

Color Change Kinetics of Green Bell Pepper Dried under Vacuum-Assisted Microwave System

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ABSTRACT

Experiments were conducted to study the color change kinetics of green bell pepper during vacuum-assisted microwave (VAM) drying at three levels of microwave power (100, 200, and 300 W) and vacuum (200, 400, and 600 mmHg). The color change, measured by a tristimulus colorimeter, in VAM dried sample was found better with least browning at lower microwave power and higher vacuum level combinations. L^* , ΔE^* and H^* were fitted well to zero-order kinetic model, while a^* , b^* , C^* and BI^* followed a first-order kinetic model. All these color parameters were fitted to a quadratic equation as a function of microwave and vacuum level ratio. Both ΔE^* and BI^* increased with the increase in microwave power and decrease in vacuum level, whereas other color parameters decreased under the same condition of the process variables. The rate constant was assumed to have Arrhenius-type dependence on power density. The activation energy was calculated for color change kinetic parameters by using an exponential expression based on Arrhenius equation. The activation energy values were calculated and found within the range of 3.20-13.58 Wg⁻¹, except for b^* ($E_a = 26.708$ Wg⁻¹) and C^* value ($E_a = 20.4105$ Wg⁻¹). The b^* and C^* values obtained were relatively higher and thus were more sensitive measures of color change, which must be taken care of during postharvest drying of green bell pepper for getting a quality product.

Keywords: Activation energy, Arrhenius equation, Color parameters, Zero-order kinetic model.

INTRODUCTION

Green bell pepper (*Capsicum annum* L.) belongs to genus *Capsicum* from nightshade family Solanaceae, which are grown mostly in tropical or temperate regions (Kumar and Shrivastava, 2017a). They are rich source of vitamin A and C (Lee *et al.*, 1995), and are used in soups, salads, noodles and many different cuisines all over the world. Green bell pepper has always gained consumer interest due to its health enhancing vitamin and antioxidant contents (Penchaiya *et al.*, 2009).

Fresh harvested green bell pepper (GBP) has moisture content of 90-94% (wet basis), which makes it highly perishable. Drying can reduce physical, chemical, and biochemical deterioration of GBP, thus minimizing the post-harvest losses and permitting the availability of the product all-around the year. However, food materials may encounter high temperature during drying process, which can have detrimental effect on quality, nutritional value, and organoleptic properties. Color is an important aspect to assess the quality by visual recognition of surface properties and acceptability of the final dried product (Tijskens *et al.*, 2001; Dadali *et al.*, 2007b;

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Demirhan and Özbek, 2015). Green bell peppers are sensitive to temperature; therefore, they need proper drying process, which can retain their color, nutritional, and organoleptic properties.

Green bell pepper has been dried by different drying methods, for example. sun/solar drying, conventional tray drying, fluidized bed drying, heat pump drying, rotary drying, microwave drying, and freeze drying (Kaymak-Ertekin, 2002; Ade-Omowaye *et al.*, 2003; Tunde-Akintunde *et al.*, 2005; Pal *et al.*, 2008; Doymaz and İsmail, 2010; Arslan and Özcan, 2011; Khan *et al.*, 2014; Kumar and Shrivastava, 2017a). However, each drying method mentioned above has the limitation ranging from longer drying time, nutritional loss, case hardening, high energy requirement, and aroma and color deterioration (Scaman and Durance, 2005).

Vacuum-assisted microwave (VAM) drying can be an alternate method overcoming all above-mentioned drawbacks. This drying method is rapid, requiring minimum maintenance and can result in better quality dried product in terms of color, quality, and nutritional retention as compared to conventional dryer. Microwave energy heats the food from inside to outside and vacuum enhances the drying process by creating pressure gradient at relatively low boiling point of water and thus at low sample temperature (Kumar and Shrivastava, 2017a). Low temperature processing due to vacuum leads to better-dried product in terms of nutritional composition and color of the final product.

In food industries, visual color standards are usually used for subjective visual inspection. Tristimulus colorimeter is quick and simple instrumental method for measuring color characteristics of the food products (Clydesdale and Ahmed, 1978; Ahmed *et al.*, 2002; Dermesonlouoglou *et al.*, 2007; Nisha *et al.*, 2011; Pathare *et al.*, 2013). The three dimensions of the measured color, namely, L^* , a^* , and b^* and the derived parameter i.e. total color difference (ΔE^*), hue angle, chroma and

browning index are used to specify color value of the material (Ozdemir *et al.*, 2008). The color quality and its degradation rate, as influenced by the drying process, can be evaluated by final values of color parameters. Apart from that, the knowledge of kinetic model parameters, color change rate constant, and activation energy are also essential to predict and optimize the drying process (Lund, 1988; Dadali *et al.*, 2007b; Nisha *et al.*, 2011). The kinetics of color change in fruits and vegetables such as green bell pepper (Khan *et al.*, 2014), broccoli (Tijskens *et al.*, 2001), okra (Dadali *et al.*, 2007b), spinach (Dadali *et al.*, 2007a), mustard leaves (Ahmed *et al.*, 2002), basil (Demirhan and Özbek, 2009), yellow bell pepper (Swain *et al.*, 2014) during drying process have been evaluated by numerous researchers and it was found to follow either zero order or first order kinetic model. The studies on color change kinetics of vegetables dried through different methods have been carried out in the past, but the effect of vacuum and microwave on kinetic parameters of GBP dried by VAM drying could not be found in literature.

