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Colour Change Kinetics of the Inner and Outer Surface of Brussels Sprouts during Microwave Drying Process

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ABSTRACT

The effect of microwave output powers on colour change kinetics of the inner and outer surface of brussels sprouts was investigated during microwave drying process. The colour changes of the materials were quantified by means of the CIELab scale parameters like L*, a*, and b*. The total color change (ΔE), chroma (C*), hue angle (h*), and browning index (BI) were also calculated by using these values. As expected, microwave drying process changed the colour parameters at different rates depending on the output power used because of browning. The values of a*, ΔE, and BI on both surfaces of the brussels sprouts increased, other values decreased during drying. The mathematical modeling study of color change kinetics indicated that all colour parameters fitted to a zero-order kinetic model and the 460 W output power occured the lowest change rates of all colour parameters. According to the values of activation energy calculated by colour change kinetic parameters, more colour change on the outer surface of brussels sprouts happened by the increase in microwave output power.

Keywords: Browning index; Brussels sprouts; Colour change kinetics; Microwave drying

1. Introduction

Fruits and vegetables are essential food for a balanced diet, but fresh ones can be quickly deteriorated due to high moisture contents of about 80% (Orsat et al 2006; Karam et al 2016). One of the oldest known methods of preserving food is probably drying (Cohen & Yang 1995; Pittia & Antonello 2016). Drying process is used to extend the shelf-life of the products by decreasing the water activity to a low level enough to inhibit enzymatic reactions, microorganisms' growth and other deteriorative reactions (Law et al 2014). This process specially causes changes in some physical properties, such as colour, texture, size and in chemical structure, such as losses of flavor and nutrients (Krokida & Marinos-Kouris 2003; Adak et al 2017). These changes in the functional properties can negatively affect the quality of food products (Kammoun Bejar et al 2011; Dehnad et al 2016). In the conventional drying techniques, the long drying times at relatively high temperatures at the falling rate periods often cause undesirable thermal degradation of final products (Mousa & Farid 2002; Zhang et al 2006). Conversely, microwave drying process reduces the browning and improves the final quality of dried products with a shorter drying time (Zhang et al 2006).

Among the quality attributes of the fruits and vegetables, colour is one of the most important quality indicators influencing the degree of acceptability of the foodstuffs by the consumer. It is an indicator of the inherent good qualities in related with the marketing values of the product (Doymaz 2012; Sabarez 2014). The variations in the product colour during drying process is the result of many browning reactions (i.e., enzymatic and non-enzymatic), pigment degradation and oxidation reactions (Barreiro et al 1997; Lozano & Ibarz 1997; Lee & Coates 1999; Maskan 2001; Serratosa et al 2011; Sabarez 2014). The kinetic modeling of colour changes in fruits and vegetables during drying process can be used to predict the evaluation of colour with time (Devahastin & Niamnuy 2010; Sabarez 2014). The ability to predict the changes in the colour during drying can be useful in optimizing and controlling the parameters of drying process that gives the desired maximum colour attributes (Sabarez 2014).

Numerous studies have reported in order to evaluate the performance of microwave drying and quality of the dried product. While these studies have examined, it has been seen that some fruits and vegetables, such as potatoes (Bouraoui et al 1994), raisins (Kostaropoulos & Saravacos 1995), pears (Kiranoudis et al 1997), apples (Feng & Tang 1998), bananas (Maskan 2000), kiwifruits (Maskan 2001), carrots (Wen et al 2003) and asparagus (Nindo et al 2003; Duenãs et al 2008) had dried and analyzed and the some characteristics of final products had determined (Karam et al 2016). While there are lots of studies on the change kinetics of fruits and vegetables, only four kinetic studies related to colour change during microwave drying are found in the literature. These studies are related to the drying of bamboo shoot slices (Bal et al 2011), okra (Dadali et al 2007a), basil (Demirhan & Özbek 2009) and spinach (Dadali et al 2007b) by microwave at different output powers. In the literature, no information on the colour degradation of brussels sprouts under different output power conditions during the microwave drying process is available.

The objective of this work is to study the kinetics of colour degradation on the inner and outer surface of brussels sprouts during the microwave drying processes whose theoretical output power is at 460, 600, and 700 W, and to calculate the activation energies for colour change kinetic parameters using the exponential expression based on Arrhenius's equation. Brussels sprouts are one of the popular consumed vegetables due to their rich nutritional content. But the consumption of brussels sprouts is limited to winter months. In this study, optimization of the microwave process conditions to be based on the stability of the color parameters is performed in order to enable the consumption of brussels cabbages every month of the year. This study is important in terms of good understanding of the colour changes during microwave drying. Moreover, this study can be helpful for engineering design and optimization of the microwave drying systems, and obtaining the final products that has optimum colour attributes.

2. Material and Methods

2.1. Material

Fresh brussels sprouts were purchased from a local supplier in Izmir, Turkey and were stored at a temperature of 4±1 ºC until the experiments were carried out. Prior to drying experiments, brussels sprouts divided perpendicular to the fruit axis into approximately equally-sized two part by knife. To determine the initial moisture content, 5 g of samples were dried in an oven (Dedeoğlu, Turkey) at 105 ºC until the weight did not change any more (Miglio et al 2008). The initial moisture content of brussels sprouts was calculated as 6.71±0.34 (g water g^{-1} dry matter).

