Gaziosmanpaşa Üniversitesi Ziraat Fakültesi Dergisi
Journal of Agricultural Faculty of Gaziosmanpasa University
http://ziraatdergi.gop.edu.tr/

Araştırma Makalesi/*Research Article*

JAFAG
ISSN: 1300-2910
E-ISSN: 2147-8848
(2016) 33 (2), 79-88
doi:**10.13002/jafag983**

Effect of Different Drying Methods on Drying Characteristics, Colour and Microstructure Properties of Barbunia Bean (*Phaseolus vulgaris* L.)

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Alındığı tarih (Received): 06.03.2016 Kabul tarihi (Accepted): 20.06.2016
Online Baskı tarihi (Printed Online): 11.08.2016 Yazılı baskı tarihi (Printed): 26.09.2016

Abstract: In this study, the effects of microwave, convective, and microwave-convective drying treatments on the drying parameters, colour and microstructure properties of barbunia samples were investigated. To select the best thin-layer drying models for the drying treatments, 9 mathematical models were fitted to the experimental data and the performances of these models were compared for the following statistical parameters: reduced chi-squared (χ^2), root mean square error (*RMSE*) and coefficient of determination (R^2). Among the drying models investigated, the Midilli et al. model was found to be the best model for describing the drying behaviour of barbunia beans. The experimental results showed that increasing the drying temperature or microwave power level caused shorter drying time and the combined microwave-convective method provided the greatest time savings in comparison to other methods tested. At all drying conditions, the closest values to the colour of fresh barbunia was obtained at 50°C. It was found that browning increased with an increase in drying temperature and microwave power. Scanning electron microscopy images revealed that the applications of all the drying methods led to different physical changes in the products' microstructures when compared to fresh samples.

Keywords: Barbunia, Browning, Drying parameters, Mathematical model, Microwave drying, Scanning electron microscopy

Barbunya Fasülyesinin (*Phaseolus vulgaris* L.) Kurutma Karakteristikleri, Renk ve Mikro Yapı Özellikleri Üzerine Farklı Kurutma Yöntemlerinin Etkisi

Öz: Bu çalışmada, barbunya örneklerinin kurutma karakteristikleri, renk ve mikro yapı özellikleri üzerine farklı kurutma yöntemlerinin etkisi incelenmiştir. Kurutma işlemlerinde en iyi ince tabaka kurutma modelini seçmek için 9 matematiksel model deneysel verilere uygulanmış ve bu modellerin performansları ki-kare (χ^2), hataların karelerinin karekök ortalaması (*RMSE*) ve belirtme katsayısı (R^2)'na göre karşılaştırılmıştır. İncelenen kurutma modelleri arasında, Midilli ve ark. modeli barbunya fasulyelerinin kurutma davranışlarının tanımlanmaları için en iyi model olarak bulunmuştur. Artan kurutma hava sıcaklığı ve mikrodalga güç seviyeleri daha kısa kurutma süresine neden olduğunu deneysel sonuçlar göstermiş ve mikrodalga-konvektif birleşimi yöntemi diğer yöntemlerle karşılaştırıldığında en büyük zaman kazanımı sağlamıştır. Tüm kurutma şartlarında taze barbunya rengine en yakın değerler 50 °C 'de elde edilmiştir. Kurutma hava sıcaklığı ve mikrodalga gücünde artış ile esmerleşmenin arttığı saptanmıştır. Tüm kurutma uygulamalarının taze örneklerle karşılaştırıldıkları zaman ürünlerin mikro yapılarında farklı fiziksel değişikliklere neden olduklarını taramalı elektron mikroskobu görüntüleri ortaya çıkarmıştır.

Anahtar Kelimeler: Barbunya, Esmerleşme, Kurutma parametreleri, Matematiksel model, Mikrodalga kurutma, Taramalı elektron mikroskobu

1. Introduction

The barbunia bean (*Phaseolus vulgaris* L.) is a cultivated plant grown for fresh and dry consumption and is a raw material for the canned food industry (Isik and Unal, 2007). It contains approximately 25.0% protein, 1.5% oil and 57.0% carbohydrates (Cetin, 2007). In addition to contributing nutritional requirements, consumption of barbunia beans has been linked to reduced risks of heart disease and obesity (Kayisoglu and Ertekin, 2011).

