J. Agr. Sci. Tech. (2017) Vol. 19: 613-626

Internal and External Color Development Kinetics during Microwave Assisted Fluidized Bed Drying of Hazelnut

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ABSTRACT

Microwave assisted fluidized bed drying is a novel drying technique which reduces drying time and yields higher quality products. In this study the effect of this method on color changes of whole and cut hazelnut kernels was investigated. The parameters of color and resulting total color change, chroma, Hue angle and browning index were also calculated during drying in three temperatures (40, 50 and 60°C) and microwave power levels (0, 450 and 900W). Comparison was made to investigate the effect of drying condition on browning of hazelnut surface and internal cavity. The zero and first order kinetic models were also fitted to whole and cut kernel color parameters. The results showed similar behavior in color parameters of whole and cut kernels. *L* value and Hue angle decreased with increasing drying time, drying air temperature and microwave power but *a, b, ΔE,* chroma and browning index increased. *L* and *b* values of whole kernels were higher than cut kernels but the *a* value was lower. Zero-order model was selected as the best model for predicting *a, b* and *ΔE* while first order model best described the kinetics of color changes of *L*, chroma, Hue angle and browning index.

Keywords: Color Parameters, Fluidized Bed Drying, Hazelnut, Kinetic Modeling, Microwave

INTRODUCTION

Hazelnuts (*Corylus avellana* L.) have major beneficial roles in human nutrition and health because of their unique nutrient contents including proteins, carbohydrates, fats, vitamins and minerals (Şimşek, 2007). Iran produced 24,300 MT of hazelnuts in 2010, ranking 6th in world hazelnut production. Northern Iran has a suitable climate for production of high-quality hazelnuts (Hosseinpour *et al.*, 2013a). Hazelnuts are one of the most important raw materials for the chocolate and confectionary industries, also they are used as flavoring and texturizing agent and adding fiber to different foods (Moscetti *et al.*, 2012, Uysal *et al.*, 2009).

Because of climate changes in the season of hazelnut harvest, it is harvested before being naturally dried on the tree with a moisture content of about 25%. Therefore, hazelnut should be dried to reduce its moisture content to a safe level for storage. The best moisture content to prevent the microbial growth is 7 to 8% for unshelled hazelnuts and 4 to 5% for shelled hazelnuts (Lopez *et al.*, 1997a). High temperatures during drying hazelnuts may have adverse physical, structural, chemical, organoleptic, and nutritional effects (Demirhan and Özbek, 2015; Nadian *et al.*, 2015). The combination of microwave power with hot air convective drying has recently been proposed due to short start-up times, volumetric heating and reduced processing times (Askari *et al.*, 2013; Gowen *et al.*, 2006).

Many authors proposed color as a quality indicator of food products because, increasing the browning and caramelization reactions cause more brown pigments formation (Dadalı *et al.*, 2007b; Lixia *et al.*, 2015; Özdemir and

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Devres, 2000a; Özdemir *et al.*, 2001). Color changes may be an indicator of decreased nutritional value due to off-flavor development, protein loss, decreased solubility, undesirable color, destruction of vitamins, textural changes, and increased acidity (Lopez *et al.*, 1997b).

During the drying of hazelnut, the color gradually changes from white to a creamy color starting at the outside of the kernel. Internal browning has also been reported for almonds (Halbrook *et al.*, 1983) and hazelnuts (Özdemir *et al.*, 2001) and may be due to accumulation of reducing sugars in the center of the kernel reacting with amino acids to form Maillard browning products.

Since, the kinetics of color change of food products is a complex phenomenon, determination of kinetic parameters such as reaction rate, order and constant is important in order to optimize the thermal process (Saxena *et al.*, 2012). Browning of agricultural and food products was explained using zero or first-order reaction kinetics (Şimşek, 2007). There are some works on studying the influence of roasting on hazelnut color kinetics (Alamprese *et al.*, 2009; Demir *et al.*, 2002; Özdemir and Devres, 2000a; Özdemir and Devres, 2000b; Özdemir *et al.*, 2001; Richardson and Ebrahem, 1996; Şimşek, 2007; Uysal *et al.*, 2009), but there are few works on microwave assisted fluidized bed drying and the influence of this process on whole and cut hazelnut browning. Therefore, the aim of the current study was evaluation of the kinetics of color changes of whole and cut hazelnut (for investigation of the internal browning) in microwave assisted fluidized bed dryer and choosing the best model to predict color changes during drying.

MATERIAL AND METHODS

Raw Material Preparation

Freshly harvested hazelnuts were purchased from a local garden in Eshkevarat, Guilan, Iran and kept at 4°C refrigeration until used. Before the experiments hazelnuts were shelled and the poor quality kernels were removed.

Drying Experiments

Drying experiments were conducted using a laboratory scale microwave assisted fluidized bed dryer (Figure 1). Drying air temperature and velocity were controlled precisely. Drying chamber was positioned on a digital balance with accuracy of 0.01 g and the samples were weighted when the blowing air was switched off. The drying

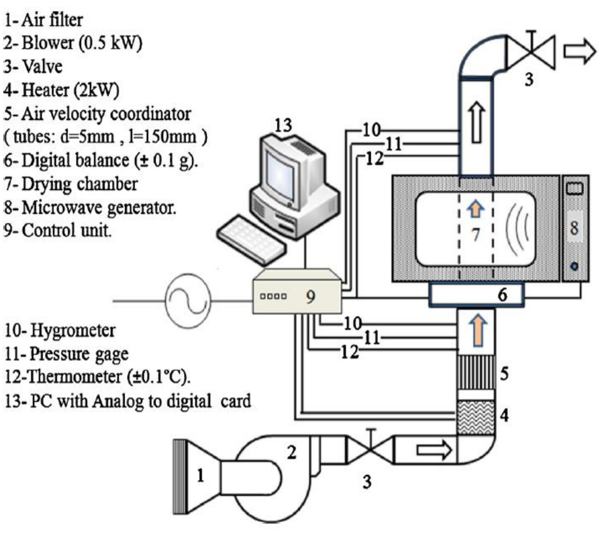

Figure 1. Drying apparatus [picture adapted by Askari *et al.*, 2013].

experiments were conducted at three air temperatures (40, 50 and 60°C) and combined with three microwave power levels (0, 450 and 900W). Raw hazelnut was used as control treatment. The initial moisture content of the samples was 24-25% (db). 100 g hazelnut was used for each experiment. The drying experiments were continued until the moisture content of the samples reached 5-6%.