2.2. Method

2.2.1. Drying equipment and drying procedure

In the microwave drying experiments, a programmable microwave oven (Arçelik, MD 674, Turkey) with a maximum output power of 700 W was used. The dimensions of microwave cavity were 452 mm×312 mm×262 mm. The technical properties of microwave oven were ~230 V, 50 Hz, and 2650 W, a frequency of 2450 MHz (a wavelength of 12.24

cm). The microwave oven was run by a control terminal that controlled both microwave power level and emission time. Drying experiments were applied with 460, 600 and 700 W microwave output power levels to determine the effects of microwave output power on colour change of brussels sprouts. Samples (38±0.5 g) were placed at the center of a rotating glass plate in the microwave oven. Moisture loss of the samples was recorded every 0.75 min until no discernible weight change was observed. Three replications of each experiment were performed, and the data given were as an average of these results. In the experiments, the reproducibility was found in the range of ± 5%. The microwave output power was applied until the final moisture content of samples was equal to 0.03 (g water g^{-1} dry matter) as an average of the results obtained.

2.2.2. Colour measurements

The colour of the inner and outer surface of brussels sprouts was measured periodically during the microwave drying processes by a reflectance Minolta colourimeter (CR-400 Model Colourimeter, Konica Minolta Sensing, Inc., Osaka, Japan). Five measurements were taken at random locations by putting the head of colourimeter directly above the sample. L*, a* and b* values were determined at the result of the measurements. The chroma (C*) (Equation 1) and hue (h*) (Equation 2) values were estimated by the a* and b* values. Moreover, the total colour change (ΔE) (Equation 3) and browning index (BI) (Equation 4) were calculated from the values of L*, a*, b*.

$$C^* = \sqrt{\left((a^*)^2 + (b^*)^2\right)} \quad (1)$$

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (2)$$

$$\Delta E = \sqrt{\left((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right)} \quad (3)$$

$$\Delta L^* = L_0^* - L^*$$
$$\Delta a^* = a_0^* - a^*$$
$$\Delta b^* = b_0^* - b^*$$

$$BI = \frac{[100(x-0.31)]}{0.17} \qquad x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \quad (4)$$

Where; L_0*, a_0*, b_0* were the colour values of brussels sprouts at the beginning of drying; *L**, *a**, *b** were colour values of brussels sprouts at the pre-specified time.

The L* value expresses lightness (from 0 to 100), the value of a* defines colour of green (-a*) to red (a*), and the value of b* also represents colour of blue (-b*) to yellow (b*) (Mirzabeigi Kesbi et al 2016). The one of the other parameters derived from the values of L,* a*, and b* scale is C* which shows colour saturation and is proportional to its intensity. The h* is widely used to specify colour in food products, especially meats, fruits and green vegetables. The angles of 0º or 360º point out red hue as angles of 90º, 180º, and 270º show yellow, green, and blue hues, respectively. ΔE is utilized in evaluation of food quality during thermal processing (Ahmed & Shivhare 2001). Browning index (BI) shows the purity of brown colour, which is an important colour parameter for drying processes where enzymatic and non-enzymatic browning occur (Barreiro et al 1997; Maskan 2001; Bal et al 2011).

2.2.3. Kinetic considerations

In order to describe how the colour change of foodstuffs as a function of drying time, the general equation that expresses the reaction rate is represented by (Equation 5);

$$\frac{dC}{dt} = -k(C)^n \quad (5)$$

Where; *k* represents the kinetic rate constant, *C* is the rate of change in the quality factor at time *t*, and *n* is the order of reaction. The zero-order and first-order kinetic models that obtained by integration Equation (5) are given as Equation (6) and (7), respectively. In literature, it seems that both of these kinetic models were used (Maskan 2001; Dadali et al 2007a; Dadali et al 2007b; Demirhan & Özbek 2009; Bal et al 2011) to study the colour change of foods during microwave drying process.

$$C_t - C_0 = \pm k.t \quad (6)$$

$$\frac{C_t}{C_0} = exp(\pm k \cdot t) \quad (7)$$

Where; C_0, indicates the initial value of colour parameters (L*, a*, b*, C*, h*, ΔE and BI) at zero time and C_t is the value at pre-defined time t, *k,* represents the reaction rate (min^{-1}) in the kinetic model. In the equations, the sign of "±" shows formation and degradation of any quality parameter (Maskan et al 2002; Prachayawarakorn et al 2004; Bal et al 2011).

The kinetic parameters (*k* and C_0) for each colour parameters related with colour change of the inner and outer surface of brussels sprouts were determined by fitting the experimental data to both of Equations (6) and (7) using least square method. The reaction order of all colour parameters, the best fit and its kinetic reaction rate was determined for each process.