In this study, the objective was to observe the effect of vacuum and microwave on color change of GBP undergoing VAM drying. Kinetic models were fitted to color data and kinetic parameters were evaluated to study the influence of independent parameters i.e. microwave power and vacuum levels. A quadratic equation was developed to predict the relationship between microwave power to vacuum level ratio and all color parameters. Estimated kinetic parameters were related with the power density using Arrhenius-type equation and activation energy for color change kinetics was calculated.

MATERIALS AND METHODS

Fresh samples of GBP were procured from Agricultural Farm, IIT Kharagpur, India, and were kept at 4 °C and 80–90% relative humidity. For drying experiments, GBP were

cut with a stainless steel knife into approximate size of 40 mm×40 mm and thickness of 4±0.5 mm. Moisture content of fresh sample was determined by using standard method, taking five replications of 10 g sample in a vacuum oven at 70 °C for 24 h over a desiccant (magnesium sulfate) (AOAC, 2016). Initial moisture content was determined as 13.60 ± 0.5 g water·g dry matter⁻¹.

Drying Equipment and Procedure

The details of the drying equipment and drying procedures are explained elsewhere (Kumar and Shrivastava, 2017b). The VAM dryer (Figure 1) consisted of a microwave oven (Model: Samsung; 2.45 GHz, 0.8 kW), a voltage variac, a vacuum glass desiccator, a hose pipe, a condenser, and a pressure gauge. Hundred gram of fresh cut sample was dried under three levels of microwave power (100, 200, 300 W) and vacuum (200, 400, 600 mm Hg). The final moisture content of the samples achieved was 0.06 to 0.07 g water·g dry matter⁻¹.

Color Measurement

Change in color of GBP samples dried under VAM drying condition was measured by a tristimulus colorimeter (Chroma Meter CR-

400, Konica Minolta, Japan). Color parameters were measured in triplicates and mean values were taken for calculation of derived color parameters. The color scale used was L^* , a^* , and b^* of CIE color space. The coordinate L^* measures values between white (100) to black (0). The chromaticity coordinate a^* measures values between red (+127) to green (-128), while b^* measures between yellow (+127) to blue (-128). The total color difference (ΔE^*), chroma (C^*), hue angle (H^*) and browning index (BI^*) were estimated from L^* , a^* , and b^* values and then compared to those with the standard or control. The following equations were used to calculate all these interrelated parameters (Pathare *et al.*, 2013).

$$\Delta E^* = \sqrt{(L_o^* - L_t^*)^2 + (a_o^* - a_t^*)^2 + (b_o^* - b_t^*)^2} \quad (1)$$

Where, ΔE^* is the total color difference, L_o^* , a_o^* , b_o^* , are the initial color measurements of fresh GBP samples and L_t^* , a_t^* , b_t^* are the color measurement at a pre-specified time.

$$\text{Chroma}, C^* = \left[(a_t^*)^2 + (b_t^*)^2 \right]^{0.5} \quad (2)$$

$$\text{HueAngle}, H^* = 180^\circ + \arctg \left(\frac{b_t^*}{a_t^*} \right) \quad \text{For } a_t^* < 0; b_t^* > 0 \quad (3)$$

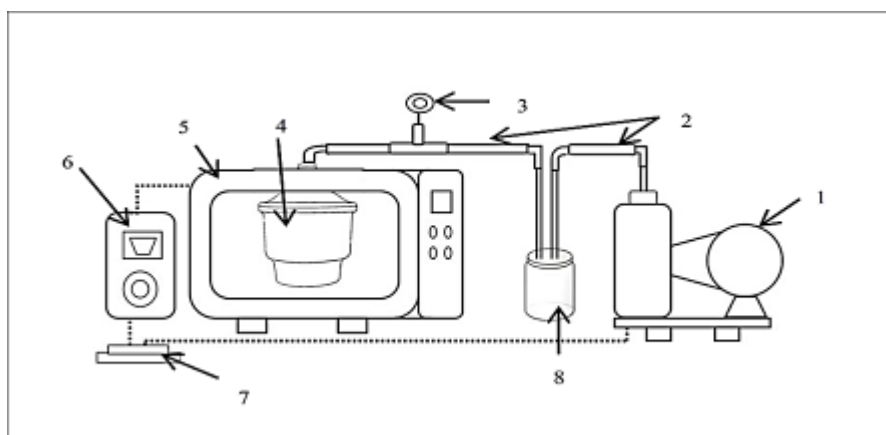


Figure 1. Schematic diagram of vacuum assisted microwave dryer (1) Vacuum pump; (2) Hose pipe; (3) Pressure gauge; (4) Glass vacuum desiccator; (5) Microwave oven; (6) Control panel; (7) Electrical board; (8) Condenser (Kumar and Shrivastava, 2017a).



$$\text{Browning Index, } BI^* = \frac{[100(f - 0.31)]}{0.17} \quad (4)$$

Where,

$$f = \frac{(a_t^* + 1.75L_t^*)}{(5.64L_t^* + a_t^* - 3.012b_t^*)} \quad (5)$$

In this color measurement, chroma (C^*) indicates color saturation and intensity. Hue (H^*) expresses the color tone and is extensively used to specify color in green vegetables, fruits and meat (Pathare *et al.*, 2013). Red hue is represented by an angle of 0° or 360° , while yellow, green and blue hue are represented by angles of 90° , 180° , and 270° , respectively. Browning index (BI^*) represents the purity of brown color and is an important parameter in food processing where enzymatic and non-enzymatic browning reactions take place (Lozano and Ibarz, 1997; Lijuan *et al.*, 2005; Gamli, 2011; Demirhan and Özbek, 2015). The instrument was initially calibrated with the standard white ceramic plate supplied with the colorimeter.