Drying is one of the oldest methods of food preservation, and it represents a very important aspect of food processing. The main aim of drying products is to prolong storage periods, minimize packaging requirements and reduce shipping weights (Doymaz, 2006). Different drying methods are used in the drying of fruits and vegetables. Convective drying is the most popular and efficient way to reduce the moisture content in food and to preserve food (Mundada et al., 2010). Nevertheless, the relatively long drying time, the high temperatures used and the high velocities of drying air flow constitute serious disadvantages for this method. These results in the products' flavour and nutrients being seriously damaged the degradation of biological components and to far-reaching changes in the quality of the product (Funebo and Ohlsson, 1998; Maskan, 2001; Zhang et al., 2006). Microwave drying is an alternative method with various advantages, including uniform energy, high thermal conductivity to the inner sides of the material, space utilization, sanitation, energy savings, precise process control, and fast start-up and shut-down conditions (Maskan, 2000). However, microwave drying alone has some major drawbacks that include uneven heating, possible textural damage, high investment cost, and limited product penetration of the microwave radiation (Zhang et al., 2006). To reduce these problems, faster and more effective drying processes, such as microwave applications, should be considered for food drying (Contreras et al., 2008). Microwave drying is relatively a new addition in the existing drying techniques, viz. convective air drying (cabinet, fluidized bed and tunnel), spray, vacuum, foam mat and freeze drying (Sharma et al., 2009). Microwave-convective drying appears to be a promising possibility for producing dried fruits with a suitable shelf life and quality in a short time and with reasonable energy consumption (Piotrowski et al., 2004). The study of the drying kinetics of foods during microwave-convective heat treatments has recently been the subject of interest for various investigators. Some subjects of the recent studies on microwave-convective drying include garlic (Sharma and Prasad, 2004), soybeans (Gowen et al., 2008), strawberries (Piotrowski et al., 2004), spinach (Karaaslan and Tuncer, 2008), cranberries (Sunjka et al., 2004) and carrots (Prabhanjan et al., 1995).

The objectives of this study were to determine drying characteristics of barbunia, to select the most suitable the thin-layer drying model and to examined the colour and microstructural differences between the fresh and dried samples.

2. Materials and methods

Drying equipment and drying procedure

Fresh barbunia bean samples were purchased from a local store in Bursa, Turkey and stored at a temperature of 4 ± 0.5°C until dried. The initial moisture content of the fresh samples was determined as 1.22 (g water/g dry matter) on a dry basis (d.b.) by oven ((ED115 Binder, Tuttlingen, Germany) drying at 105°C for 24 h (Cetin, 2007). The drying process continued until the moisture content of barbunia beans fell down to 0.1 (g water/g dry matter) d.b.

The drying treatment was performed in a laboratory modified microwave-convective oven (Whirlpool AMW 545, Turkey) with technical features of ~230V, 50 Hz and a frequency of 2450 Mhz. The drying experiments were conducted using three different drying methods: microwave, convective and microwave-convective drying. The system was operated in convective mode at an air velocity of 1 m/s with air temperatures of 50 and 75°C; in the microwave mode at output power levels of 90 and 160W; and in the microwave-convective mode at four different combinations of power level and temperature (90W-50°C, 90W-75°C, 160W-50°C and 160W-75°C). In the experiments, 200 g samples of barbunia beans were placed on a glass plate in a thin layer and dried. For the mass determination, a digital balance (Baster, Istanbul, Turkey) with 0.01 g precision was placed under the oven (Izli and Isik, 2014). Moisture losses were recorded in 10-min intervals without stopping the drying process by the digital balance. All the experiments were performed in triplicate.

Mathematical modeling of drying data

To determine the moisture ratios as a function of drying time, 9 thin-layer drying models were used (Table 1).