Color Measurements

During each experiment 5 hazelnut kernels were removed from the drying chamber in specified time intervals and were immediately cooled and kept in the polyethylene bags until performing the color measurements. The *L*, *a*, and *b* values were determined using an image analysis system. This system consisted of CCD camera (PROLINE UK, Model 565s with 510 by 492 pixel resolutions, London, United Kingdom), capture card (WinFast DV2000 with a 320Hx240V resolution), 2 fluorescent tubes around camera and a personal computer. The camera was mounted 10 cm above the white background and powered by a 24V power supply. The light source and camera were mounted on a frame and were attached to the measurement table. The whole system was covered by a tarpaulin to omit the effects of surrounding lights. Captured signals by the camera were transferred to the computer and stored on the computer into RGB coordinates (Taghadomi-Saberi *et al.*, 2015). Image-Pro Plus 7 software (Media Cybernetics, USA) was used to convert RGB color values to Lab. The *L*-value represents the light-dark spectrum with a range of 0 (black) to 100 (white), the *a*-value represents the green-red spectrum with a range of 60 (green) to +60 (red) while the *b*-value represents the blue-yellow spectrum with a range of 60 (blue) to +60 (yellow) (Mohammadi *et al.*, 2008).

The color of surface and center of 5 randomly selected hazelnut kernels were measured and they are referred to as whole and cut-kernel color throughout the manuscript.

Conversion of the Lab readings to total color difference (ΔE), Hue angle (H), Chroma (C) and Browning Index (BI) provides a more realistic assessment of how the consumer perceives color of foods (Pathare *et al.*, 2013). These parameters were calculated using Equations (1-4) (Hosseinpour *et al.*, 2013b):

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \quad (1)$$

Where L_0, a_0, b_0 are the initial color measurements of raw hazelnut samples and L, a, b are the color measurements at prespecified time.

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

$$Hue\ angle = tan^{-1}(\frac{b}{a}) \quad (3)$$

$$BI = \frac{[100(x - 0.31)]}{0.17} \quad (4)$$

Where:

$$x = \frac{(a + 1.75L)}{(5.645L + a - 3.012b)} \quad (5)$$

Kinetic Modeling

Two of the best models for describing the kinetics of color changes of food material are zero and first order models (Ling *et al.*, 2015; Pathare *et al.*, 2013). Generally, the rate of change of a quality factor C can be represented by:

$$\frac{dC}{dt} = -kC^n \quad (6)$$

Where, k is the kinetic rate constant and n is the order of reaction.

By integrating Equation (6), zero-order Equation (7) and first-order kinetic model Equation (8) can be derived as:

$$C = C_0 \pm kt \quad (7)$$

$$C = C_0 \exp(\pm kt) \quad (8)$$

Where, C_0 is the initial value of color and C is the color value at a pre-specified time. The order of reaction for the color parameters during microwave drying of hazelnut was determined by adjustment of the experimental data to the integrated Equations (7) and (8) using linear regression analysis.

The Microsoft excel solver was used in the numerical calculations. The parameters were evaluated by the nonlinear least squares method until minimal error was achieved between experimental and calculated values. The residual SSR was defined as the sum of the squares of the differences between experimental and calculated data and given by Equation (9) (Demirhan and Özbek, 2015):

$$SSR = \sum_{m=1}^{N_d} (C^{obs}m - C^{cal}m)^2 \qquad (9)$$

Wherem m is the observation number and N_d is total number of observations. The estimated variance of the error was calculated by dividing the minimum SSR by its degrees of freedom:

$$\sigma^2 \approx S^2 = (SSR)_{min}/(m-p) \qquad (10)$$

Where, p is the number of parameters and s^2 is the variance. The standard error, σ (the estimated standard deviation) is calculated by taking the square root of the estimated variance of the error. The best model describing color formation kinetics of hazelnut kernels during drying was chosen as the one with the highest correlation coefficient and the least sum of squares error and the least estimated standard deviation**.**

Statistical Analysis

Each number presented in figures and tables is the mean of three repetitions. A full factorial design was used to study the effect of drying temperature (three levels) and microwave power (three levels) on hazelnut color parameters and these effects were statistically determined using Analysis of Variance (ANOVA). Comparison of means was done using Duncan's test at a level of significance *P*< 0.05 using SPSS 18 software (SPSS Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

Effect of drying conditions on *L, a, b* and *ΔE* of whole and cut kernels is shown in Figures 2 and 3 respectively. There was significant difference between color parameters between dried and control sample in all of the drying treatments. As it is shown in Figure 2-A, the *L* values of whole kernel decreased with increasing drying time in all of the treatments. Changes in the brightness of dried samples can be taken as a measurement of browning. The *L* value was 83.45 for raw hazelnut and total change of this parameter was from 82.87 to 81.93 for hot air drying (40-60°C) without microwave and between 82.87 and 77.09 in all treatments. Higher values of darkness may be due to high volumetric temperature produced in microwave drying. These findings were confirmed by other authors for hazelnut (Demir *et al.*, 2002; Özdemir and Devres, 2000b; Özdemir *et al.*, 2001; Richardson and Ebrahem, 1996; Şimşek, 2007). Analytical analysis showed that there was no significant difference (P> 0.05) between *L* values at 40 and 50°C but significant difference was observed between 60°C and other temperatures. These findings are in accordance with the study of Lopez *et al.* (1997b) in hot air drying of hazelnut and Lixia *et al.* (2015) for thermal treatment of chestnut. Also there was no significant difference (P> 0.05) between the treatments with the same microwave power and different hot air temperatures. This may be due to high temperatures produced during microwave heating, which diminished the effect of temperature increment.

