of total phenolic content and antioxidant capacity

The Folin-Ciocalteu spectrophotometric method was used for the determination of total phenolics as described by Spanos and Wrolstad (1990). Total phenolic content was reported in mg gallic acid equivalents (GAE) per 100 g dry weight (mg GAE/100 g dw).

The antioxidant capacity of the fresh and dried celery slices was measured according to the cupric-reducing antioxidant capacity (CUPRAC) (Apak *et al.,* 2008), DPPH reduction (Katalinic *et al.,* 2006) and the ferric-reducing ability of plasma (FRAP) (Benzie and Strain, 1996), and the results were given as µmol Trolox equivalents (TEs) per g dry weight (µmol TE/g dw) in all assays.

Statistical analysis

JMP software version 6.0 (SAS Institute Inc., Cary, NC, USA) was utilized to perform statistical analyses. The least significant difference test was used if significant differences (P<0.05) were found between means.

3. Results and discussion

Drying characteristics of celery slices

The variations in the moisture content of celery slices at each drying temperature (70, 85 and 100 °C), microwave power level (190, 375 and 680 W) and vacuum pressure level (500, 600 and 700 mbar) are shown in Figure 1. Drying time decreased with increasing oven temperature and microwave power level; however, drying time increased with increasing vacuum pressure level. Similar behaviour was observed by Izli et al. (2017) for the microwave and convective drying of apple slices and by Arevalo-Pinedo et al. (2004) for

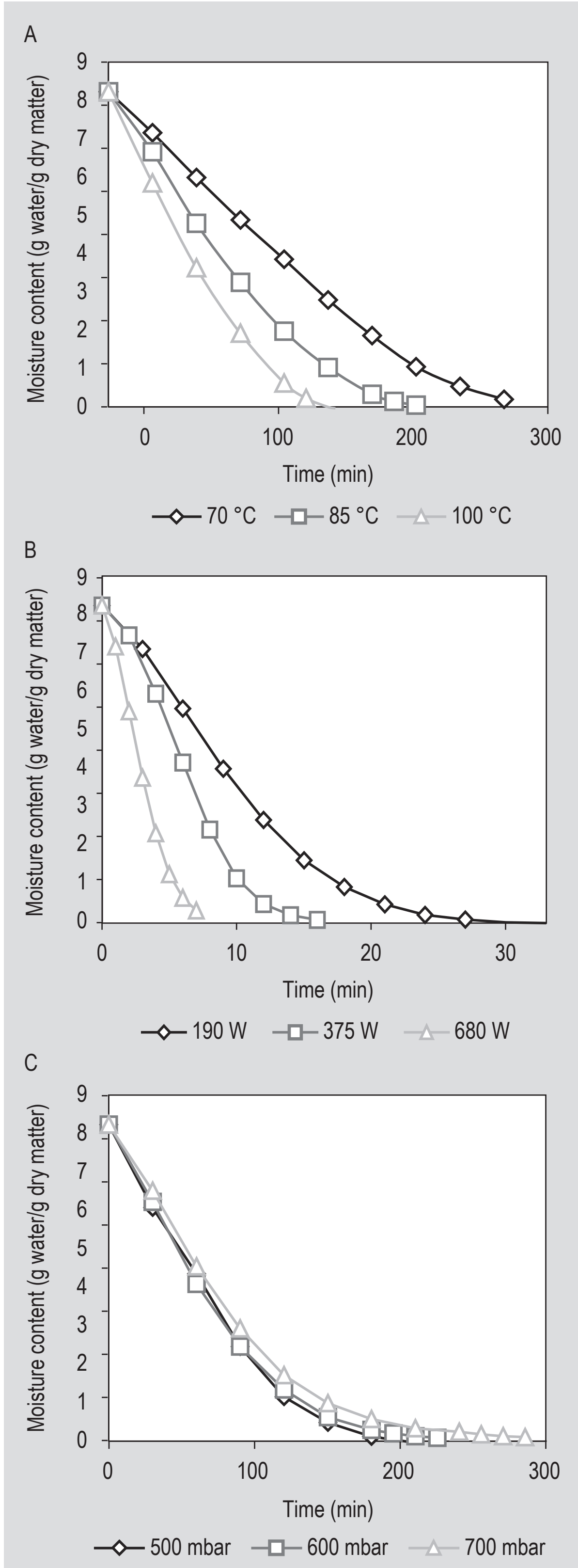

Figure 1. Drying curves of celery slices at different (A) oven temperatures, (B) microwave power levels and (C) vacuum pressure levels.

the vacuum drying of carrot samples. While the longest drying time (285 min) was obtained with vacuum drying at 700 mbar, microwave drying at 680 W resulted in the fastest drying time (7 min). The time was saved with microwave drying because microwaving causes rapid evaporation of water. Similar results were found by several researchers. (Arslan and Ozcan, 2010; Dadali *et al.*, 2007b; Maskan, 2000; Tavakolipour and Zirgani, 2014).