The moisture ratio (MR) of barbunia beans during the drying experiments were calculated using the following equations (Doymaz, 2006; Therdthai and Zhou, 2009):

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where, is the moisture content at a specific time (g water/g dry matter), is the initial moisture content (g water/g dry matter), is the equilibrium moisture content (g water/g dry matter). The values of are relatively small compared with or . Therefore, the moisture ratio was simplified as (Xiao et al., 2010; Radhika et al., 2011):

$$MR = \frac{M_t}{M_o} \quad (2)$$

Table 1. Selected thin-layer mathematical drying models used for the drying curves of barbunia samples.

No	Model name	Model	References
1	Henderson and Pabis	$MR = a\exp(-kt)$	Westerman *et al*. (1973)
2	Newton	$MR = \exp(-kt)$	Ayensu (1997)
3	Page	$MR = \exp(-kt^n)$	Agrawal and Singh (1977)
4	Logarithmic	$MR = a\exp(-kt) + c$	Yagcioglu *et al*. (1999)
5	Two Term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Madamba *et al*. (1996)
6	Two Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Sharaf-Eldeen *et al*. (1980)
7	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
8	Diffusion Approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Kassem (1998)
9	Midilli *et al*.	$MR = a\exp(-kt^n) + bt$	Midilli *et al*. (2002)

Colour measurement

The colour of fresh and dried barbunia beans was measured using a colourimeter (MSEZ-4500L, HunterLab, Virginia, USA). The colours were expressed as L-values (lightness), a-values (redness/greenness) and b-values (yellowness/blueness). The colourimeter was calibrated on a standard white plate before each colour measurement. A black plastic cell with a diameter just close to the nose cone of colourimeter, containing sample, was placed above the light source and L*, a* and b* colour values were recorded (Odjo et al., 2012). The reading was performed on the external surface of the sample, and the mean of three readings at random locations on the sample was reported (Cheng et al., 2006). Using the following equations (Maskan, 2001; Soysal, 2004; Karaaslan and Tuncer, 2008), a* and b* values were used to calculate Chroma (C) [Eq. (3)] and Hue angle (α) [Eq. (4)] values to aid in describing the colour changes during drying.

$$C = \sqrt{(a^2 + b^2)} \quad (3)$$

$$\alpha = \tan^{-1}\left(\frac{b}{a}\right) \quad (4)$$

Structural analysis

A scanning electron microscope (Carl Zeiss/EVO 40, Oberkochen, Germany) was used to examine the microstructure of fresh and dried barbunia beans. The samples were cut in half longitudinally along the central pith (Bondaruk et al., 2007) and fixed on the SEM stub. The samples were subsequently coated with gold to provide a reflective surface for the electron beam. Gold coating was performed using a sputter coater (BALTEC SCD-005, Wetzlar, Germany) under a low vacuum (20 kV) with the presence of the inert gas argon (Giri and Prasad, 2007).

Statistical analysis

The research was conducted using a randomised plots factorial experimental design. Determination of the investigated components was performed in three replicates. The results were analyzed using the MATLAB (MathWorks Inc., Natick, MA) and MINITAB (Version 14, University of Texas, Austin, TX, USA) software programs. Mean differences were tested for significance with a least significant difference (LSD) test at a 1% level of significance. The best model describing the thin layer drying characteristics of barbunia beans was chosen as the one with the lowest reduced chi-squared (χ^2) and root mean square error (RMSE) values and the highest coefficient of determination (R^2) (Goyal et al., 2006; Özbek and Dadalı, 2007). These statistical values are defined as the following:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (MR_{pre,i} - MR_{\exp,i})}{N}} \quad (6)$$

where,

$MR_{\exp,i}$, stands for the experimental moisture ratio in test number i,

$MR_{pre,i}$, stands for the estimated moisture ratio in test number i,

N stands for the observation number and

n is the number of constants in the drying model (Sharma et al., 2005; Wang et al., 2007).

3. Results and discussion

Drying kinetic of dried barbunia beans

The drying curves of the barbunia samples with the elapsed drying time at each of the microwave powers (90 and 160W), drying temperatures (50 and 75°C) and microwave-convective combinations (90W-50°C, 90W-75°C, 160W-50°C and 160W-75°C) with an air velocity of 1 m/s. is presented in Figure 1.