L value for cut kernels was 82.24 for raw hazelnut and changed from 81.16 to 75.44 during different treatments. As it is shown in Figure 4-A. the *L* values of whole kernels were always higher than cut kernels but the differences between these values are not significantly different in all treatments. This shows that more internal browning occurs in the internal cavity of the hazelnuts. The internal browning is especially a problem for the product that is consumed as whole-kernels because the difference between outside and inside color of roasted product makes the product unpleasant for the consumer (Özdemir *et al.*, 2001). Other studies also confirmed higher darkness in the internal cavity of hazelnuts (Özdemir and Devres, 2000b; Özdemir *et al.*, 2001; Şimşek, 2007).

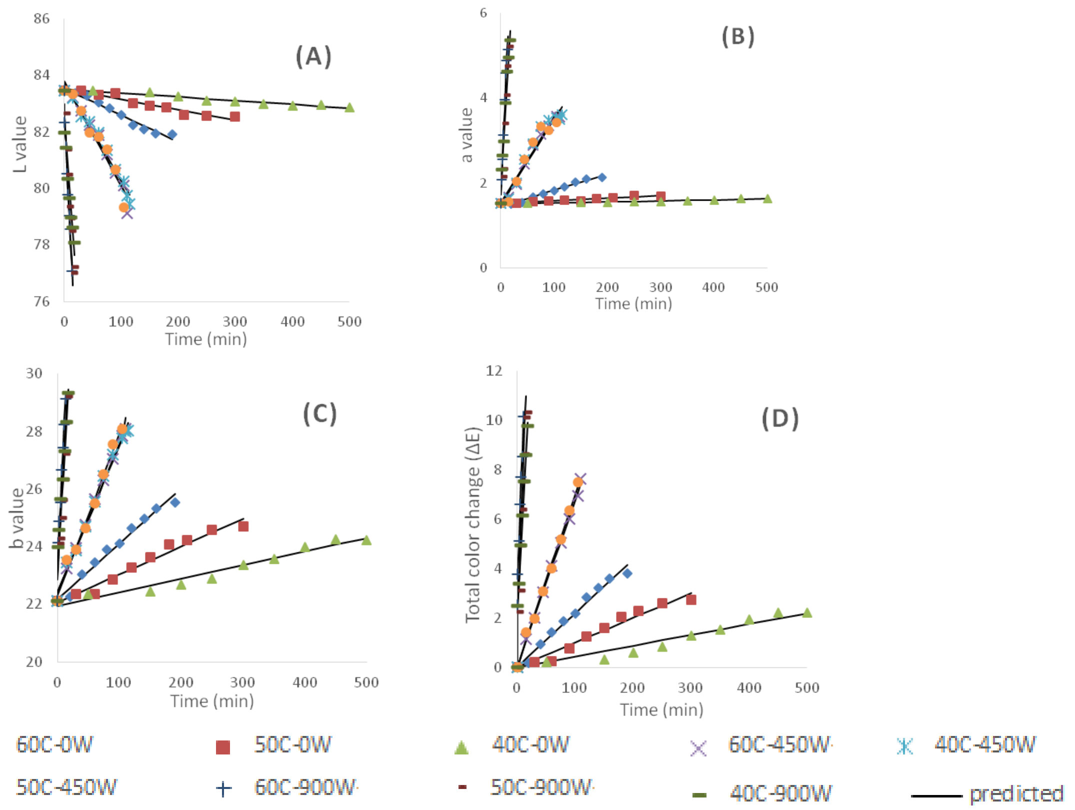

Figure 2. Kinetics of change of the (A) *L* value, (B) *a* value, (C) *b* value, and (D) Total color change (ΔE) as a function of drying time at various drying conditions for whole kernel (The drying process was terminated when the moisture content reached to 5-6% moisture content).

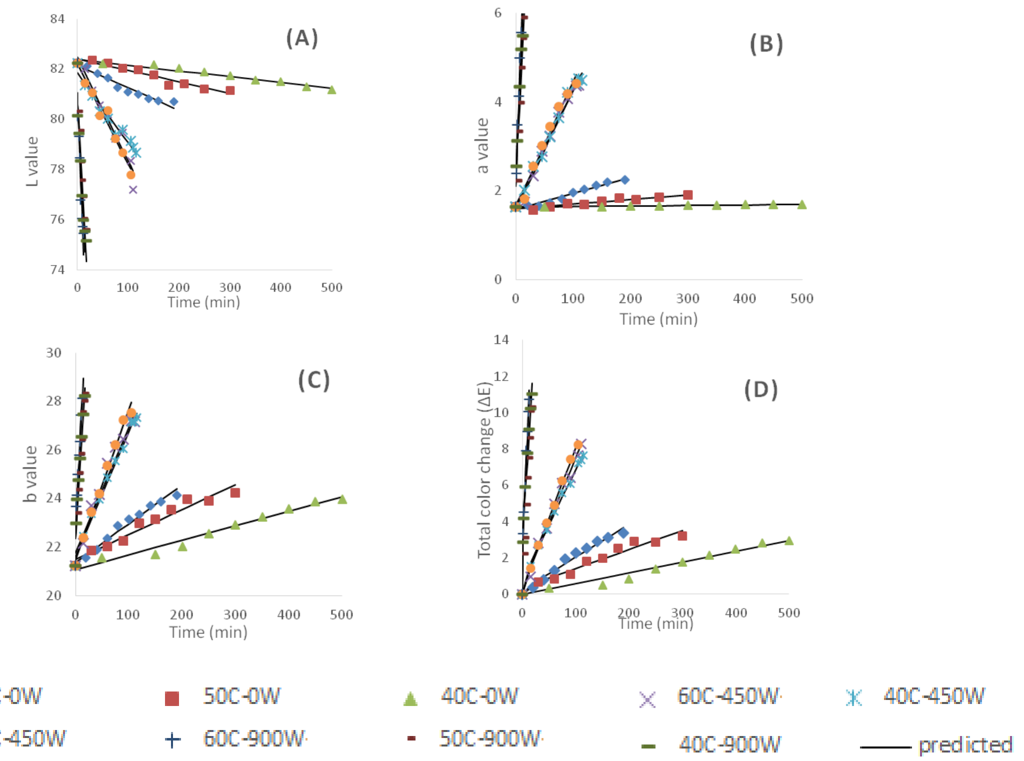

Figure 3. Kinetics of change of the (A) *L* value, (B) *a* value, (C) *b* value, and (D) Total color change (ΔE) as a function of drying time at various drying conditions for cut kernel (The drying process was terminated when the moisture content reached to 5-6% moisture content).