The calculated drying rates of celery are shown in Figure 2. As seen from this figure, drying rates ranged from 0.03 (g water/g dry matter (min)) for experiments at an oven temperature of 70 °C to 1.73 (g water/g dry matter (min)) for experiments at a microwave power level of 680 W. The drying rate of celery slices increased with increasing drying temperature and drying power for oven and microwave drying, respectively. However, it was reduced with increasing vacuum pressure. In microwave drying at 190 and 375 W, a constant-rate period was observed after a brief heating period. The constant rate varied from 4 to 6 (g water/g dry matter) for a microwave power level of 375 W and nearly 6 to 7 (g water/g dry matter) for a microwave power level of 190 W. The rate of celery slice drying with oven and vacuum drying methods generally decreased, whereas a constant rate of drying was not clearly observed. As seen in Figure 2, a constant-rate period was not observed in drying celery slices. The drying rate decreased after a very short acceleration at the beginning. Our results were in agreement with the studies of onion slices and apple pomace reported by Demiray et al. (2016) and Wang et al. (2007), who claimed that a constant-rate period was not observed during drying.

Evaluation of the models

The statistical results from drying celery slices obtained from different models, including drying model coefficients, R^2, RMSE and χ^2, are illustrated in Table 2. The R^2, RMSE and χ^2 values varied from 0.8454 to 0.9994, 0.001912 to 0.136406 and 0.000045 to 0.215306, respectively. The suitable drying methods with the highest value of R^2 and the lowest values of RMSE and χ^2 were determined from Page and Modified Page models in all cases. Moisture ratios obtained by Page's equation were illustrated in Figure 3.

The correlation between the estimated and the experimental moisture ratios using the Page model is depicted in Figure 4. The predicted results and the experimental data perfectly agreed, as expected. Similar results were reported by some researchers to describe the drying of okra (Dadali *et al.*, 2007b), parsley (Soysal, 2004), onion (Arslan and Ozcan, 2010), peach (Zhu and Shen, 2014) and garlic (Demiray and Tulek, 2014).

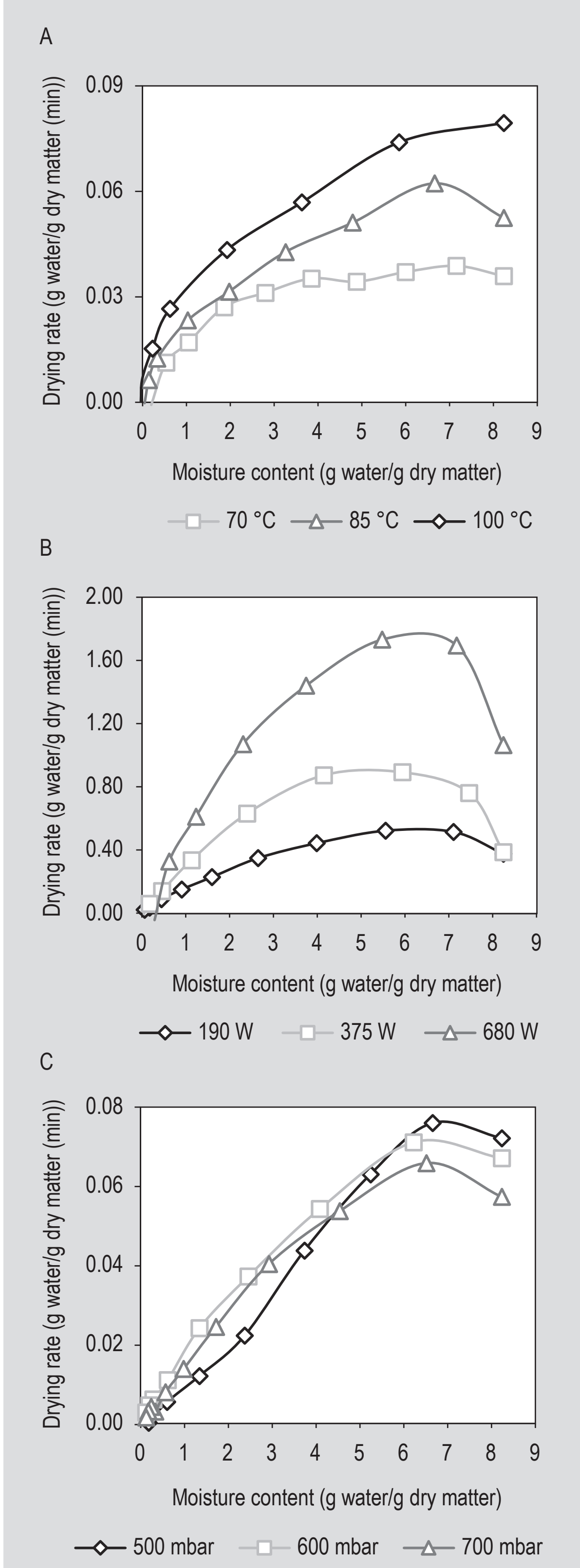

Figure 2. Drying rate curves for celery slices versus the moisture content at different (A) oven temperatures, (B) microwave power levels and (C) vacuum pressure levels.