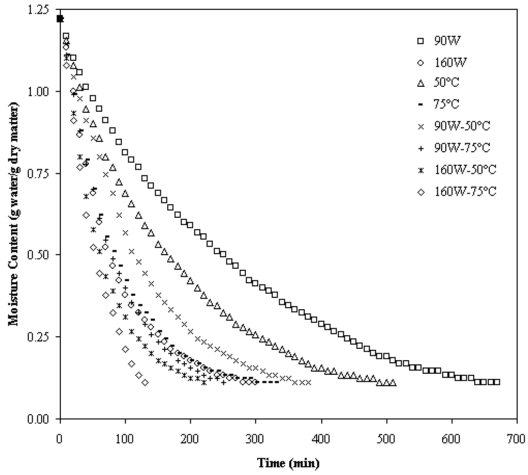

Figure 1. Drying curves of barbunia samples at different drying condition

The time required to reduce the moisture content to any given level was dependent on the drying conditions, being highest at 90W (670 min) and lowest at 160W-75°C (130 min). The experimental results indicated that there was a marked reduction in the drying time with the microwave-convective combination compared to the microwave or air-drying treatment alone. For example, the total drying time required to reach the final moisture content was 380 min at a microwave-convective power combination level of 90W-50°C. The drying time at this level was 43.28 % shorter than the drying period at a microwave-only power of 90W and 25.49 % shorter than the drying period at a convective-only temperature of 50°C. Similarly, a marked reduction occurred in the drying time at all the microwave-convective combination levels compared to convective or microwave drying alone (Funebo and Ohlsson, 1998; Maskan, 2000; Contreras et al., 2008).

Fitting of drying curves

The results of the statistical analyses of the different models, including drying model coefficients and the comparison criteria used to evaluate the fitting quality, R^2, *RMSE* and χ^2, are presented in the Tables 2-4. In all cases, the value of R^2 was greater than 0.96, and the *RMSE* and χ^2 values were lower than 0.056 and 31.54 x 10^{-4}, respectively. The models with same R^2 values were compared in terms of *RMSE* and χ^2 parameters. The values of R^2, *RMSE* and χ^2 for Midilli et al. model changed from 0.9987 to 0.9998, 0.0038 to 0.0104 and 0.1867 x 10^{-4} to 1.1773 x 10^{-4}, respectively. Among the considered thin layer drying models, the Midilli *et al*. model, using average values for R^2, χ^2 and *RMSE*, was found to be more suitable for the predictable drying of barbunia.

Table 2. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of barbunia samples at different temperatures

No	50°C				75°C			
	Model coefficients	R^2	***RMSE***	χ^2 **(10^{-4})**	**Model coefficients**	R^2	***RMSE***	χ^2 **(10^{-4})**
1	a=1.003 k=0.00655	0.9959	0.0176	2.8399	a=1.017 k=0.01284	0.9991	0.0084	0.6702
2	k=0.006529	0.9960	0.0175	2.8086	k=0.01263	0.9988	0.0096	0.9581
3	k=0.005241 n=1.042	0.9965	0.0163	2.3928	k=0.01004 n=1.05	0.9995	0.0062	0.3600
4	a=1.032 k=0.005619 c=-0.05447	0.9992	0.0077	0.6033	a=1.024 k=0.01225 c=-0.01473	0.9996	0.0054	0.3388
5	a=6.845 k_o=0.007345 b=-5.841 k_1=0.007499	0.9961	0.0171	2.6750	a=0.06604 k_o=0.01302 b=0.9499 k_1=0.01281	0.9990	0.0087	0.7255
6	a=1.443 k=0.007501	0.9969	0.0153	2.1135	a=1.448 k=0.01454	0.9995	0.0061	0.4144
7	a=-0.004656 b=0.00000556	0.9799	0.0390	15.4525	a=-0.008282 b=0.00001687	0.9620	0.0545	30.4554
8	a=0.001856 k=0.2002 b=0.03255	0.9958	0.0179	2.8867	a=1.854 k=0.01046 b=0.8131	0.9996	0.0054	0.3600
9	a=0.9974 k=0.008049 n=0.941 b=-0.0001211	0.9995	0.0064	0.3819	a=1.003 k=0.01113 n=1.025 b=-0.000031	0.9996	0.0053	0.3198