The activation energy required for colour change of brussels sprouts depending on the influence of microwave output power was calculated to use the best fit kinetic reaction rates and least square method by the exponential expression based on Arrhenius's equation (Equation 8) (Dadali et al 2007a; Dadali 2007b; Dadali et al 2007c; Demirhan & Özbek 2009):

$$k = k_0 \exp\left(\frac{-E_a \cdot m}{P}\right) \quad (8)$$

Where; E_a is the activation energy (minimum energy needed for colour change during microwave drying process) (W g^{-1}); *m* is the initial weight of fresh sample before drying (g); *P* is microwave output power (W), *k* is the kinetic reaction rate of the quality parameters (min^{-1}) and k_0 is the pre-exponential constant (min^{-1}).

2.2.4. Statistical analysis

The values of kinetic parameters (C_0, k, k_0 and E_a) were calculated by fitting the model to the experimental data utilizing the nonlinear least squares procedure (Microsoft Excel 2010 and Solver Add-In package of Excel). The coefficient of determination (R^2), chi-square (χ^2) (Equation 9), the residual sum of squares (RSS) (Equation 10) and root mean square error (RSME) (Equation 11) were used as main criterias to decide the best fit of the used mathematical model to the experimental data. The higher values of R^2 and the lower values of RMSE and $\chi2$, especially, pointed out a better model in terms of fitting (Erbay & Icier 2010; Balbay & Şahin 2012; Içier et al 2014).

$$\chi^2 = \frac{\sum_{i=1}^{N} (C_{\exp,i} - C_{pre,i})^2}{N - P} \quad (9)$$

$$\text{RSS} = \sum_{i=1}^{N} (C_{\exp,i} - C_{pre,i})^2 \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (C_{\exp,i} - C_{pre,i})^2}{N}} \quad (11)$$

Where; $C_{exp,i}$ is the experimental value of the i^{th} analysis; $C_{pre,i}$ is the predicted value of i^{th} analysis, *N* is the total number of data experimentally determined and *P* is the constants' number in a particular kinetic model.

3. Results and Discussion

3.1. Colour changes in dried product

3.1.1. L, a*, b* and total colour change (ΔE)*

To determine the influence of microwave output power to colour change kinetics of the inner and outer surface of brussels sprouts, three microwave output powers that were as 460, 600, and 700 W, were used at drying process. The L*, a*, b* and total colour change (ΔE) values of the inner and outer surface of brussels sprouts dried at different microwave output power are shown in Figures 1a-d.

The change of L* values is presented in Figure 1a. According to microwave output powers used, the values of L* on the outer surface of the brussels