Table 2. Statistical results obtained from the modelling of dried celery slices.[1]

Model name	Applications	Model coefficients	R^2	RMSE	χ^2
Page	Vacuum-500 mbar	n=1.6363, k=0.0007	0.9983	0.002886	0.000088
	Vacuum-600 mbar	n=1.3948, k=0.0024	0.9994	0.001912	0.000045
	Vacuum-700 mbar	n=1.1303, k=0.0029	0.9977	0.064621	0.060132
	Microwave-190 W	n=1.5913, k=0.0234	0.9958	0.003680	0.000195
	Microwave-375 W	n=1.9228, k=0.0239	0.9979	0.004376	0.000222
	Microwave-680 W	n=1.6443, k=0.1339	0.9994	0.002944	0.000078
	Oven-70 °C	n=1.4665, k=0.0008	0.9818	0.009945	0.001236
	Oven-85 °C	n=1.5976, k=0.0008	0.9821	0.009567	0.001059
	Oven-100 °C	n=1.5253, k=0.0017	0.9833	0.009225	0.000908
Modified Page	Vacuum-500 mbar	n=1.6363, k=0.0128	0.9983	0.002886	0.000088
	Vacuum-600 mbar	n=1.3948, k=0.0130	0.9994	0.001912	0.000045
	Vacuum-700 mbar	n=1.1380, k=0.0100	0.9829	0.007029	0.000712
	Microwave-190 W	n=1.5913, k=0.0944	0.9958	0.003680	0.000195
	Microwave-375 W	n=1.9228, k=0.1435	0.9979	0.004376	0.000222
	Microwave-680 W	n=1.6443, k=0.2945	0.9994	0.002944	0.000078
	Oven-70 °C	n=1.4665, k=0.0077	0.9818	0.009945	0.001236
	Oven-85 °C	n=1.5976, k=0.0115	0.9821	0.009567	0.001059
	Oven-100 °C	n=1.5253, k=0.0155	0.9833	0.009225	0.000908
Logarithmic	Vacuum-500 mbar	k=0.0216, a=1.5346	0.9507	0.068672	0.060363
	Vacuum-600 mbar	k=0.0244, a=1.7469	0.9486	0.077636	0.086104
	Vacuum-700 mbar	k=0.0204, a=1.6894	0.9610	0.060251	0.058084
	Microwave-190 W	k=0.1896, a=2.0972	0.9289	0.096009	0.147484
	Microwave-375 W	k=0.2938, a=1.8331	0.9088	0.098226	0.130253
	Microwave-680 W	k=0.5171, a=1.4326	0.9227	0.082599	0.081871
	Oven-70 °C	k=0.0123, a=1.4110	0.9069	0.049688	0.035271
	Oven-85 °C	k=0.0229, a=1.9711	0.8955	0.112285	0.170206
	Oven-100 °C	k=0.0322, a=1.9883	0.8454	0.126217	0.203913
Lewis	Vacuum-500 mbar	k=0.0192	0.9033	0.043554	0.017343
	Vacuum-600 mbar	k=0.0185	0.9651	0.027577	0.008449
	Vacuum-700 mbar	k=0.0109	0.9802	0.009309	0.001134
	Microwave-190 W	k=0.1475	0.8889	0.036901	0.017826
	Microwave-375 W	k=0.2569	0.8580	0.064767	0.042472
	Microwave-680 W	k=0.4075	0.9181	0.058877	0.024959
	Oven-70 °C	k=0.0105	0.8650	0.039765	0.017569
	Oven-85 °C	k=0.0186	0.8524	0.047905	0.023235
	Oven-100 °C	k=0.0218	0.8930	0.034852	0.011105
Henderson and Pabis	Vacuum-500 mbar	k=0.0229, a=1.6109	0.9380	0.078904	0.066408
	Vacuum-600 mbar	k=0.0209, a=1.4941	0.9820	0.050766	0.032215
	Vacuum-700 mbar	k=0.0108, a=0.9694	0.9804	0.011216	0.001811
	Microwave-190 W	k=0.1801, a=1.8589	0.9319	0.075444	0.081963
	Microwave-375 W	k=0.3255, a=2.1749	0.9156	0.136406	0.215306
	Microwave-680 W	k=0.4856, a=1.4777	0.9533	0.084652	0.064493
	Oven-70 °C	k=0.0128, a=1.5707	0.9088	0.064025	0.051239
	Oven-85 °C	k=0.0229, a=1.9711	0.8955	0.112285	0.145891
	Oven-100 °C	k=0.0254, a=1.4609	0.9201	0.061017	0.039713

[1] RMSE = root mean square error; R^2 = correlation coefficient.