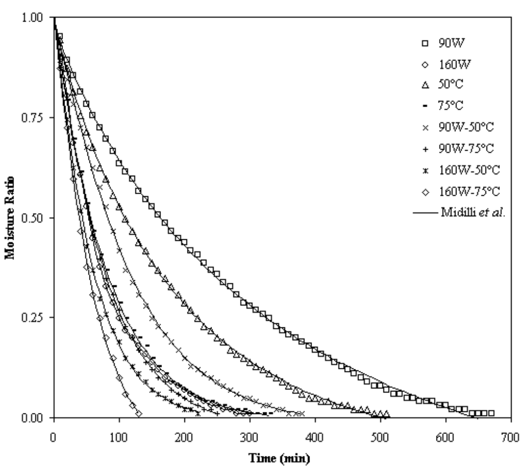

Figure 2. Variation of experimental and predicted moisture ratio by the Midilli *et al*. model with drying time at different drying conditions

Figure 2 shows the comparison between predicted values from the Midilli et al. model and the experimental data for all the drying conditions. The model presented a slight over or under estimation in comparison with the experimental data under different drying processes, but they are all very close to the experimental data.

Thus, the Midilli et al. model was satisfactory in describing the thin-layer drying behavior of barbunia beans at the experimental conditions investigated. Similar results were obtained by Ertekin and Yaldiz (2004), Akpinar (2006), McMinn (2006) and Taheri-Garavanda et al. (2011) for the Midilli et al. model.

Table 3. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of barbunia samples at different microwave powers

No	90W				160W			
	Model coefficients	R^2	*RMSE*	χ^2 (10^{-4})	**Model coefficients**	R^2	*RMSE*	χ^2 (10^{-4})
1	a=1 k=0.004463	0.9905	0.0268	6.6290	a=1.031 k=0.01374	0.9985	0.0109	1.2608
2	k=0.004461	0.9906	0.0266	6.5328	k=0.01333	0.9976	0.0138	2.1205
3	k=0.003118 n=1.064	0.9918	0.0247	5.5023	k=0.01019 n=1.059	0.9986	0.0108	1.3174
4	a=1.072 k=0.003369 c=-0.1136	0.9987	0.0101	0.9309	a=1.033 k=0.01346 c=-0.006398	0.9986	0.0108	1.2549
5	a=1.006 k_o=0.003627 b=-0.04419 k_1=-0.001119	0.9987	0.0100	0.9010	a=17.56 k_o=0.01173 b=-16.7 k_1=0.01174	0.9681	0.0508	26.6381
6	a=1.505 k=0.005298	0.9927	0.0234	4.9312	a=1.467 k=0.01552	0.9983	0.0118	1.5816
7	a=-0.003254 b= 0.00000028	0.9847	0.0339	11.2186	a=-0.00891 b=0.0000197	0.9619	0.0555	31.5343
8	a=0.00585 k=0.2594 b=0.0171	0.9903	0.0270	6.6975	a=1.038 k=0.01316 b=0.7161	0.9975	0.0141	2.1393
9	a=0.987 k=0.006142 n=0.9081 b=-0.0001707	0.9990	0.0085	0.6262	a=1.018 k=0.01154 n=1.036 b=-0.0000014	0.9987	0.0104	1.1773

Colour analysis

The colour of products is an important attribute for quality assessment (Cheng et al., 2006; Kose and Erenturk, 2010). The results of colour measurements on fresh and dried barbunia beans during different drying conditions are presented in Table 5.