The initial value of redness-greenness (a value) for raw whole hazelnuts was 1.52 as it is shown in Figure 2-B. The *a*-values changed from 1.63 to 2.13 at the end of hot air drying (40-60°C) without microwave and between 1.52 and 5.37 in all treatments. The difference between *a*-value of 40 and 50°C was not significantly different (P> 0.05) but it was significantly different between 60°C and other temperatures. These results show that the redness of the samples increased with temperature increase and microwave power. The same trend was observed for a-values of cut kernels (Figure 3-B). Figure 4-B indicates that cut kernels have higher redness than whole kernels. The b value for raw whole hazelnut was 22.13 and changed between 24.29 and 29.34 at the end of all treatments. This shows that higher yellowness of samples occurred with increasing drying temperature and microwave power. The changes of *b* value for cut kernel was between 23.97 and 28.33 in all treatments (Figure 3-C). The difference between b value of whole and cut kernel was not significant in any of the treatments except at treatment with the temperature of 60°C without microwave which may be due to higher surface temperature produced during air drying without microwave. These findings are in accordance with the results of Şimşek (2007) who reported that b value increased with temperature rise in hazelnut roasting but Lixia *et al.* (2015) reported opposite results.

The total color change of whole and cut kernels are calculated using Equation (1) and are shown in Figures 2-D and 3-D. An increasing trend is shown in both whole and cut kernel. *ΔE* was between 0 and 10.31 for whole kernel and 0 and 11.05 for cut kernels. This shows browning of the kernels occurred during drying which may be a result of non-enzymatic browning and pigment formation during drying. It is shown that total color change in cut kernels is higher than whole kernels. Some authors suggest that, this higher internal browning in internal cavity may be due to accumulation

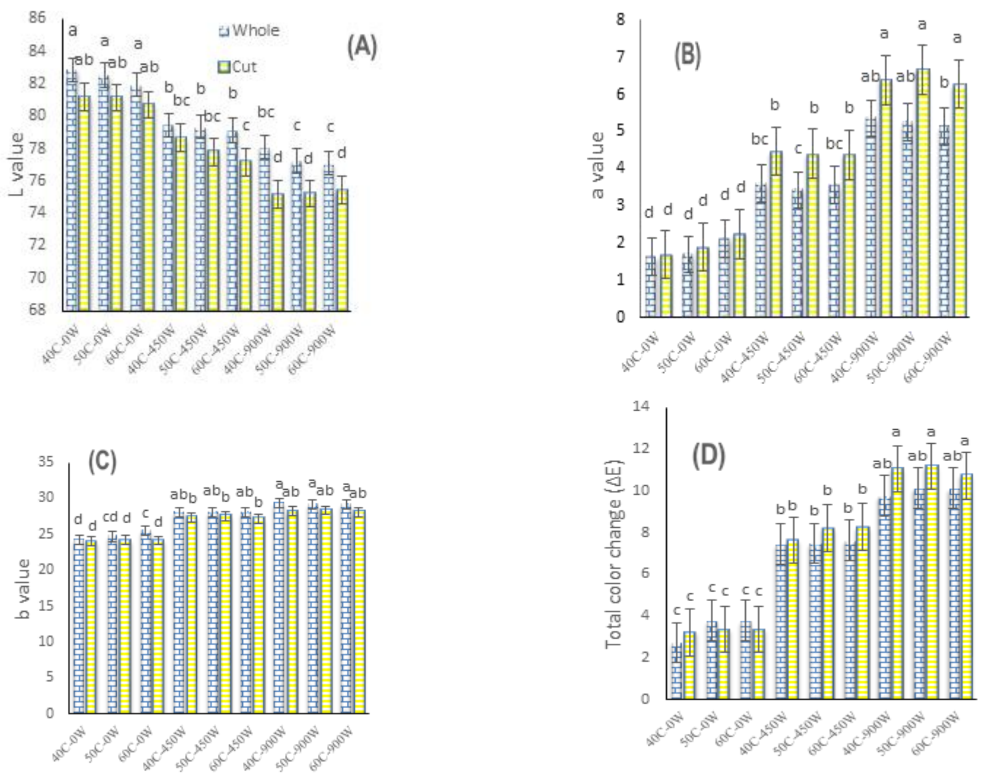

Figure 4. Comparison between color parameters (L, a, b and ΔE) of whole and cut kernels after drying.

of reducing sugars in the center of the kernel reacting with amino acids to form Maillard browning products (Wall and Gentry, 2007) and some others refer it to the difference in temperature and moisture distribution within the kernel (Özdemir and Devres, 2000a).