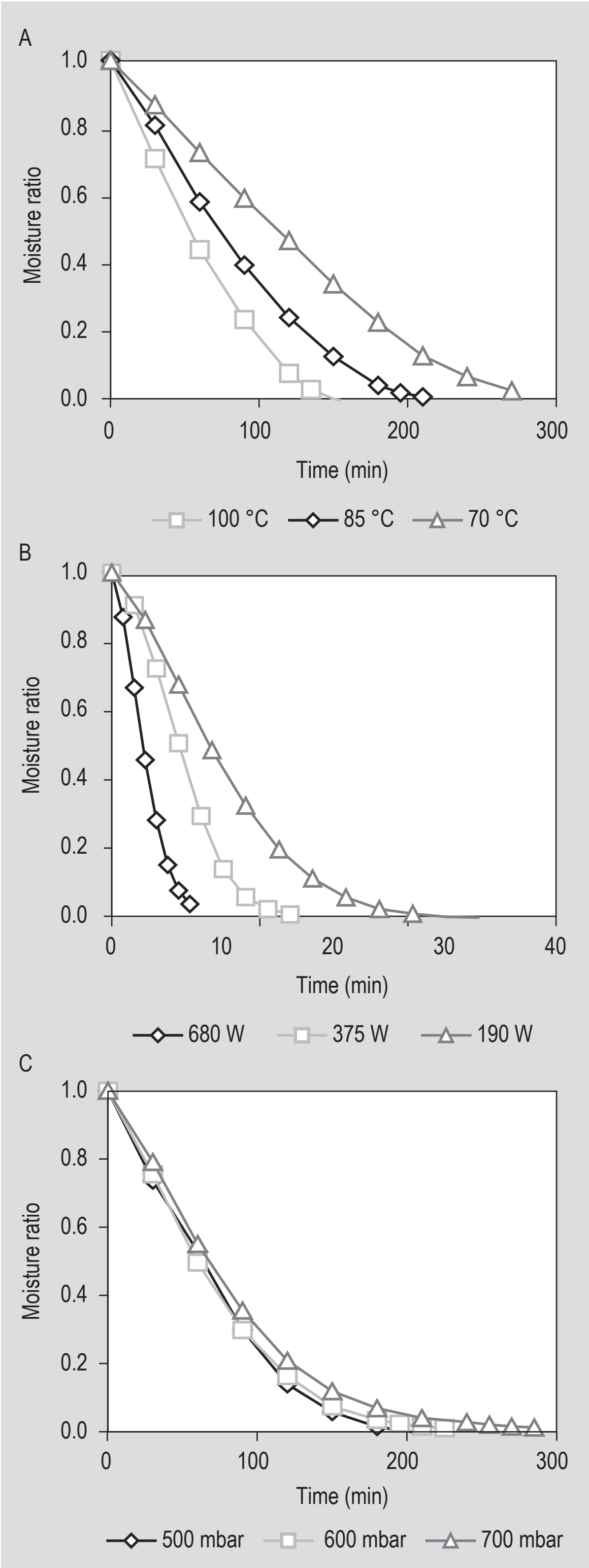

Figure 3. Moisture ratio of celery slices versus drying time at different (A) oven temperatures, (B) microwave power levels and (C) vacuum pressure levels, determined by Page's equation.

Colour analysis

Colour is a crucial quality factor because it affects the acceptance of dried foods by consumers. The colour parameters acquired from the drying processes are presented in Table 3. L^* (lightness) values were significantly lower ($P<0.05$) in all of the dried celery samples than the fresh celery sample. Microwave treatment at 680 W resulted in the lowest L^* value (37.34±1.57). Dried celery samples from an 85 °C oven (50.84±0.74), 100 °C oven (52.24±1.70) and 500 mbar vacuum (51.51±1.02) showed no significant differences in L^* ($P>0.05$). Similarly, 190 W microwave (48.09±0.21), 375 W microwave (45.85±1.10) and 700 mbar vacuum (45.70±2.76) dried celeries did not significantly differ ($P>0.05$) in their L^* values. L^* was lower in vacuum-dried samples than oven-dried samples in our study. Vacuum treatments are generally expected to result in higher L^* values than oven drying (Orikasa *et al.*, 2014). However, colour values might be affected by several factors such as time and temperature. The moisture of the fresh celery might not be sufficiently removed from the air during vacuum drying, thus increasing the drying time. As a result of the longer drying times, the drying was performed slowly (Polatci, 2012).