Kinetic Consideration and Activation Energy

The kinetic rate order of change in color parameter as a function of drying time was determined by using the following equation:

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

Where, C : measured value of target color parameter at time t , k : reaction rate constant, and n : reaction rate order. If color change during drying follows zero order kinetics and first-order kinetics, Eq. 6 can be rearranged as Eqs. 7 and 8, respectively (Maskan, 2001; Devi and Das, 2017):

$$C = C_o \pm kt; \quad \text{for } n = 0 \quad (7)$$

$$C = C_o \exp(\pm kt); \quad \text{for } n = 1 \quad (8)$$

Where, C_o is the color value at time $t = 0$ and C is the color value at a pre-specified time t in min, (+) and (−) indicate formation and degradation of any quality parameter,

respectively. Microwave, absorption is closely related to moisture content in materials. Therefore, the weight of samples is a very important parameter. Weight of the sample helps in evaluating power density, which further helps in activation energy for color change. Activation energy is the minimum energy needed for change in color during VAM drying. It was calculated by solving an exponential expression between kinetic rate constant and power density term (P/m), based on Arrhenius equation (Eq. 9) (Dadali *et al.*, 2007b; Demirhan and Özbek, 2015).

$$k = k_o \exp \left[\frac{-E_a}{\left(\frac{P}{m} \right)} \right] \quad (9)$$

Where, P is microwave power applied (W), and m is the weight of fresh GBP sample (g), E_a is the activation energy (Wg^{-1}), k_o is pre-exponential constant (min^{-1}), and k is kinetic rate constant of the color parameter (min^{-1}). The activation energy can be calculated from the slope of the plot of $\ln(k)$ versus $(1/(P/m))$.

A relationship between microwave power and vacuum level was evaluated, and its effect on all color parameters was analyzed by a quadratic model (Eq. 10).

$$Q = x + (y \times D) + (z \times D^2) \quad (10)$$

Where, Q is any color parameter (like L^* , a^* , b^* , ΔE^* , C^* , H^* , and BI^*) and x , y and z are the coefficients of the model calculated by non-linear regression iterative procedure; D is the ratio of microwave power to vacuum level applied (microwave power/vacuum level) to the samples in the VAM drying process.

Statistical Analysis

Origin Pro 8.5.0 (Origin Lab Corporation, USA) software was used to perform analysis of variance (ANOVA) and to find out the effects of different combinations of microwave power and vacuum level on the color parameters of VAM dried GBP samples. The least significant difference test

was applied for multiple comparisons at the 95% confidence level. The corresponding parameters of kinetics models (Eqs. 7- 9) were estimated by linear and non-linear regression iterative procedure. The best regression for each combination of microwave power and vacuum level experiments were selected based on the coefficient of determination (Eq.11) and reduced Chi-square (Eq.12). By definition,

$$R^2 = \frac{\sum_{i=1}^N (X_{p,i} - \bar{X}_{e,i})^2}{\sum_{i=1}^N (X_{e,i} - \bar{X}_{e,i})^2} \quad (11)$$

$$\chi^2 = \frac{\sum_{i=1}^N (X_{e,i} - X_{p,i})^2}{N - n} \quad (12)$$

Where, R^2 is the coefficient of determination, $X_{p,i}$ is the i^{th} predicted value; $X_{e,i}$ is the i^{th} experimental value; $\bar{X}_{e,i}$ is the i^{th} average experimental value; χ^2 is the reduced Chi-square, N is the number of data points and n is total number of constants.

RESULTS AND DISCUSSION

Color kinetics of GBP samples were observed by drying 100 g of samples at different combinations of microwave power (100, 200, 300 W) and vacuum level (200, 400, 600 mm Hg). Regression analysis of experimental data was performed using Eq. 6 to determine the order of change for color parameters. Maximum value of R^2 and minimum values of χ^2 (Table 1) were used as a criteria to select the best-fit equation (Eqs.7-8) to experimental data and the kinetic rate constant was determined for each color parameter (Bal *et al.*, 2011). In all cases, data fittings were considered significant at a probability level of 95%. The lightness (L^* value), greenness (negative a^* value) and yellowness (positive b^* value) of fresh GBP were observed as 36.32 ± 1.36 , -12.5 ± 0.88 , and 22.25 ± 1.01 , respectively. Results of changes in color values of L^* , a^* , and b^* obtained from the VAM drying of

GBP samples at the various combinations of microwave powers and vacuum levels are given in Figure 2.