Zero-order and first-order kinetic models were used for the mathematical modeling of color changes of whole and cut hazelnut kernels. Similar statistical values were observed for *L, b,* and total color change (ΔE) using two models. Tables 1 and 2 show k, C_0, r^2 and δ values for *L, a, b* and *ΔE.* It was observed that the values of coefficient of determination were high in both zero and first order kinetic models except the treatments without microwave power in which the values of r^2 are lower. This may be because of an initial induction period which was observed for *L, a* and *b* values in first stages of hazelnut drying without microwave which is reported by some other authors (Lopez *et al.*, 1997b; Özdemir and Devres, 2000b). *L, a* and *b* values of whole-kernel measurements remained relatively constant before a significant color change was observed. It was observed that, a slight lightening of the nuts at the beginning of the process also occurred. The length of this time delay or induction period was inversely proportional to temperature and microwave power used, as reported by other authors (Özdemir and Devres, 2000b). During the induction period several precursor reactions such as Amadori rearrangements and concentration of substrates are likely to occur. Both models had high coefficient of determination and low standard errors and could be used in kinetic modeling of this color parameters but zero order kinetics showed better fitting parameters than first order kinetics for *a*, *b* and *ΔE.* The best model for describing kinetics of *L* value changes was first order model. Similar results were reported for modeling kinetics of *L* and *ΔE* values by Chutintrasri and Noomhorm (2007). As it is shown in Tables 1 and 2 the kinetic rate (k) is 10 fold higher in 450W microwave power than the treatment without microwave. The kinetic rate was also 10 folds higher in 900W than 450W which indicates superior rates of color change in higher microwave powers. Elevating microwave power, accelerated the degradation rate of color as a result of higher energy transferred to the inside of food material, which causes an increase in temperature of the product. These results were confirmed by other authors (Dadali *et al.*, 2007a, Dadalı *et al.*, 2007b, Demirhan and Özbek, 2015). The predicted values of best model for each parameter are shown as solid line in Figures 2 and 3.

Chroma, Hue angle, and browning index were calculated using Equations (2-4) and are illustrated in Figures 5 and 6 for whole and cut kernel respectively. The initial value of chroma was 22.18 for raw whole hazelnut and changed from 24.29 to 29.83 during drying. Chroma, indicates an increase with increase in the drying time. For raw cut kernel the initial value of chroma was 21.27 and changed from 24.12 to 29.83 during drying (Figure 5-A). Cut kernels also followed a similar trend. The initial value of chroma for raw cut hazelnut was 21.27 and changed from 24.03 to 29.10 during drying (Figure 6-A). The values of chroma were not significantly different at the end of all treatment between cut and whole kernel (Figure 7-A). Hue angle decreased with increasing drying time, drying air temperature and microwave power. Hue angle is frequently used to specify color in food products (Lopez *et al.*, 1997b). An angle of 0 or 360° represents red hue, while angles of 90, 180, and 270 ° indicate yellow, green, and blue hues, respectively. The values of Hue angle for whole raw hazelnut was 86.07 and did not change significantly during hot air fluidized bed dying without microwave. The changes of Hue angle were between 86.15 and 79.65 during drying (Figure 5-B). These values for cut kernels were 85.97- 77.25 (Figure 6-B) and as it is shown in Figure 7-B there wasn't any significant difference between the treatments without microwave power but the treatments with 900W microwave power were significantly different ($P < 0.05$).

Table 1. The estimated kinetic parameters and the statistical values of zero and first-order models for *L*, *a*, *b*, and total color change (ΔE) for various drying condition for whole kernel.

First-order model				Zero-order model						
δ	r^2	C_0	k (min^{-1})	δ	r^2	C_0	k (min^{-1})	Quality parameter	Power (W)	Temperature (°C)
0.0035	0.9374	83.5063	0.0000	0.0035	0.9370	83.5048	0.0013	*L*	0	40
0.0001	0.9184	1.5105	0.0002	0.0002	0.9134	1.5100	0.0002	*a*		
0.0328	0.9532	21.9546	0.0002	0.0356	0.9489	21.9416	0.0047	*b*		
0.0570	0.9283	0.3184	0.0041	0.0527	0.9252	0.0000	0.0044	*ΔE*		
0.0560	0.9748	83.7133	0.0004	0.0522	0.9766	83.7020	0.0342	*L*	450	
0.0763	0.8828	1.7518	0.0068	0.0411	0.9436	1.5494	0.0196	*a*		
0.0600	0.9880	22.5130	0.0020	0.0381	0.9923	22.4260	0.0510	*b*		
0.2152	0.9753	1.6387	0.0136	0.0168	0.9982	0.2733	0.0629	*ΔE*		
0.2848	0.9999	82.4897	0.0034	0.2988	0.9999	82.4654	0.2683	*L*	900	
0.1559	0.9746	2.1882	0.0536	0.0626	0.9901	1.9032	0.2044	*a*		
0.3111	0.9987	23.2423	0.0134	0.2673	0.9988	23.1505	0.3509	*b*		
0.3903	0.9873	2.9576	0.0701	0.0229	0.9993	2.1857	0.4295	*ΔE*		
0.0105	0.9270	83.5211	0.0000	0.0105	0.9267	83.5201	0.0037	*L*	0	50
0.0003	0.9451	1.5198	0.0004	0.0002	0.9453	1.5181	0.0007	*a*		
0.0399	0.9601	22.0945	0.0004	0.0363	0.9639	22.0634	0.0097	*b*		
0.1699	0.8444	0.5791	0.0057	0.0460	0.9632	0.0000	0.0100	*ΔE*		
0.0025	1.0000	83.5124	0.0057	0.1208	0.9999	83.7706	0.0367	*L*	450	
0.0834	0.9706	1.6863	0.0076	0.0477	0.9836	1.5008	0.0207	*a*		
0.0553	0.9997	22.3746	0.0022	0.0536	0.9998	22.2949	0.0559	*b*		
0.1255	0.9923	1.4348	0.0161	0.0441	0.9974	0.0683	0.0690	*ΔE*		
0.1470	0.9998	82.9385	0.0053	0.1638	0.9998	82.8979	0.4224	*L*	900	
0.2976	0.9247	2.2549	0.0649	0.1279	0.9702	1.8537	0.2667	*a*		
0.2026	0.9980	22.9490	0.0160	0.2028	0.9980	22.8711	0.4125	*b*		
1.7045	0.9216	2.3299	0.1032	0.1742	0.9932	1.7096	0.6184	*ΔE*		
0.0147	0.9627	83.5479	0.0001	0.0148	0.9625	83.5450	0.0095	*L*	0	60
0.0020	0.9674	1.4788	0.0021	0.0018	0.9704	1.4567	0.0038	*a*		
0.0423	0.9735	22.2378	0.0008	0.0338	0.9791	22.1881	0.0192	*b*		
0.2225	0.8917	0.8677	0.0084	0.0436	0.9820	0.0248	0.0216	*ΔE*		
0.0983	0.9590	83.7944	0.0005	0.0932	0.9613	83.7834	0.0369	*L*	450	
0.0411	0.9388	1.6712	0.0074	0.0169	0.9768	1.4876	0.0203	*a*		
0.0792	0.9838	22.5269	0.0015	0.0461	0.9906	22.4244	0.0378	*b*		
0.1911	0.9792	1.4855	0.0151	0.0144	0.9985	0.0557	0.0669	*ΔE*		
15.6072	0.9932	82.9798	0.4408	0.0963	1.0000	82.9798	0.4408	*L*	900	
0.1595	0.9731	2.0717	0.0764	0.0474	0.9923	1.7348	0.2857	*a*		
0.2965	0.9987	23.1809	0.0183	0.2492	0.9989	23.0837	0.4798	*b*		
0.6369	0.9776	2.6896	0.1007	0.0377	0.9988	1.9744	0.6225	*ΔE*		