The a^*(redness) values significantly increased with drying of celery samples. The highest a^* values were observed with oven drying at 70, 85, and 100 °C (3.21±0.06, 3.35±0.09, 3.52±0.27) and microwave drying at 680 W (3.42±0.24). Visually, celery samples became darker with higher powers of microwave drying.

The value of b^* (yellowness) increased during oven and microwave drying but decreased during vacuum drying of celery samples from its value in fresh samples. The celery dried in 500 mbar of vacuum (13.07±2.35) had the lowest yellow colour value, whereas samples dried in a 70 °C oven (22.81±0.69) were the yellowest samples.

The total colour difference (ΔE_{ab}^*), which indicates the saturation of colour, was dependent on the drying method and parameters. The ΔE_{ab}^* values of celery samples were significantly ($P<0.05$) lower than in fresh samples. The lowest total colour difference value resulted from the microwave treatment at 680 W (42.05±1.24), while the highest value was produced by an oven at 70 °C (66.16±1.99).

Chroma (C_{ab}^*) values were used to represent the colour intensity. Compared to the values of the fresh sample, the C_{ab}^* value significantly increased ($P<0.05$) with microwave and oven drying and decreased in dried celeries with vacuum drying. The decrease in h° values reflects the darkening of celery slices. The sample dried at 500 mbar (89.31±1.72°) was close to the hue angle value of fresh samples (93.53±1.14°). The highest h° value was obtained from fresh celery samples (93.53±1.14°), whereas the lowest values were calculated

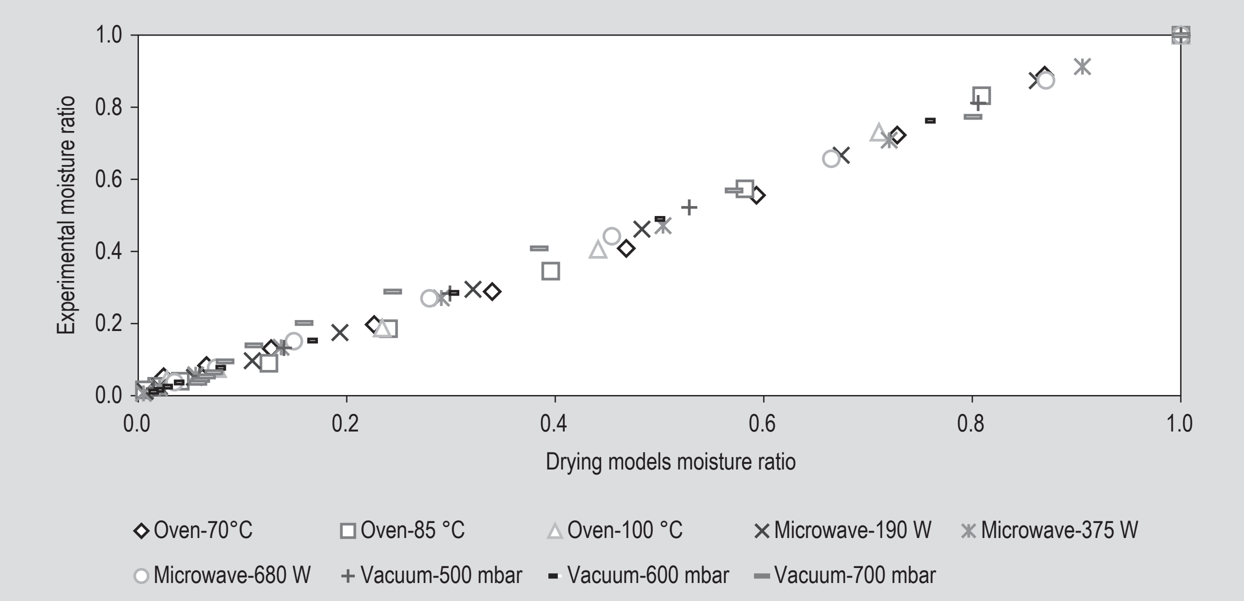

Figure 4. Comparison of experimental and drying model moisture ratios for the Page model.

Table 3. Colour values of fresh and dried celery slices.[1]