The lightness (L^*) value of all the samples decreased from 67.167 to 53.160 and the hue angle (α) decreased from 71.638 to 61.390. However, the redness/greenness (a^*), yellowness/blueness (b^*) and Chroma (C) values increased from 4.507 to 8.333, 13.55 to 16.057 and 14.281 to 17.704, respectively. All the colour values (except b^*) of the fresh barbunia differed significantly from the values of the dried barbunia samples ($P < 0.01$). At all the drying conditions, the closest values to the colour of fresh barbunia were obtained at 50°C. It was observed that the lightness, L^*, for the barbunia beans decreased with an increase in temperature and microwave power levels for all the drying conditions. On the other hand, the redness/greenness, a^*, increased with an increase in temperature and microwave power levels in comparison to the fresh samples and the samples dried with hot air, microwave or combined microwave-hot air. Additionally, the statistical analysis showed that there were significant differences (P<0.01) in the L^* and a^* values between the fresh samples and the samples dried with all the drying conditions. However, there were some variations within the same homogenous group (LSD test, P<0.01) in the b^*, C and α values for all the drying conditions. This indicated that the L^* and a^* were inversely correlated with the microwave power and temperature. It is clear that browning increases with an increase in drying temperature (Wang and Chao 2002; Sacilik and Elicin, 2006) and microwave power (Funebo and Ohlsson, 1998; Orsat et al., 2007).

Table 4. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of barbunia samples at different microwave power and temperature combinations

No	90W-50°C				90W-75°C				160W-50°C				160W-75°C			
	Model coefficients	R^2	*RMSE*	χ^2 (10^{-4})	**Model coefficients**	R^2	*RMSE*	χ^2 (10^{-4})	**Model coefficients**	R^2	*RMSE*	χ^2 (10^{-4})	**Model coefficients**	R^2	*RMSE*	χ^2 (10^{-4})
1	a=1.038 k=0.009362	0.9957	0.0190	3.3311	a=1.033 k=0.01379	0.9973	0.0152	1.8007	a=1.031 k=0.01724	0.9986	0.0111	1.2854	a=1.052 k=0.02099	0.9876	0.0357	12.5239
2	k=0.009029	0.9943	0.0218	4.7088	k=0.01336	0.9962	0.0180	3.3050	k=0.01673	0.9976	0.0144	2.2430	k=0.01997	0.9849	0.0395	15.7791
3	k=0.004774 n=1.13	0.9988	0.0100	0.7874	k=0.008222 n=1.108	0.9994	0.0072	0.4733	k=0.01189 n=1.0800	0.9993	0.0079	0.7937	k=0.0078 n=1.232	0.9970	0.0175	2.9113
4	a=1.062 k=0.008234 c=-0.04608	0.9985	0.0111	1.1354	a=1.057 k=0.01226 c=-0.04275	0.9996	0.0055	0.3652	a=1.039 k=0.01643 c=-0.01615	0.9990	0.0093	0.9961	a=1.177 k=0.01505 c=-0.1608	0.9988	0.0113	1.5334
5	a=-0.06201 k_o=0.009087 b=1.098 k_1=0.009328	0.9954	0.0195	3.5366	a=0.5178 k_o=0.01373 b=0.5135 k_1=0.01382	0.9971	0.0159	2.3924	a=1.5 k_o=0.01485 b=-0.4747 k_1=0.01108	0.9990	0.0095	1.0116	a=0.5272 k_o=0.02101 b=0.5246 k_1=0.02096	0.9852	0.0391	15.0342
6	a=1.636 k=0.01151	0.9990	0.0093	0.6820	a=1.592 k=0.01664	0.9994	0.0070	0.4939	a=1.531 k=0.02015	0.9991	0.0090	1.0216	a=1.773 k=0.02761	0.9966	0.0188	3.3898
7	a=-0.006416 b=0.000011	0.9878	0.0319	10.3346	a=-0.009561 b=0.000023	0.9879	0.0324	10.8392	a=-0.01158 b=0.000034	0.9761	0.0454	21.4741	a=-0.01475 b=0.0000561	0.9972	0.0169	3.1851
8	a=3.297 k=0.006207 b=0.8546	0.9987	0.0105	1.0685	a=2.386 k=0.01116 b=0.8824	0.9978	0.0138	1.9033	a=1.633 k=0.01424 b=0.7853	0.9985	0.0116	1.5035	a=6.075 k=0.01175 b=0.8996	0.9961	0.0200	3.9522
9	a=0.9894 k=0.004935 n=1.116 b=-0.0000395	0.9991	0.0085	0.6034	a=1.002 k=0.009773 n=1.0620 b=-0.000088	0.9998	0.0038	0.1867	a=1.011 k=0.01305 n=1.059 b=-0.000014	0.9993	0.0078	0.7569	a=1.005 k=0.0119 n=1.099 b=-0.000551	0.9992	0.0092	1.0432