Table 2. The estimated kinetic parameters and the statistical values of zero and first-order models for *L, a, b,* and total color change (ΔE) for various drying condition for cut kernel.

First-order model				Zero-order model						
δ	r^2	C_0	k (min^{-1})	δ	r^2	C_0	k (min^{-1})	Quality parameter	Power (W)	Temperature (°C)
0.0082	0.9488	82.3747	0.0000	0.0081	0.9497	82.3742	0.0023	*L*	0	40
0.0001	0.8379	1.6289	0.0001	0.0001	0.8345	1.6289	0.0001	*a*		
0.0275	0.9755	21.0962	0.0003	0.0300	0.9732	21.0700	0.0060	*b*		
0.0840	0.9380	0.4859	0.0038	0.0503	0.9611	0.0000	0.0059	*ΔE*		
0.0629	0.9571	81.8475	0.0003	0.0652	0.9554	81.8350	0.0277	*L*	450	
0.0428	0.9644	1.9284	0.0079	0.0122	0.9905	1.6716	0.0259	*a*		
0.0694	0.9863	21.6871	0.0021	0.0432	0.9914	21.5903	0.0514	*b*		
0.2204	0.9750	2.0204	0.0120	0.0214	0.9977	0.8241	0.0603	*ΔE*		
0.5673	0.9997	80.9224	0.0047	0.6049	0.9997	80.8755	0.3629	*L*	900	
0.4809	0.9480	2.7289	0.0526	0.2196	0.9774	2.3093	0.2567	*a*		
0.3921	0.9982	22.4316	0.0136	0.3273	0.9985	22.3294	0.3462	*b*		
0.8887	0.9789	3.9106	0.0619	0.1992	0.9954	2.8342	0.4889	*ΔE*		
0.0160	0.9280	82.4033	0.0001	0.0160	0.9280	82.4018	0.0046	*L*	0	50
0.001284	0.8891	1.5962	0.0006	0.0013	0.8901	1.5920	0.0010	*a*		
0.0699	0.9371	21.5191	0.0004	0.0614	0.9456	21.4784	0.0103	*b*		
0.1526	0.8890	0.9168	0.0046	0.0556	0.9646	0.3531	0.0105	*ΔE*		
0.0755	1.0000	82.2216	0.0005	0.0733	1.0000	82.2083	0.0399	*L*	450	
0.0769	0.9825	1.8938	0.0087	0.0241	0.9947	1.6292	0.0283	*a*		
0.0987	0.9995	21.5690	0.0025	0.0557	0.9997	21.4450	0.0619	*b*		
0.3892	0.9820	1.8999	0.0146	0.0234	0.9990	0.3692	0.0768	*ΔE*		
0.4330	0.9995	81.0389	0.0054	0.4639	0.9995	80.9909	0.4176	*L*	900	
0.3683	0.9380	2.6097	0.0685	0.1153	0.9821	2.0987	0.3344	*a*		
0.5087	0.9949	22.6716	0.0165	0.4261	0.9957	22.5487	0.4261	*b*		
1.7045	0.9216	2.3299	0.1032	1.3092	0.9555	1.7096	0.6184	*ΔE*		
0.0206	0.9418	82.1595	0.0001	0.0211	0.9404	82.1559	0.0090	*L*	0	60
0.0020	0.9663	1.5874	0.0019	0.0023	0.9613	1.5700	0.0037	*a*		
0.0350	0.9687	21.3768	0.0007	0.0284	0.9749	21.3385	0.0161	*b*		
0.1777	0.8864	0.8880	0.0076	0.0471	0.9742	0.2192	0.0182	*ΔE*		
0.1805	0.9395	82.4707	0.0005	0.1760	0.9412	82.4552	0.0411	*L*	450	
0.0612	0.9487	1.8340	0.0085	0.0194	0.9851	1.5638	0.0271	*a*		
0.3434	0.9318	21.8842	0.0015	0.2630	0.9486	21.7502	0.0386	*b*		
0.5287	0.9503	1.9005	0.0136	0.1273	0.9889	0.3893	0.0712	*ΔE*		
0.5245	0.9997	81.0987	0.0064	0.5597	0.9997	81.0494	0.4958	*L*	900	
0.3723	0.9590	2.5859	0.0756	0.1334	0.9860	2.1282	0.3578	*a*		
0.4472	0.9979	22.5090	0.0180	0.3976	0.9982	22.4114	0.4565	*b*		
0.6409	0.9844	3.6723	0.0892	0.1472	0.9965	2.7946	0.6492	*ΔE*		