Drying conditions	L^*	a^*	b^*	ΔE_{ab}^*	C_{ab}^*	h°
Fresh	90.92±0.95[a]	-0.95±0.21[e]	15.79±1.49[de]	92.29±0.69[a]	15.82±1.48[de]	93.53±1.14[a]
Oven-70 °C	62.02±1.87[b]	3.21±0.06[ab]	22.81±0.69[a]	66.16±1.99[b]	23.04±0.68[a]	81.99±0.33[de]
Oven-85 °C	50.84±0.74[cd]	3.35±0.09[ab]	21.69±1.07[ab]	55.37±1.07[c]	21.94±1.04[ab]	81.19±0.64[de]
Oven-100 °C	52.24±1.70[c]	3.52±0.27[a]	19.19±0.84[bc]	55.77±1.87[c]	19.51±0.87[bc]	79.60±0.37[e]
Microwave-190 W	48.09±0.21[de]	1.37±0.24[c]	18.19±0.78[cd]	51.43±0.45[de]	18.24±0.76[cd]	85.65±0.94[c]
Microwave-375 W	45.85±1.10[e]	2.26±1.46[bc]	19.59±3.17[bc]	49.99±1.35[ef]	19.74±3.32[bc]	83.75±2.95[cd]
Microwave-680 W	37.34±1.57[g]	3.42±0.24[a]	19.01±0.54[c]	42.05±1.24[g]	19.32±0.57[bc]	79.79±0.48[e]
Vacuum-500 mbar	51.51±1.02[c]	0.20±0.45[d]	13.07±2.35[f]	53.19±0.51[cd]	13.08±2.36[f]	89.31±1.72[b]
Vacuum-600 mbar	41.82±2.70[f]	1.26±0.43[cd]	14.80±0.09[ef]	44.39±2.51[g]	14.86±0.13[ef]	85.16±1.62[c]
Vacuum-700 mbar	45.70±2.76[e]	1.65±1.06[c]	14.76±1.79[ef]	48.11±2.03[f]	14.87±1.90[ef]	83.87±3.22[cd]

[1] Different letters in the same column indicate significant differences ($P<0.05$).

from samples dried in an oven at 100 °C (79.60±0.37°) and samples dried in a microwave at 680 W (79.79±0.48°). This result showed that the darkening of celery slices increased with the reduction in h° value from 90° to 0°. Eventually, the best colour values were obtained using the vacuum drying method under all of the drying conditions. The discoloration of celery samples could generally be due to non-enzymatic Maillard browning or the decomposition of pigments (Ibarz *et al.*, 1999; Maskan, 2001).

Total phenolic content

The total phenolic contents of fresh and dried celery slices are displayed in Figure 5. The total phenolic content of fresh celery was determined to be 307.64±35.41 mg GAE/100 g dw. Priecina and Karklina (2014) reported the total phenolic content of fresh celery as 330.84 mg GAE/100 g dw, similar to our findings. Additionally, the values found in our experiments were higher than those obtained by Yao et al. (2010), which were 3.48±0.07-5.02±0.06 mg GAE/100 g dw. Of the dried samples, the total phenolic content was highest (189.16±0.11 mg GAE/100 g dw) after microwave drying at 375 W and lowest (75.85±14.75 mg GAE/100 g dw) after vacuum drying at 500 mbar. Priecina and Karlina (2013) determined the total phenolic content of celery samples that had been microwave-vacuum-dried (35 °C, 500 GAE/100 g dw) or steamed 1.5 min and then microwave-vacuum-dried (1,250 mg GAE/100 g dw). In another study, the total phenolic content of convectively dried (45 °C) celery (*A. graveolens*) and celery root (*A. graveolens* var.