Effect of Microwave Power on Color Kinetics of VAM Dried GBP

Figure 2 shows the effect of different combinations of microwave power and vacuum level on L^* , a^* , and b^* values of VAM dried GBP samples. The dried samples showed a significant difference ($p < 0.05$) in final values of L^* , a^* , and b^* as compared to the respective values of fresh GBP, at all microwave power and vacuum level combinations studied. As can be seen from Figure 2, at a fixed vacuum level of 400 mm Hg, the L^* value decreased from a value of 36.32 of the fresh sample to 32.25 and 28.71 when subjected to increasing microwave power level from 100 to 300 W, respectively. The change in the brightness of dried samples can be taken as an indicator of browning (Tijskens *et al.*, 2001; Demirhan and Özbek, 2009). This shows that luminance obtained at a particular vacuum level was better for samples dried at lower microwave power.

It is evident from Figure 2 that the greenness ($-a^*$) value of GBP varied from an initial value of -12.5 (fresh sample) to -11.89 and -9.23 at 100 W and 300 W, respectively. At a fixed vacuum level of 400 mm Hg, the a^* value of VAM dried samples showed negative value at all microwave power levels, indicating that the samples maintained their greenness. The b^* value decreased from an initial value of 22.25 to 21.77 and 19.75 at a microwave power of 100 and 300 W, respectively. Final values of L^* , a^* , and b^* indicate that the color of the dried GBP sample was dull in comparison with the fresh sample, but still maintained its greenness. A possible reason for this may be the decomposition of the green pigment viz. chlorophyll (Weemaes *et al.*, 1999) and formation of brown pigments (Maskan, 2001; Demirhan and Özbek, 2009) which can be concluded by the least change in brightness of VAM dried GBP samples.