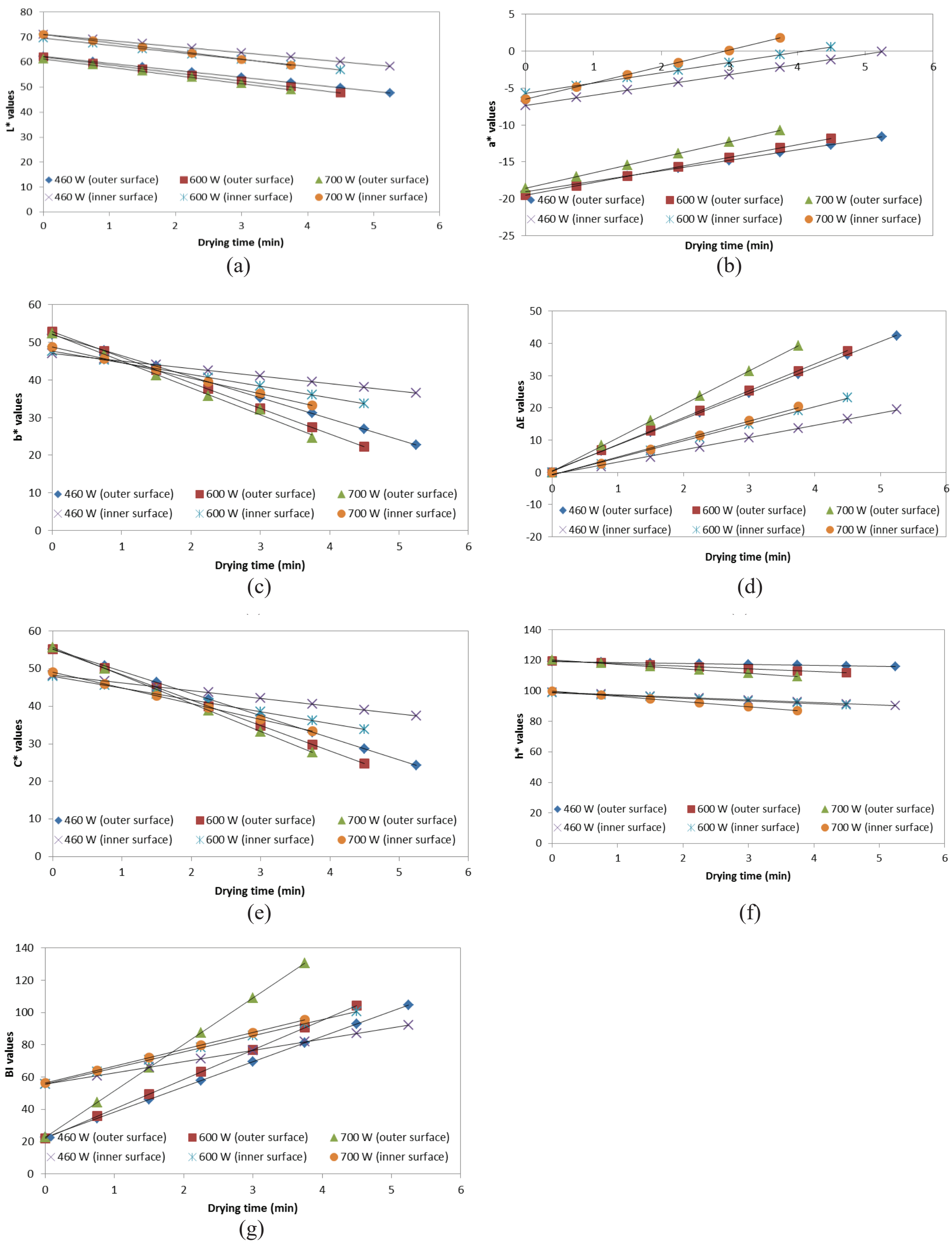

Figure 1- Kinetics of change of the (a), L* values; (b), a* value; (c), b* value; (d), ΔE; (e), C*; (f), h*, and (g) BI as a function of drying time at different microwave output powers comparing experimental curve with predicted model (-)

sprouts changed between 47.70 and 48.90 while the L* values on the inner surface of the brussels sprouts varied between 56.90 and 58.66. It is observed from Figure 1a that the L* values decrease simultaneously with the increase in drying time at all microwave power outputs. The decrease in L* values observed by the using of different microwave output powers between 460-700 W is an indication of the browning on both the inner surface and the outer surface of the brussels sprouts.

The value of a* is a redness/greenness scale. A sharp increase in negative direction was observed in the values of a* (Figure 1b) during microwave drying. The initial colour of both the inner surface and the outer surface of samples showed negative a* values, indicating greenness. At the end of the microwave drying, the inner surface colours of the samples dried at 600 W and 700 W had the positive a* values as 0.58 and 1.79, respectively. As a result of these, it can be said that brussels sprouts samples partially lost their greenness and the colour of samples, especially the inner surface, became redder when dried by microwave.

The value of b* is also a yellowness/blueness scale. Undergoing microwave drying process, the b* values on the outer surface of samples decreased sharply while the b* values of the inner surface decreased slowly. As shown in Figure 1b, the final values of b* changed from 22.31 to 24.68 on the outer surface of samples and from 33.32 to 36.55 in the inner surface of samples depending on the microwave output powers. It can be stated that during the microwave drying process the yellowness reduced in the sample, but this decrease was more pronounced on the outer surface of the samples.

After microwave drying, the lightness and yellowness was decreased and the redness was increased on both the inner surface and the outer surface of the brussels sprouts. On the inner surface of samples, light green-brown colour is more dominant due to a decrease slowly of yellowness and more increasing of redness. The dark green-brown colour on the outer surface of samples is seemed owing to sharp decrease of lightness and yellowness. The samples became redder as they lost their greenness and yellowness when dried. This may be owing to decomposition of chlorophyll and carotenoid pigments (Kostaropoulos & Saravacos 1995; Lee & Coates 1999; Weemaes et al 1999; Maskan 2001) nonenzymatic Maillard browning and formation of brown pigments (Rhim et al 1989; López et al 1997; Maskan 2000; Maskan 2001). Similar trends about changing of the lightness, redness/greenness and yellowness/blueness on colour during microwave drying at different output powers were also reported by Maskan (2001), Dadali et al (2007a), Dadali et al (2007b), Demirhan & Özbek (2009), Bal et al (2011).

As a whole, the total colour change (ΔE) on the outer surface of brussels sprouts increased significantly during microwave drying depending on microwave output power used and ranged from 37.61 to 42.39 (Figure 1d). The ΔE values on the inner surface of brussels sprouts also varied between 19.60 to 23.20 by changing of microwave output power applied (Figure 1d). From these results, it can be understood that the final colour and colour change of brussels sprouts have depended on the output power used in the microwave drying process. The microwave output power chosen is very important for determining the final product's colour that effects the acceptation of product by the consumer. The obtained results about the change of ΔE values depending on the microwave power applied was determined to be in agreement with earlier reported literature by Dadali et al (2007a), Dadali et al (2007b), Demirhan & Özbek (2009), Bal et al (2011).

3.1.2. Chroma (C), hue angle (h*), and browning index (BI)*

It is seen that C* values of both the inner and the outer surface of brussels sprouts decreased slightly during the microwave drying process and closely followed the b* values (Figure 1c and Figure 1e). This indicates that yellow colour is more stable in inner surface than outer surface of brussels sprouts due to the fact that the C* value shows the degree of colour's saturation and is commensurate with the strength of the colour (Maskan 2001). The final C* values changed slightly (24.23-27.68 in the inner surface of brussels sprouts and 33.34-37.48 in the outer surface of brussels sprouts) according to the microwave output powers applied. The similar observations have been reported in several studies published in the literature by Maskan (2001), Dadali et al (2007a), Bal et al (2011).