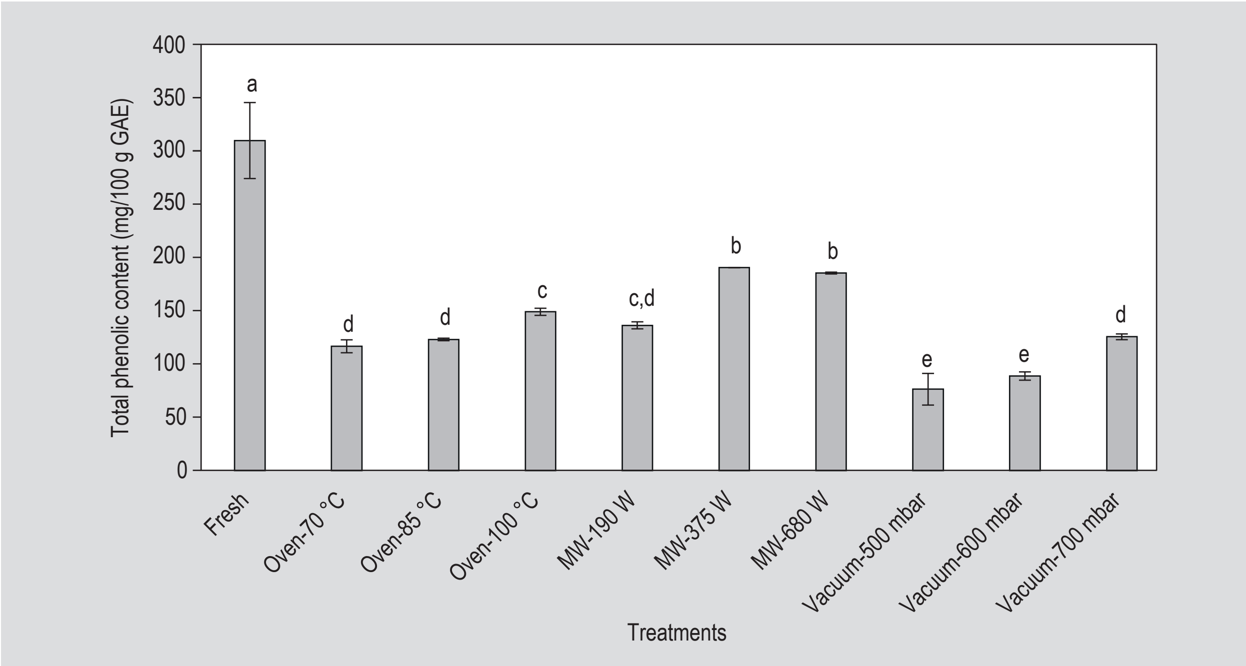

Figure 5. The effects of different drying methods (fresh, oven-70 °C, oven-85 °C, oven-100 °C, MW-190 W, MW-375 W, MW-680 W, vacuum-500 mbar, vacuum-600 mbar, and vacuum-700 mbar) on total phenolic content of sliced celery samples (dw = dry weight; GAE = gallic acid equivalent; MW = microwave). Bars with different letters represent significantly different values (*P*<0.05).

rapaceum) samples were reported as 1,961.00 and 441.76 mg GAE/100 g dw, respectively (Priecina and Karklina, 2014). The values that they found were higher than ours, and this variation was related to the differences in drying conditions and pretreatments.

According to Vega-Gálvez et al. (2009), high drying temperatures result in the formation of phenolics, which is consistent with our data: 115.89, 122.27 and 148.02 mg GAE/100 g dw after drying in an oven at 70, 85 and 100 °C, respectively. In addition, microwave drying at 375 and 680 W resulted in values closest to that of fresh samples and exhibited fast drying times (Figure 5). Several studies also revealed that microwave drying gave higher total phenolic content than convective drying (Al-Juhaimi *et al.*, 2016; Arslan and Ozcan, 2010; Valadez-Carmona *et al.*, 2016).

The total phenolic content was significantly affected by the drying method ($P<0.05$), decreasing from 38.51-75.34% during the process. The decrease in total phenolic content during drying could be ascribed to the binding of polyphenols to other compounds or changes in the chemical structure such as degradation (Crozier *et al.*, 1997; Garau *et al.*, 2007; Qu *et al.*, 2010). Our results indicated that drying caused a loss of phenolics, which is consistent with previous studies (Horuz *et al.*, 2017; Martin-Cabrejas *et al.,* 2009; Mendez-Lagunas *et al.*, 2017; Sahlin *et al.*, 2004; Tomsone and Kruma, 2014; Valadez-Carmona *et al.*, 2016; Vega-Galvez *et al.*, 2009). Additionally, vacuum drying resulted with lower phenolic content than oven drying in our study (Figure 5). This result is thought to be related to the long drying times associated with vacuum drying. However, total phenolic content increased with this drying process in some studies (Priecina and Karklina, 2014; Turkmen *et al.*, 2005). The effects of drying on total phenolic content thus change depending on the material used, the drying method and the process conditions.

Antioxidant capacity

The antioxidant capacity of the fresh and the dried celery slices is depicted in Figure 6. Several methods were developed to measure the capacity of the antioxidant substances as one mechanism may not reflect its exact value. As a result, the use several techniques together is recommended. For this aim, CUPRAC, DPPH and FRAP assays were all used in this research. The antioxidant capacity of the fresh sample was found to be 0.43, 4.18 and 7.72 μmol TE/g dw using DPPH, CUPRAC and FRAP assays, respectively. Values from previous studies agreed with our results. (Chu *et al.*, 2002; Priecina and Karklina, 2014).

The antioxidant capacity of fresh samples was the lowest, and this value was significantly different from those obtained from samples subjected to any of the drying treatments ($P<0.05$). The highest values in FRAP (49.35±3.10 μmol TE/g dw) and CUPRAC (33.29±1.02 μmol TE/g dw) assays were obtained from 680 W microwave-treated samples, while 375 W microwave-treated samples gave the best results in the DPPH (9.87±0.04 μmol TE/g