**Table 1.** The estimated kinetic parameters and the statistical values of zero-order and first- order models.

Power (W)	Vacuum (mm Hg)	Color parameter	Zero-order model				First-order model			
			C_o	k (min ⁻¹)	χ^2	R ²	C_o	k (min ⁻¹)	χ^2	R ²
100	200	L_t^*	36.9023	0.0138	0.2326	0.9581	36.9463	0.00040	0.2962	0.9466
		a_t^*	-12.4910	0.0021	0.0020	0.9841	-12.4966	-0.00017	0.0017	0.9859
		b_t^*	22.3138	0.0010	0.0069	0.7952	22.3139	0.00004	0.0070	0.7978
		ΔE^*	-0.5689	0.0139	0.2178	0.9617	0.6139	0.00520	0.3509	0.9383
		C^*	25.5716	0.0019	0.0037	0.9622	25.5729	0.00007	0.0039	0.9640
		H^*	119.2452	0.0031	0.0250	0.9160	119.247	0.00002	0.0248	0.9151
		BI^*	54.9677	0.0460	0.0217	0.9579	55.2928	0.00071	0.6405	0.9736
	400	L_t^*	36.7538	0.0142	0.1383	0.9613	36.7881	0.00041	0.1605	0.9550
		a_t^*	-12.5014	0.0018	0.0001	0.9980	-12.5036	-0.00014	0.00009	0.9981
		b_t^*	22.3052	0.0015	0.0030	0.9280	22.3059	0.00006	0.0030	0.9287
		ΔE^*	-0.4288	0.0143	0.1366	0.9626	0.5495	0.00633	0.3667	0.8998
		C^*	25.5695	0.0022	0.0026	0.9684	25.5709	0.00008	0.0027	0.9691
		H^*	119.2719	0.0018	0.0024	0.9605	119.272	0.00001	0.0024	0.9603
		BI^*	55.7083	0.0398	0.0430	0.9628	55.8650	0.00063	0.7645	0.9727
	600	L_t^*	36.5147	0.0162	0.0268	0.9884	36.5425	0.00046	0.0319	0.9862
		a_t^*	-12.5510	0.0023	0.0016	0.9632	-12.5521	-0.00018	0.0017	0.9659
		b_t^*	22.3000	0.0018	0.0016	0.9461	22.3004	0.00008	0.0016	0.9476
		ΔE^*	-0.2034	0.0164	0.0279	0.9883	0.5542	0.00812	0.2246	0.9063
		C^*	25.5891	0.0027	0.0029	0.9547	25.5898	0.00011	0.0031	0.9564
		H^*	119.3748	0.0025	0.0016	0.9720	119.375	0.00002	0.0016	0.9717
		BI^*	56.3398	0.0442	0.2271	0.9868	56.4603	0.00071	0.1730	0.9899
	200	L_t^*	37.3267	0.0482	0.8025	0.8994	37.3566	0.00140	0.9779	0.8774
		a_t^*	-12.8567	0.0150	0.1575	0.7886	-12.8589	-0.00126	0.1777	0.8127
		b_t^*	22.2581	0.0042	0.0020	0.9653	22.2595	0.00019	0.0020	0.9660
		ΔE^*	-1.0575	0.0507	0.9137	0.9773	0.4192	0.01951	0.2003	0.8966
		C^*	25.6892	0.0107	0.0262	0.9268	25.6927	0.00043	0.0281	0.9319
		H^*	120.0704	0.0263	0.7638	0.7270	120.069	0.00022	0.7772	0.7222
		BI^*	51.7008	0.1914	0.3920	0.7709	51.7932	0.00307	0.3014	0.8301
	400	L_t^*	36.9705	0.0365	0.3048	0.9217	36.9902	0.00105	0.3499	0.9102
		a_t^*	-12.6165	0.0144	0.0147	0.9686	-12.6327	-0.00124	0.0183	0.9747
		b_t^*	22.2841	0.0041	0.0012	0.9718	22.2848	0.00018	0.0013	0.9730
		ΔE^*	-0.6145	0.0393	0.2712	0.9606	0.3858	0.01947	0.1751	0.9390
		C^*	25.6010	0.0103	0.0053	0.9801	25.6050	0.00041	0.0059	0.9822
		H^*	119.5470	0.0251	0.0604	0.9660	119.552	0.00021	0.0622	0.9649
		BI^*	54.5500	0.1325	0.7029	0.9092	54.7194	0.00212	0.5716	0.9311
	600	L_t^*	36.8100	0.0363	0.1593	0.9443	36.8306	0.00104	0.1826	0.9362
		a_t^*	-12.4754	0.0154	0.0041	0.9916	-	-0.00134	0.0026	0.9945
		b_t^*	22.2458	0.0039	0.0008	0.9716	22.2464	0.00011	0.0009	0.9721
		ΔE^*	-0.3733	0.0392	0.0923	0.9716	0.5035	0.01878	0.2160	0.9337
		C^*	25.5008	0.0106	0.0003	0.9983	25.5054	0.00042	0.0002	0.9988
		H^*	119.303	0.0273	0.0211	0.9871	119.310	0.00023	0.0201	0.9864
200	400	BI^*	55.3044	0.1332	0.6149	0.9575	55.5021	0.00213	0.1657	0.9693
		L_t^*	37.3781	0.0896	1.4936	0.8014	37.5460	0.00330	1.3441	0.8753
		a_t^*	-12.7395	0.0516	0.0450	0.9625	-	-0.00472	0.0801	0.9789
		b_t^*	22.3933	0.0373	0.0232	0.9730	22.4108	0.00177	0.0301	0.9791
		ΔE^*	-0.9428	0.1098	1.1177	0.9831	0.5181	0.03761	0.1754	0.8924
		C^*	25.7484	0.0567	0.0393	0.9770	25.7850	0.00239	0.0589	0.9846
	200	H^*	119.783	0.0712	0.2028	0.9511	119.795	0.00060	0.2125	0.9488
		BI^*	53.6508	0.1988	0.2169	0.6020	53.5997	0.00339	0.1655	0.6375
		L_t^*	36.9819	0.0689	0.3313	0.9172	37.3845	0.00257	1.6779	0.7769
		a_t^*	-12.6443	0.0463	0.0304	0.9769	-	-0.00424	0.0395	0.9822
		b_t^*	22.4566	0.0314	0.0702	0.9159	22.4108	0.00177	0.0301	0.9730
		ΔE^*	-0.6167	0.0885	0.2747	0.9570	0.6117	0.03212	0.3026	0.9527
	400	C^*	25.7627	0.0491	0.0577	0.9703	25.7850	0.00239	0.0589	0.9770
		H^*	119.4806	0.0648	0.2122	0.9488	119.795	0.00060	0.2125	0.9389
		BI^*	55.7881	0.1423	0.1681	0.8774	55.8858	0.00234	0.3055	0.8838
		L_t^*	37.9619	0.0770	2.0927	0.6702	37.9933	0.00217	2.1530	0.6607
		a_t^*	-12.5524	0.0325	0.0182	0.9722	-12.5804	-0.00286	0.0235	0.9784
		b_t^*	22.3871	0.0227	0.0180	0.9521	22.3924	0.00105	0.0201	0.9571
	600	ΔE^*	0.4919	0.0574	0.9025	0.7345	0.9954	0.02209	0.8822	0.7284
		C^*	25.6609	0.0352	0.0239	0.9708	25.6743	0.00144	0.0290	0.9759
		H^*	119.3323	0.0432	0.0674	0.9558	119.338	0.00036	0.0681	0.9554
		BI^*	53.5001	0.1681	0.6171	0.6547	53.6311	0.00283	0.3828	0.6623