Table 5. Colour values of fresh and dried barbunia beans at different drying methods

Drying method	Colour parameters				
	L*	***a****	***b****	***C***	***α*,°**
Fresh	67.167(0.767)^{a}	4.507(0.186)^{i}	13.55(0.101)^{e}	14.281(0.050)^{h}	71.638(0.826)^{a}
Convective drying					
50°C	63.123(0.023)^{b}	5.267(0.015)^{h}	13.653(0.006)^{e}	14.634(0.002)^{g}	68.941(0.064)^{b}
75°C	59.400(0.115)^{d}	5.777(0.015)^{g}	14.920(0.078)^{c}	15.999(0.069)^{e}	68.869(0.145)^{b}
Microwave drying					
90W	61.190(0.147)^{c}	6.6400(0.044)^{e}	15.503(0.144)^{b}	16.866(0.116)^{c}	66.847(0.328)^{c}
160W	58.267(0.142)^{e}	6.960(0.027)^{d}	15.630(0.056)^{b}	17.110(0.062)^{b}	66.030(0.015)^{d}
Microwave-convective drying					
90W-50°C	58.683(0.021)^{de}	6.337(0.025)^{f}	14.177(0.032)^{d}	15.528(0.038)^{f}	65.950(0.051)^{de}
90W-75°C	57.290(0.040)^{f}	7.387(0.012)^{c}	16.057(0.006)^{a}	17.674(0.001)^{a}	65.329(0.042)^{e}
160W-50°C	56.070(0.044)^{g}	7.790(0.010)^{b}	14.263(0.015)^{d}	16.252(0.013)^{d}	61.390(0.046)^{f}
160W-75°C	53.160(0.527)^{h}	8.333(0.006)^{a}	15.620(0.010)^{b}	17.704(0.007)^{a}	61.951(0.031)^{f}

$^{a-i}$ Means superscript with different alphabets in the same column differ significantly ($P < 0.01$).