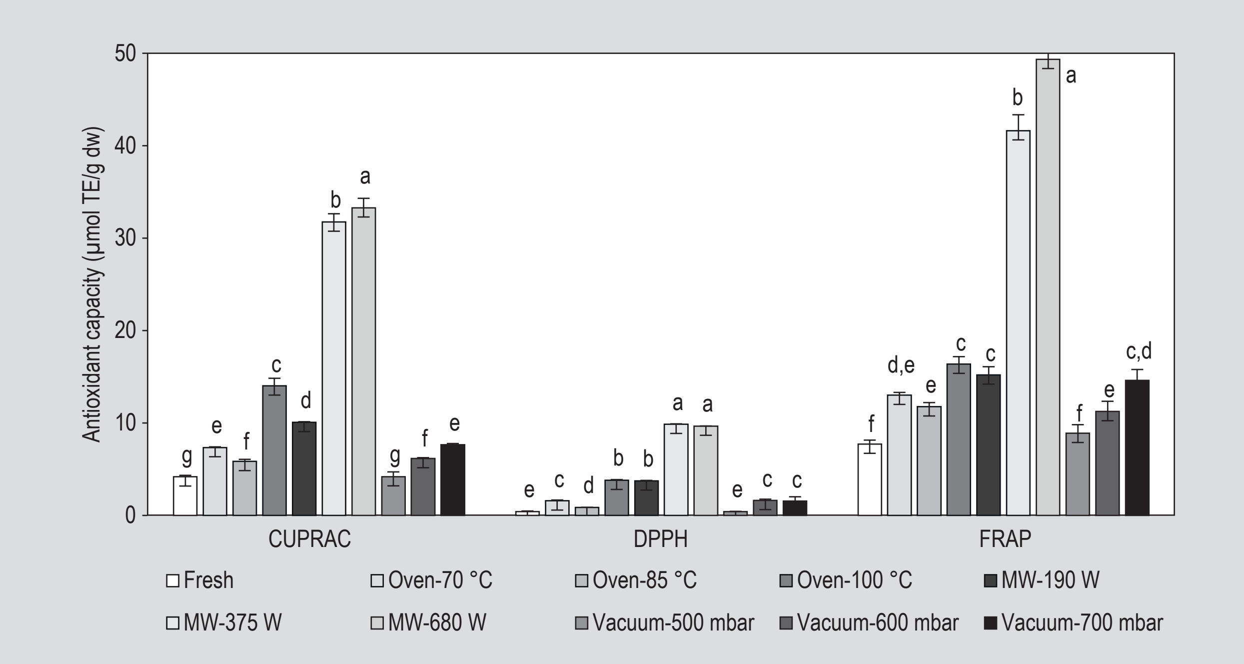

Figure 6. The effects of different drying methods (CUPRAC = cupric-reducing antioxidant capacity; DPPH = 2,2-diphenyl-2-picrylhydrazyl; FRAP = ferric-reducing ability of plasma) on antioxidant capacity of sliced celery samples (dw = dry weight; MW = microwave; TE = Trolox equivalent). Bars with different letters represent significantly different values (*P*<0.05).

dw) assay (Figure 6). The data of this study are compatible with the values reported by Priecina and Karklina (2014). Additionally, the microwave-dried celery showed higher values than oven- and vacuum-dried samples in all assays, consistent with literature (Degirmencioglu *et al.*, 2016; Valadez-Carmona *et al.*, 2016). Several researchers reported increased antioxidant activity in food after it had been dried (Turkmen *et al.*, 2005; Vega-Galvez *et al.*, 2016). This increase was attributed to the development of antioxidant properties of naturally forming components or resulting from Maillard reaction products with antioxidant activity (Manzocco *et al.*, 1998, 2001).

According to our research, total phenolic content decreased, and antioxidant activity increased with drying treatments. Our results agreed with literature reports (Miranda *et al.*, 2010; Vega-Galvez *et al.*, 2009). Correlation between total phenolics and antioxidant activity was also reported to occur from drying (Deepa *et al.*, 2007). Nevertheless, information on the impacts of dehydration on the total phenolic content and antioxidant activity of vegetables conflict when related to parameters such as the type of drying treatment, the extraction solvent identity and the method used to determine the antioxidant capacity, together with interactions with antioxidant reactions (Manzocco *et al.*, 2001; Que *et al.*, 2008).

4. Conclusions

In this study, the effects of oven, microwave and vacuum drying on the drying kinetics, colour, total phenolic content and antioxidant capacity of sliced celery were studied. Our results confirmed that the first and the second shortest drying times were obtained from microwave treatments of 680 W and 375 W, respectively. Among the mathematical models evaluated, the Page and Modified Page models were the best models to describe the drying characteristics of celery slices. While L^*, ΔE_{ab}^*, and h° decreased, the a^* value increased in all dried samples. Additionally, b^* and C_{ab}^* values both increased with oven and microwave treatments and decreased with vacuum drying. Vacuum drying was the best method for maintaining colour values. The total phenolic content of dried samples was lower than that of fresh samples, but the samples exerted higher antioxidant activity after drying. Microwave treatment at 680 W resulted in the highest antioxidant capacity in CUPRAC and FRAP assays, whereas microwave treatment at 375 W resulted in the highest values in total phenolic content and DPPH assays. Microwave drying was consequently more applicable to reduce the drying time and retain the nutritional value and bioactive compounds of celery than the oven and vacuum drying treatments.

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