The value of h* also slightly decreased from 119.79 to 109.41-116.03 in the outer surface of brussels sprouts and from 99.30 to 86.95 (at 700 W)-90.71 in the inner surface of brussels sprouts during microwave drying (Figure 1f). This explains that the colour of brussels sprouts, except the inner surface colour of product dried with 700 W, did not lose greenness exactly but greenness decreased. (90 ºC < h* < 180 ºC). The inner surface colour of brussels sprouts dried with 700 W started to turn orange-red (h* < 90 ºC). It is also observed that the values of h* were influenced by the microwave output power used. In the literature, several authors have reported similar observations about the change of h* value depending on the microwave output power (Dadali et al 2007a; Dadali et al 2007b; Demirhan & Özbek 2009; Bal et al 2011).

The BI values of outer surface of dried brussels sprouts varied between 104.34 and 130.51 while the BI values of inner surface of dried brussels sprouts changed between 92.38 and 100.74 (Figure 1g). The BI values increased during microwave drying process and varied depending upon microwave output powers applied. The results supporting this phenomenon are also found in different studies (Maskan 2001; Dadali et al 2007a; Dadali et al 2007b; Demirhan & Özbek 2009; Bal et al 2011).

3.2. Kinetic considerations of colour parameters

Experimental data related with changes of all colour parameters in the outer and inner surface of brussels sprouts were fitted to a zero-, and first-order kinetics model by using nonlinear least squares procedure. The values estimated from the fittings and statistical parameters are given in Tables 1-4. The kinetic constants obtained from different models for the colour degradation were seen to have different values owing to microwave output power in the same surface. For example, in the using 700 W as a microwave output power, the kinetic reaction rates for ΔE value of inner surface of brussels sprouts calculated from zero- and first-order kinetics models were 5.8878 min^{-1} and 0.4871 min^{-1}, respectively (Table 1). Similar trends were also observed in the other colour parameters of brussels sprouts for processes in which different microwave output powers are used. The kinetic reaction rates (*k*) of zero-order model kinetics were higher in whole cases than those of first-order model. These results are in agreement with the findings of Maskan (2001) and Bal et al (2011).

It was observed that the zero-order kinetic model was an appropriate representation for defining the changes in L*, a*, b*, ΔE, C*, h* and BI values with higher R^2 and lower RMSE and $\chi 2$ values. The kinetic reaction rates in both outer and inner surface colour for the values of all colour parameters increased while the microwave output power increased from 460 to 700 W (Table 1). As observed in the studies of Dadali et al (2007a), Dadali et al (2007b), Demirhan & Özbek (2009) and Bal et al (2011), these findings means that the degradation rate of colour in the both of two surfaces with the increasing microwave output power, was faster due to high energy transferred into the food material. It is guessed that the products are exposed to high temperature with the increasing power levels undergoing microwave drying (Chua & Chou 2005; Alibas 2007). High temperature could cause the replacement of magnesium in the chlorophyll with hydrogen, thereby converting chlorophylls to pheophytins exhibits a grey–brown colour (Rudra et al 2008; Therdthai & Zhou 2009). For this reason, the product colour is adversely affected.

3.3. Estimation of activation energy

To determine the effect of microwave output powers on the outer and inner surface's colour of brussels sprouts, the activation energies that are energies

Table 1- The estimated kinetic parameters and the statistical values of zero-order and first-order models for the values of L*, a*, b* and ΔE on the outer surface of brussels sprouts at the different microwave output powers applied

Kinetic model types	*Power (W)*	*Quality parameters*	*Kinetic parameters*		*Statistical parameters*			
			k (min^{-1})	*C_0*	*R^2*	*RSS*	*RMSE*	*χ^2*
Zero order	460	L*	-2.7945	62.3714	0.9999	9.0546E-07	3.3643E-04	1.5091E-07
		a*	1.4192	-19.0412	0.9998	1.0926E-06	3.6957E-04	1.8211E-07
		b*	-5.5742	52.0666	0.9999	6.8404E-07	2.9241E-04	1.1401E-07
		ΔE	7.9345	0.7380	0.9999	2.3193E-08	5.3843E-05	3.8654E-09
	600	L*	-3.1741	62.0165	0.9998	1.2095E-06	4.1568E-04	2.4190E-07
		a*	1.7081	-19.5193	0.9999	6.3035E-07	3.0008E-04	1.2607E-07
		b*	-6.7821	52.8276	0.9999	1.0629E-06	3.8967E-04	2.1258E-07
		ΔE	8.2036	0.6911	0.9999	6.8750E-08	9.9103E-05	1.3750E-08
	700	L*	-3.3228	61.3598	0.9999	3.3972E-07	2.3795E-04	8.4931E-08
		a*	2.0918	-18.5960	0.9999	1.1995E-09	1.4139E-05	2.9987E-10
		b*	-7.1393	52.2190	0.9995	2.8190E+00	6.8545E-01	7.0476E-01
		ΔE	10.2525	0.7344	0.9997	6.7821E-06	1.0632E-03	1.6955E-06
First order	460	L*	-0.0517	62.8585	0.9985	2.7273E-01	1.8464E-01	4.5456E-02
		a*	-0.0957	-19.4981	0.9949	n.c	n.c	n.c
		b*	-0.1562	54.9809	0.9863	5.1137E+00	7.9951E-01	8.5228E-01
		ΔE	0.3095	8.7987	0.7610	1.1393E+03	1.1934E+01	1.8988E+02
	600	L*	-0.0591	62.5104	0.9986	2.2716E-01	1.8014E-01	4.5432E-02
		a*	-0.1132	-20.0299	0.9946	n.c	n.c	n.c
		b*	-0.1917	56.2628	0.9847	1.2165E+01	1.3183E+00	2.4330E+00
		ΔE	0.3551	7.9668	0.7676	8.6559E+02	1.1120E+01	1.7312E+02
	700	L*	-0.0616	61.7663	0.9989	1.3226E-01	1.4847E-01	3.3064E-02
		a*	-0.1501	-19.2265	0.9933	n.c	n.c	n.c
		b*	-0.1944	54.8183	0.9751	9.6590E+00	1.2688E+00	2.4148E+00
		ΔE	0.4172	8.5117	0.7754	9.3410E+02	1.2477E+01	2.3352E+02