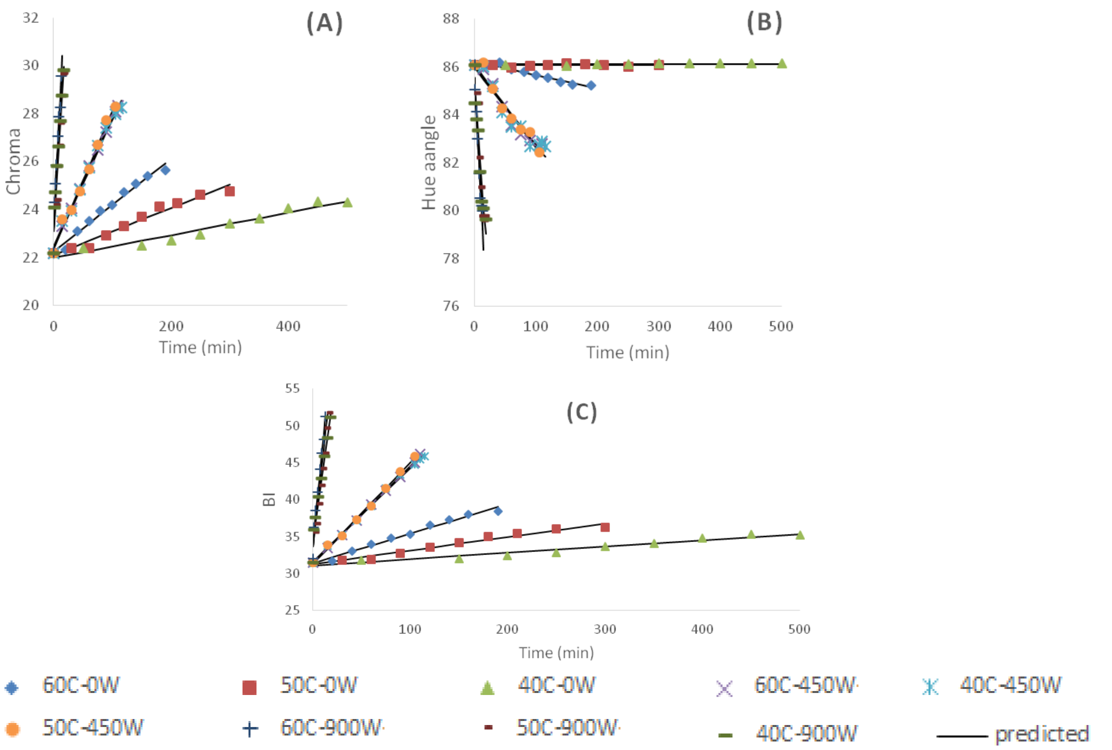

Figure 5. Kinetics of change of the (A) Chroma, (B) Hue angle, and (C) Browning index as a function of drying time at various drying condition for whole kernel (The drying process was terminated when the moisture content reached to 5-6% moisture content).

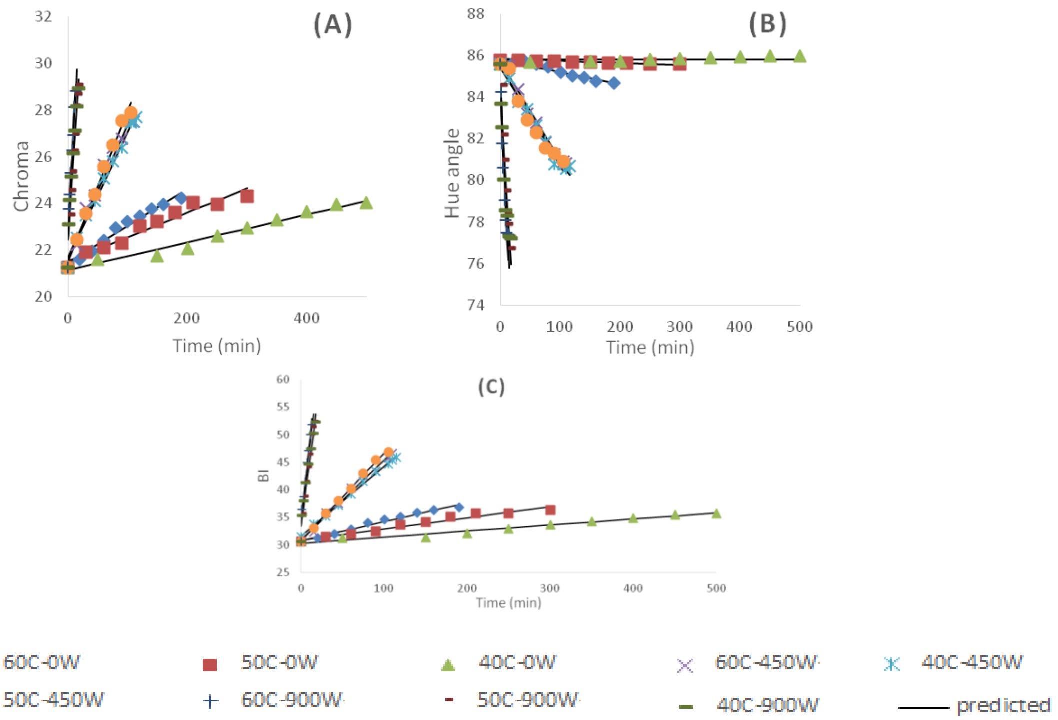

Figure 6. Kinetics of change of the (A) Chroma, (B) Hue angle, and (C) Browning index as a function of drying time at various drying conditions for cut kernel (The drying process was terminated when the moisture content reached to 5-6% moisture content).

Browning Index (BI) represents the purity of brown color and is reported as an important parameter in drying processes where enzymatic and non-enzymatic browning takes place. As it is obvious in Figure 5-C the browning index increased from 35.26 to 51.75 during drying and was 31.47 for raw whole kernels. These values were 35.74 to 52.48 and 30.64 for cut kernel, respectively. These observations are in agreement with previous works (Alamprese *et al.*, 2009; Demir *et al.*, 2002; Lopez *et al.*, 1997b; Özdemir and Devres, 1999). Figure 7-C shows no significant difference between *BI* index of whole and cut kernel.

The model and statistical parameters for chroma, Hue angle, and browning index for various drying conditions for whole and cut kernel are shown in Tables 3 and 4. The results showed that the fitting parameters were higher than those for *L*, *a*, *b* and *ΔE* (Tables 1 and 2). As it is shown in Tables 3 and 4 the values of r^2 were higher than 0.99 in most of the cases which show the accuracy of model in all cases. Similarly, the rate of color changes (k) increased as microwave power and drying air temperature increased. The best model describing chroma and Hue angle was first order model but for *BI* there wasn't any significant difference between the two models.