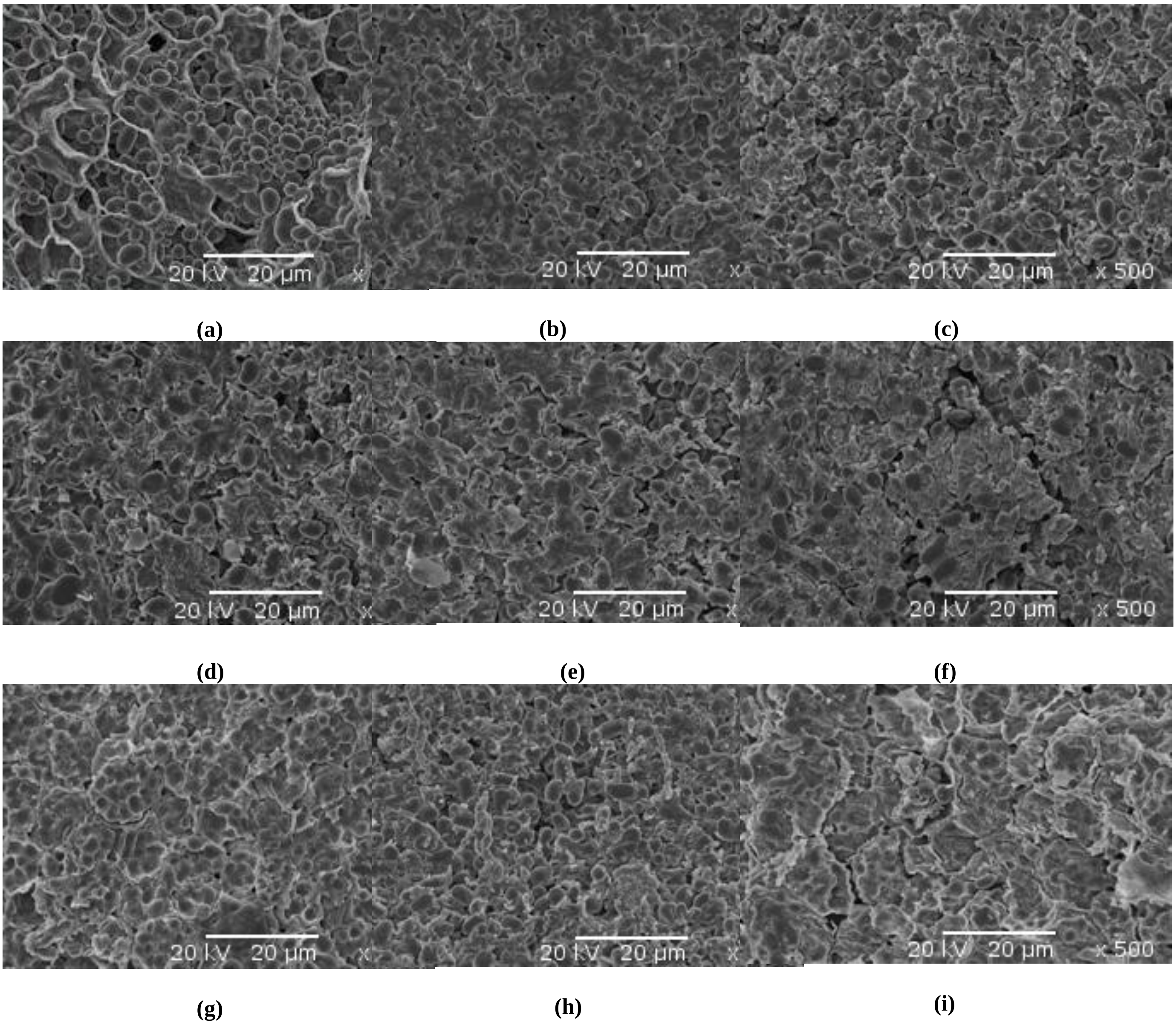

Figure 3. SEM images of fresh and dried barbunia beans: fresh (a), microwave drying at 90W (b) and 160W (c), convective drying at 50°C (d) and 75°C (e), microwave-convective drying at 90W-50°C (f), 90W-75°C (g), 160W-50°C (h) and 160W-75°C (i)

Microstructural changes

Figure 3 shows the SEM images of the fresh and dried barbunia beans obtained using different drying methods. The microstructure of the fresh sample can be seen in Figure 3a, where both a uniform pore distribution and clearly visible starch granules appear in comparison to the dried barbunia beans. For all the drying conditions, high temperature and microwave power during the drying process caused a more violent evaporation of water as well as a melting of starch granules. This could weaken the starch-protein matrix, causing structural damage and destroying the samples.

These results were comparable to the findings in the literature (Bondaruk et al., 2007; Witrowa-Rajchert and Rzaca, 2009; Vega-Gálvez et al., 2011) and were in accord with the effect of high temperatures on the structure of dried products. Drying at 160W-75°C resulted in the complete destruction of the samples' microstructure. This damage may be due to the shorter drying time, higher drying temperature and microwave power levels and some tissue expansion from internal water vapour.

4. Conclusions

Combined microwave-convective drying decreased the drying time required when compared to drying with either convective or microwave drying alone. The results verified that the drying time decreased with increasing drying air temperatures and microwave levels. Among the tested models, the Midilli et al. model exhibited the best fit in describing the drying behaviors of barbunia beans. It was found that the 50°C convective method gave colour values closest to those of fresh samples. Scanning electron microscope images showed that all the drying processes caused a deformation in the microstructure of the barbunia beans. Drying at 160W-75°C resulted in a complete destruction in the samples' microstructure.

Acknowledgments

The authors thank the Uludag University Research Foundation for their financial support (Project No. Z(U) 2009/26) and American Journal Experts (AJE) for final editing.

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