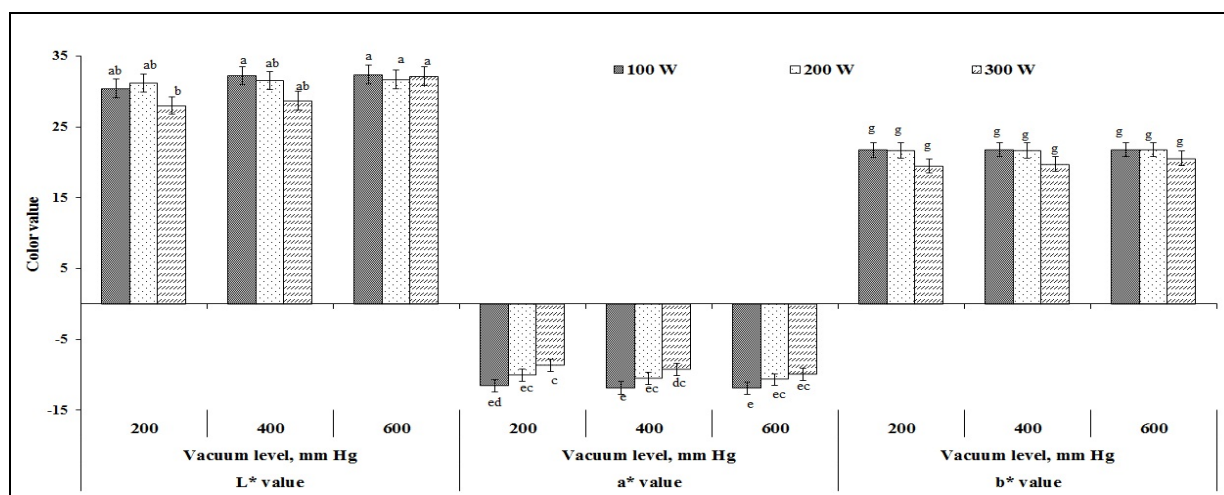


Figure 2. Effect of microwave power and vacuum level on L^* , a^* , and b^* values of VAM dried GBP samples. Vertical bars indicate standard deviation and values marked by the same letter are not significantly different ($p > 0.05$).

As a whole, there were positive changes in total color difference (ΔE^*) of GBP at all microwave power level (Figure 3a). During VAM drying, it increased significantly with time and ranged from 3.965 to 9.55 as the microwave power rose from 100 to 300 W. At any fixed vacuum level, ΔE^* increased significantly with increase in microwave power level. Thus, higher microwave power had the direct effect of inducing more color changes.

Based on the evaluated statistical parameter values (Table 1), final L^* value and ΔE^* were found to have a good fit to zero-order model, while final values of a^* and b^* followed the first-order model. Values of kinetic rate constant of L^* , a^* , b^* , and ΔE^* increased from 0.01376 to 0.0896 min^{-1} , -0.000146 to -0.00472 min^{-1} , 4.56×10^{-5} to $1.77 \times 10^{-3} \text{ min}^{-1}$, and from 0.0139 to 0.1098 min^{-1} , respectively, as the microwave power rose from 100 W to 300 W. It is evident from the data that, at higher microwave power, degradation rate of color parameters increased, which may be attributed to high energy transferred inside GBP samples causing rapid increase in its temperature. The results obtained were in agreement with studies on capsicum (Khan *et al.*, 2014), basil (Demirhan and Özbek, 2009), okra (Dadali *et al.*, 2007b), kiwifruit

(Maskan, 2001), spinach (Dadali *et al.*, 2007a), and tomato puree (Gamli, 2011).

Effect of Microwave Power on C^* , H^* , and BI^*

Color parameters, namely, chroma, hue angle, and browning index were derived from Eqs. 2 – 4 and the results are depicted in Figures 3b – 3d. The C^* value deteriorated during drying process (Figure 3b) and final values varied from 24.80 to 21.80, as microwave power increased. This implies that the yellowness of GBP samples remained stable. Hue angle decreased slightly indicating that samples did not lose their green color (Figure 3c). Values of BI^* , as shown in Figure 3d, increased with drying time in proportionality with the microwave power applied.

Table 1 shows model coefficients of color parameters from which it can be concluded that H^* accurately fitted to zero-order model while data of C^* and BI^* followed a first-order kinetic model. Kinetic rate constant values of C^* , H^* , and BI^* increased from 7×10^{-5} to 0.0039 min^{-1} , 0.00185 to 0.07122 min^{-1} , and 7.16×10^{-4} to 0.00339 min^{-1} , respectively, as microwave power increased from 100 W to 300 W. This shows that kinetic rate constant values of C^* , H^* , and