CONCLUSIONS

The results of the current study showed that the color of dried hazelnut was proportional to drying temperature and microwave power used for microwave assisted fluidized bed drying. After drying, there was significant difference between color parameters of dried and control samples in all of the drying treatments. The

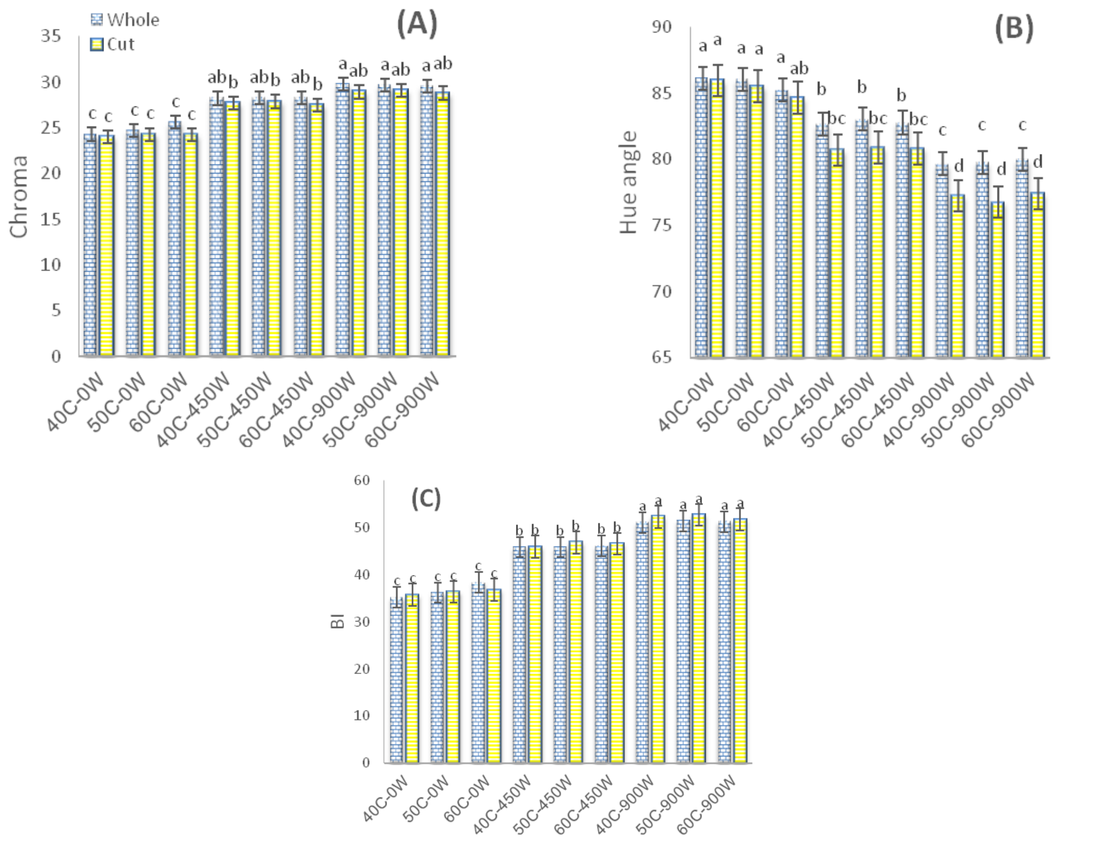

Figure 7. Comparison between color parameters (chroma, Hue angle and browning index) of whole and cut kernels after drying.

effect of microwave power was stronger than temperature. Increasing drying time, drying air temperature and microwave power resulted in lower *L* and Hue angle and higher *a, b, ΔE*, chroma and browning index in both whole and cut kernels. Kinetic modeling showed that zero order model was the best model for describing *a, b* and *ΔE*. The accuracy of fitting was higher in first order model for *L*, chroma, Hue angle and browning index. The rate of kinetic model increased 100 folds by increasing the microwave power from 0 to 900W. Although microwave assisted fluidized bed drying caused more browning than convectional drying but reviewing the available literature showed that the browning of kernels was lower than high temperature drying of hazelnuts and the dried hazelnuts were in an accepted range of color in all of the drying treatments.

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مدلسازی سینیتیک تغییرات رنگ داخلی و خارجی فندق در طی فرایند خشک کردن بستر سیال مجهز به مایکروویو

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چکیده

خشک کردن بستر سیال با استفاده از مایکروویو یک فناوری نوین خشک کردن می باشد که زمان خشک کردن را کاهش داده و منجر به تولید محصولات با کیفیت می گردد. در این مطالعه تاثیر این فناوری بر روی تغییرات رنگ رویه و داخل دانه های فندق مورد بررسی قرار گرفت. پارامترهای رنگ Lab و همچنین تغییرات رنگ کل، شاخص کروما، زاویه هیو و قهوه ای شدن در طی خشک کردن در سه سطح دمایی (۴۰، ۵۰ و ۶۰ درجه سلسیوس) و سه سطح توان مایکروویو (۰، ۴۵۰ و ۹۰۰ وات) مورد

بررسی قرار گرفت. تغییرات شاخص های رنگ در سطح و داخل دانه های فندق با یکدیگر مقایسه شد. مدل های درجه صفر و درجه یک سینیتیکی هم برای رویه و هم برای داخل فندق مورد برازش قرار گرفت. نتایج نشان داد که روند تغییرات رنگ رویه و داخل فندق مشابه بود. مقادیر L و زاویه هیو با افزایش زمان و دمای خشک کردن و قدرت مایکروویو کاهش یافت در حالی که مقادیر a، b و ΔE ، شاخص کروما و قهوه ای شدن افزایش پیدا کردند. مقادیر L و b رویه فندق بالاتر از داخل فندق بود در حالی که برای پارامتر a عکس این روند مشاهده شد. مدل درجه صفر بهترین مدل برای پیشگویی مقادیر a، b و ΔE بود در حالی که مدل درجه یک نتایج بهتری را برای پیشگویی L، کروما، زاویه هیو و شاخص قهوه ای شدن ارائه داد.