n.c, not calculated

required for the change of colour parameters was calculated with the exponential expression based on Arrhenius's equation (Table 5). The reaction kinetic constants for all colour parameters calculated from a zero-order kinetic model fitted to Equation (8). Arrhenius model described well the effect of microwave output power changes on colour of brussels sprouts due to high R^2 values, low RMSE and $\chi 2$ values for each colour parameters. The values of activation energy changed within the range of 6.1579 (L* value) - 55.6175 (h* value) in the outer surface of the brussels sprouts while they were between 11.3315 (L* value) and 28.1590 (h* value) in the inner surface of the brussels sprouts (Table

Table 2- The estimated kinetic parameters and the statistical values of zero-order and first-order models for the values of L*, a*, b* and ΔE on the inner surface of brussels sprouts at the different microwave output powers applied

Kinetic model types	*Power (W)*	*Quality parameters*	*Kinetic parameters*		*Statistical parameters*			
			k (min^{-1})	*C_0*	*R^2*	*RSS*	*RMSE*	*χ^2*
Zero order	460	L*	-2.4112	71.0729	0.9997	1.2204E-07	1.2351E-04	2.0341E-08
		a*	1.3760	-7.3221	0.9997	2.8515E-07	1.8879E-04	4.7524E-08
		b*	-2.0047	47.0704	0.9999	2.2335E-06	5.2838E-04	3.7225E-07
		ΔE	3.9575	-1.1805	0.9999	8.6879E-10	1.0421E-05	1.4480E-10
	600	L*	-2.8118	69.5510	0.9998	5.5312E-09	2.8110E-05	1.1062E-09
		a*	1.3985	-5.7093	0.9998	6.2046E-08	9.4147E-05	1.2409E-08
		b*	-3.0850	47.6298	0.9999	7.0501E-08	1.0036E-04	1.4100E-08
		ΔE	5.5103	-1.5983	0.9999	1.6973E-08	4.9242E-05	3.3947E-09
	700	L*	-3.3320	71.1560	0.9999	9.5735E-12	1.2632E-06	2.3934E-12
		a*	2.2160	-6.5220	0.9999	8.5368E-12	1.1928E-06	2.1342E-12
		b*	-4.1317	48.8157	0.9999	8.0631E-08	1.1592E-04	2.0158E-08
		ΔE	5.8878	-1.7036	0.9999	2.8288E-08	6.8663E-05	7.0720E-09
First order	460	L*	-0.0377	71.3799	0.9992	1.3383E-01	1.2934E-01	2.2305E-02
		a*	-0.3978	-9.0726	0.9987	n.c	n.c	n.c
		b*	-0.0488	47.4002	0.9987	1.2486E-01	1.2493E-01	2.0809E-02
		ΔE	0.3493	3.3248	0.8940	5.0645E+01	2.5161E+00	8.4409E+00
	600	L*	-0.0452	69.8855	0.9992	1.4232E-01	1.4259E-01	2.8464E-02
		a*	-0.5964	-7.8302	0.9974	n.c	n.c	n.c
		b*	-0.0779	48.2636	0.9975	3.7343E-01	2.3097E-01	7.4685E-02
		ΔE	0.4061	3.9336	0.9067	5.4795E+01	2.7978E+00	1.0959E+01
	700	L*	-0.0523	71.5017	0.9992	1.0635E-01	1.3314E-01	2.6588E-02
		a*	-1.0291	-11.1873	0.9967	n.c	n.c	n.c
		b*	-0.1044	49.6770	0.9969	5.5339E-01	3.0370E-01	1.3835E-01
		ΔE	0.4871	3.4281	0.9211	3.1183E+01	2.2797E+00	7.7957E+00