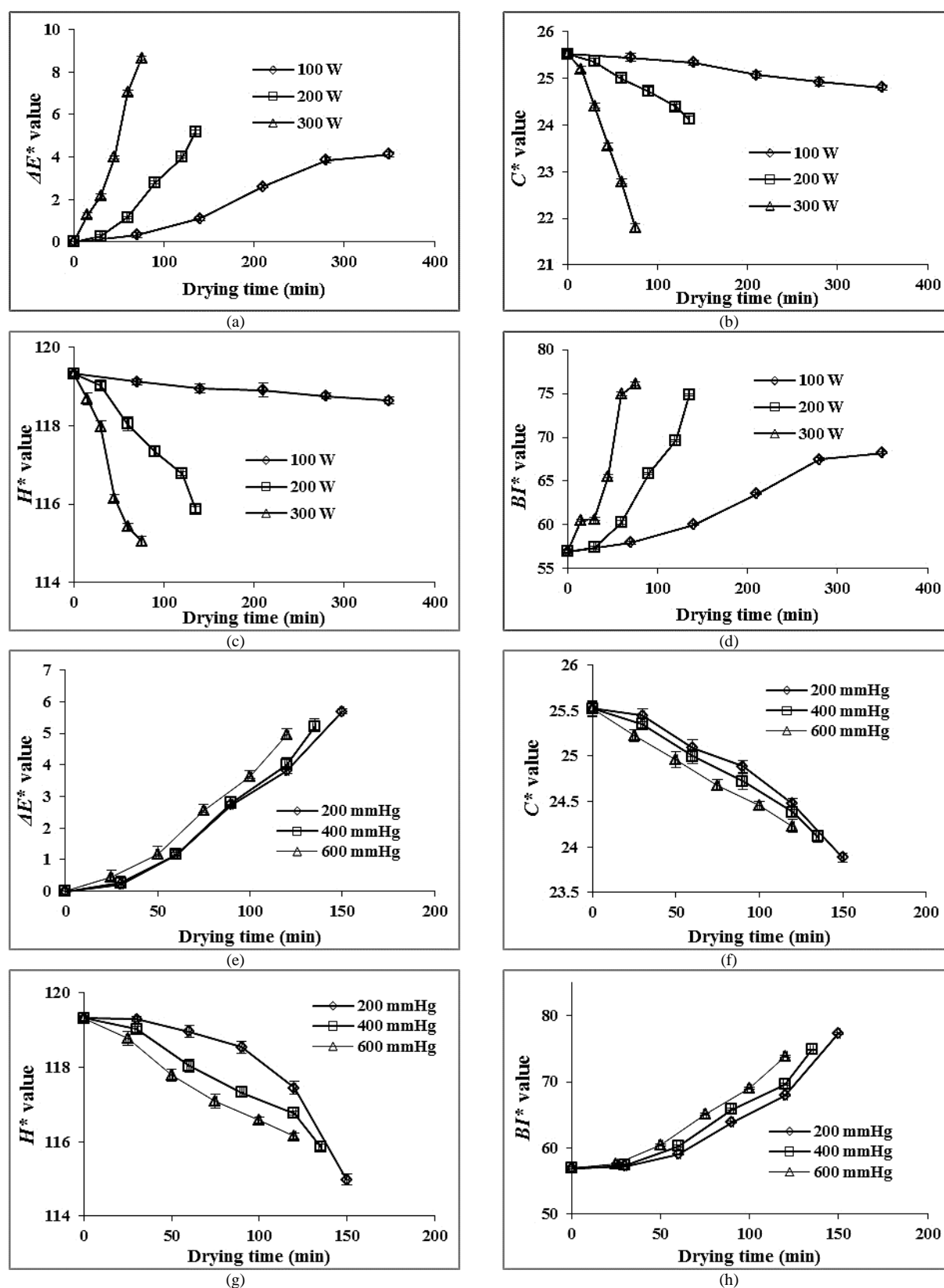


Figure 3. Kinetics of change at 400 mm Hg of the (a) ΔE^* (b) C^* (c) H^* (d) BI^* ; and at 200 W of (e) ΔE^* (f) C^* (g) H^* and (h) BI^* as a function of drying time.

BI^* were proportional to microwave power. Similar results were obtained for okra samples in a study published by Dadali *et al.* (2007b).

Effect of Vacuum Level on Color Kinetics of VAM Dried GBP

Color values of VAM dried GBP at different vacuum level can be seen in Figure 2. Compared with the fresh GBP, the dried sample showed a significant difference ($p < 0.05$) with the final values of L^* , a^* , and b^* at all vacuum levels studied. At a given microwave power level of 200 W, the L^* value decreased from a value of 36.32 of fresh sample to 31.75 and 31.2 when subjected to decreasing vacuum level from 600 mm Hg to 200 mm Hg, respectively. This shows that samples dried at higher vacuum level had better luminance. The a^* value of GBP varied from -12.5 (fresh sample) to -10.68 and -10.09 at 600 and 200 mm Hg, respectively. Therefore, at a fixed microwave power level, the sample retained better greenness at higher vacuum level. The b^* value also showed the same trend as L^* value. It declined from an initial value of 22.25 to 21.75 and 21.65 at vacuum levels of 600 and 200 mm Hg, respectively.

Final values of L^* , a^* , b^* denoted that the color of GBP samples retained better at higher vacuum levels. A possible reason may be the low sample temperature at high vacuum level during VAM drying. Total color difference (ΔE^*) of GBP increased significantly with drying time at various vacuum levels during VAM drying and ranged from 4.94 to 5.69 as the applied vacuum level decreased from 600 to 200 mm Hg, respectively (Figure 3e). Table 1 shows that zero-order model best fitted L^* and ΔE^* values, while the first-order model best fitted a^* and b^* values. Kinetic rate constant of L^* , a^* , b^* , and ΔE^* increased from 0.0364 to 0.0483 min^{-1} , -0.00134 to -0.00126 min^{-1} , 1.77×10^{-4} to 1.95×10^{-4} min^{-1} , and 0.0393 to 0.0508 min^{-1} , respectively, as vacuum level decreased.

Effect of vacuum level on C^* , H^* , and BI^*

Change of C^* , H^* and BI^* with drying time are illustrated in Figures 3f – 3h. Keeping microwave power level fixed at 200 W, value of C^* decreased from 25.52 (fresh GBP) to 24.23 and 23.88 at 600 and 200 mm Hg, respectively, indicating stability in yellowness of GBP samples at high vacuum level (Figure 3f). At 200 W microwave power level, value of H^* also declined from an initial value of 119.32 (fresh GBP) to 116.15 and 114.19 at 600 and 200 mm Hg, respectively. Values were well above 90° and below 180° indicating that dried samples maintained their greenness at all vacuum levels (Figure 3g). Contrary to C^* and H^* , the BI^* increased from 73.87 at 600 mm Hg to 77.30 at 200 mm Hg, indicating that less browning occurred in the sample at high vacuum level (Figure 3h). A possible reason may be the less heating at high vacuum level leading to less browning. Similar results were reported for microwave-vacuum drying of tomato slices by Abano *et al.* (2012).