n.c, not calculated

5). When Table 5 is examined, it is seen that the activation energies of all colour parameters, except h* and BI value, for the outer surface of brussels sprouts were lower than for the inner surface of brussels sprouts. This may indicate that there is more colour change on the outer surface of brussels sprouts as microwave output power increased. It also means that the outer surface of the brussels sprouts is sensitive to the color change and an increase of microwave output power. The results of activation energy and *k* values related with the colour change in the outer and inner surface of the brussels sprouts at different microwave output power are parallel to each other. The results obtained in this study related with activation energy values are generally lower than the results determined in the studies of spinach (Dadali et al 2007b) and basil (Demirhan & Özbek 2009) and are similar to the results obtained in the study of okra (Dadali et al 2007a), except the values of h* and BI. The reasons of these differences are

Table 3- The estimated kinetic parameters and the statistical values of zero-order and first-order models for the values of C*, h* and BI on the outer surface of brussels sprouts at the different microwave output powers applied

Kinetic model types	*Power (W)*	*Quality parameters*	*Kinetic parameters*		*Statistical parameters*			
			k (min^{-1})	C_0	R^2	*RSS*	*RMSE*	χ^2
Zero order	460	C*	-5.9049	55.2322	0.9999	3.2036E-07	2.0011E-04	5.3394E-08
		h*	-0.6111	119.2349	0.9998	1.8950E-04	4.8670E-03	3.1584E-05
		BI	15.5916	22.7588	0.9998	1.6660E-05	1.4431E-03	2.7767E-06
	600	C*	-6.7777	55.2072	0.9999	3.5156E-07	2.2411E-04	7.0313E-08
		h*	-1.7565	119.7728	0.9998	5.3468E-05	2.7637E-03	1.0694E-05
		BI	18.2969	22.0052	0.9999	2.7206E-07	1.9714E-04	5.4411E-08
	700	C*	-7.4608	55.6629	0.9999	1.3539E-07	1.5022E-04	3.3848E-08
		h*	-2.9214	120.3698	0.9999	4.0470E-07	2.5971E-04	1.0117E-07
		BI	28.7383	22.7393	0.9998	6.2784E-06	1.0229E-03	1.5696E-06
First order	460	C*	-0.1559	58.3132	0.9863	1.4437E-01	1.3434E-01	2.4062E-02
		h*	-0.0052	119.2454	0.9998	3.9933E-02	7.0651E-02	6.6554E-03
		BI	0.2198	34.1552	0.9546	3.3820E+02	6.5019E+00	5.6367E+01
	600	C*	-0.1796	58.4231	0.9867	4.2090E-01	2.4521E-01	8.4180E-02
		h*	-0.0153	119.8432	0.9998	2.2743E-02	5.7000E-02	4.5486E-03
		BI	0.2565	33.9370	0.9519	3.3699E+02	6.9384E+00	6.7397E+01
	700	C*	-0.1908	58.5346	0.9897	5.6655E-01	3.0729E-01	1.4164E-01
		h*	-0.0257	120.5177	0.9998	8.7610E-02	1.2084E-01	2.1902E-02
		BI	0.3230	39.9671	0.9392	7.2100E+02	1.0962E+01	1.8025E+02

Table 4- The estimated kinetic parameters and the statistical values of zero-order and first-order models for the values of C*, h* and BI on the inner surface of brussels sprouts at the different microwave output powers applied

Kinetic model types	*Power (W)*	*Quality parameters*	*Kinetic parameters*		*Statistical parameters*			
			k (min^{-1})	C_0	R^2	*RSS*	*RMSE*	χ^2
Zero order	460	C*	-2.0673	48.3318	0.9999	1.7268E-07	1.4692E-04	2.8780E-08
		h*	-1.7287	99.3145	0.9999	1.1434E-06	3.7806E-04	1.9057E-07
		BI	7.0180	55.5369	0.9999	2.1399E-08	5.1719E-05	3.5664E-09
	600	C*	-3.1585	48.0465	0.9999	1.0822E-06	3.9320E-04	2.1645E-07
		h*	-1.7982	98.8033	0.9999	8.8303E-07	3.5517E-04	1.7661E-07
		BI	10.0219	55.6442	0.9998	3.9774E-07	2.3837E-04	7.9548E-08
	700	C*	-4.2033	49.1011	0.9999	1.0053E-07	1.2944E-04	2.5133E-08
		h*	-3.4189	99.7759	0.9999	2.1864E-07	1.9089E-04	5.4659E-08
		BI	10.4175	56.3496	0.9998	4.2392E-06	8.4056E-04	1.0598E-06
First order	460	C*	-0.0490	48.6734	0.9987	1.4437E-01	1.3434E-01	2.4062E-02
		h*	-0.0184	99.4215	0.9998	5.3796E-02	8.2003E-02	8.9659E-03
		BI	0.0913	57.6944	0.9947	6.3104E+00	8.8815E-01	1.0517E+00
	600	C*	-0.0793	48.7071	0.9974	4.2090E-01	2.4521E-01	8.4180E-02
		h*	-0.0191	98.8937	0.9998	7.8815E-03	3.3555E-02	1.5763E-03
		BI	0.1218	58.8101	0.9927	1.2119E+01	1.3158E+00	2.4239E+00
	700	C*	-0.1058	49.9898	0.9968	5.6655E-01	3.0729E-01	1.4164E-01
		h*	-0.0371	100.0271	0.9996	7.7133E-02	1.1338E-01	1.9283E-02
		BI	0.1302	58.9637	0.9941	6.5248E+00	1.0428E+00	1.6312E+00

Table 5- The activation energies determined for the color degradation on inner and outer surface of brussels sprouts for quality parameters

	Quality parameters	*Kinetic parameters*		*Statistical parameters*			
		k_0 (min^{-1})	*Ea ($W\ g^{-1}$)*	*R^2*	*RSS*	*RMSE*	*χ^2*
Outer surface	L*	4.6593	6.1579	0.9995	6.6742E-05	4.7167E-03	6.6742E-05
	a*	4.2889	13.7157	0.9977	5.1017E-04	1.3041E-02	5.1017E-04
	b*	11.6468	8.8213	0.9991	1.2327E-03	2.0270E-02	1.2327E-03
	ΔE	15.5721	8.6364	0.9991	2.0750E-03	2.6300E-02	2.0750E-03
	C*	11.5411	8.1849	0.9992	9.7668E-04	1.8043E-02	9.7668E-04
	h*	59.7515	55.6175	0.9590	1.0982E-01	1.9133E-01	1.0982E-01
	BI	95.1603	23.3136	0.9931	5.8934E-01	4.4322E-01	5.8934E-01
Inner surface	L*	6.0210	11.3315	0.9984	6.4261E-04	1.4636E-02	6.4261E-04
	a*	5.2813	17.6528	0.9961	1.2603E-03	2.0497E-02	1.2603E-03
	b*	16.7957	26.1339	0.9913	1.9989E-02	8.1627E-02	1.9989E-02
	ΔE	12.8590	13.9977	0.9976	4.7924E-03	3.9968E-02	4.7924E-03
	C*	16.6122	25.6086	0.9916	1.9321E-02	8.0251E-02	1.9321E-02
	h*	14.2967	28.1590	0.9898	1.4953E-02	7.0600E-02	1.4953E-02
	BI	22.8652	13.9101	0.9976	1.4950E-02	7.0592E-02	1.4950E-02

that the texture, colour and chemical composition of analyzed food samples are different to each other (Dadali et al 2007b).

4. Conclusions

This study aims to explain the colour change kinetics of brussels sprouts in the both of two surfaces using colour parameters such as L*, a*, b* during microwave drying at 460, 600 and 700 W microwave output powers. It was determined that all colour parameters relating to the outer and inner surface of brussels sprouts influenced by microwave drying and microwave output power applied. All colour parameters, except ΔE and BI values, on both two surfaces of the brussels sprouts decreased while the values of ΔE and BI increased irrespective of the microwave output power used. While the decrease of brightness (L* values) accepts as an indicator of browning in the drying process, the loss of b* value explains that the yellowness of samples decreased due to decomposition of several pigments such as chlorophylls and carotenoids, formation of nonenzymatic Maillard browning, and brown pigments. The decrease in C* values shows the stability of decreasing yellowness during microwave drying. With the decreasing h* values, greenness starts to disappear and even, greenness in the inner surface of product that were dried at 700 W, turns to orange-red colour. The BI values proved that microwave drying process produced more brown colour and the increase of a* values supported this result. When the colour parameters are examined together, it is observed that the change in the colour on both the inner surface and outer surface of brussels sprouts increases as the microwave output power increases. Zero-order and first-order kinetic models were utilized to explain the colour change kinetics of the inner surface and outer surface in the brussels sprouts and it was observed that the changes of all colour parameters related to inner and outer surface of brussels sprouts during microwave drying were fitted to zero-order reaction kinetics. The obtained values of R^2, $\chi 2$ and RSME supported that the colour changes during microwave drying process took place at the zero order reaction kinetics. By examining the reaction kinetic rates of all colour parameters, the fastest colour change was observed at 700 W microwave output power while the slightest colour change was determined at 460 W microwave output powers. Although some darkening occurred, microwave drying at 460 W maintained a good colour close to that of the fresh brussels sprouts. The Arrhenius model described well the microwave output powers dependence of the kinetic parameters for all the colour parameters, which was used for the calculation of activation energy for colour change kinetic parameters in both the inner surface and outer surface of brussels sprouts. According to the results of activation energies related with colour parameters, the colour change on the outer surface of brussels sprouts has been found to be more sensitive to the increase in microwave output power. The colour criteria assessments shows that drying of brussels sprouts at 460 W occured the lowest change rates on the brightness, greenness and yellowness parameters. It was found that 460 W among the microwave output powers used is the optimum microwave power level in the microwave drying of brussels sprouts with respect to colour criteria. When the microwave output powers used are compared, the use of low output powers such as a 460 W in the microwave drying process allows the production of well quality dried brussels sprouts in terms of colour that is a very important criteria for product acceptability and consumer satisfaction.

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