In modeling studies, data calculated for C^* and BI^* accurately fitted to a first-order model, while calculated H^* followed a zero-order kinetic model (Table 1). Values of the kinetic rate constants of C^* and BI^* increased, while that of H^* decreased, as the vacuum level decreased from 600 to 200 mm Hg. The kinetic rate constant for C^* and BI^* increased from 4.28×10^{-4} to 4.3×10^{-4} min^{-1} , and from 0.00213 to 0.00307 min^{-1} , respectively, as the vacuum level decreased (Table 1). Values of kinetic rate constant for H^* declined from 0.0273 to 0.0264 min^{-1} , with the reduction in vacuum level. A possible reason for this behavior may be that at low vacuum, the rise in temperature is low causing less degradation of color inside the GBP samples.

Effect of D Ratio (Microwave Power/Vacuum Level) on Color Parameters

The desirable color development of the product could be estimated by using the ratio

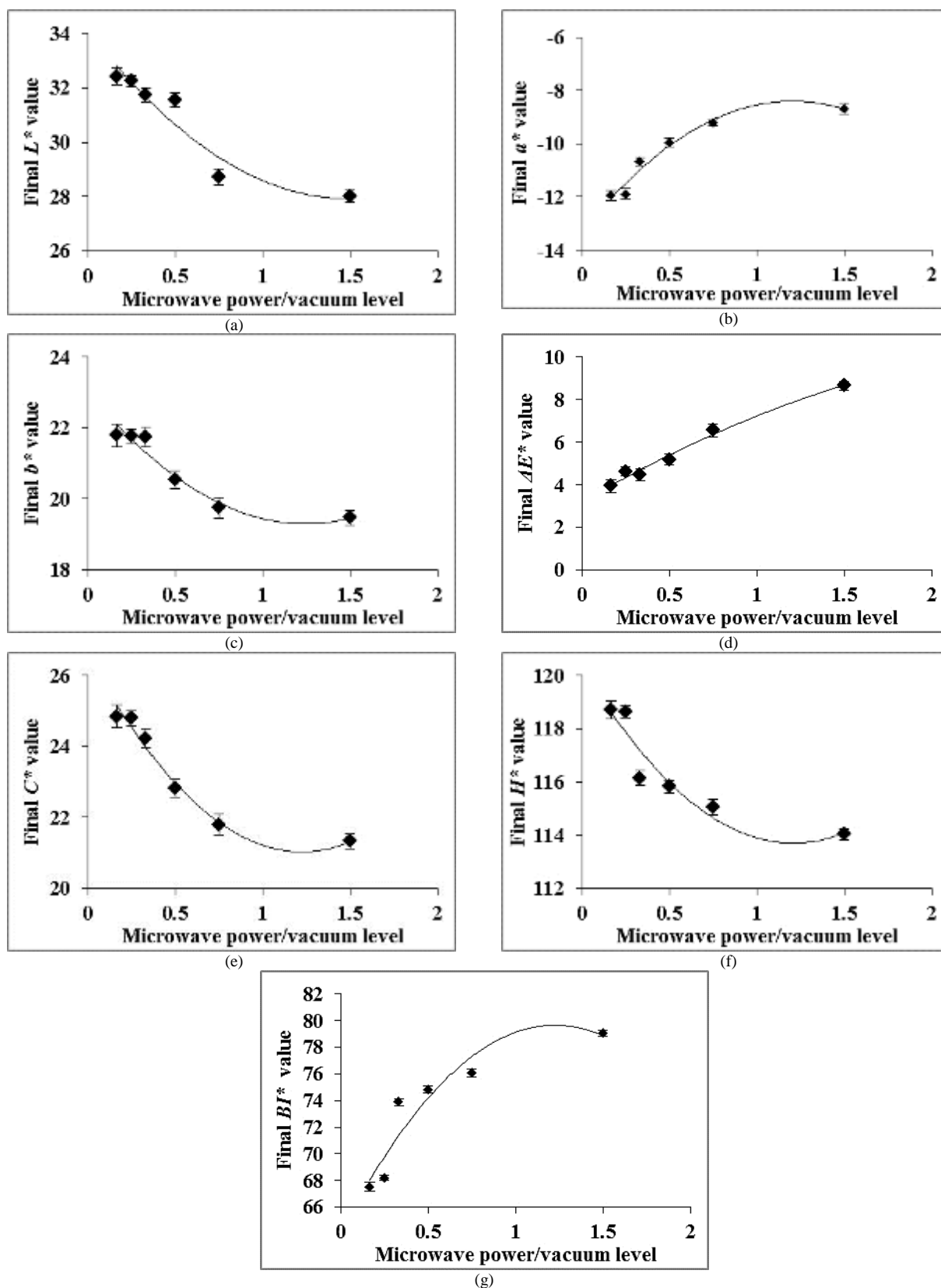


Figure 4. Final values of (a) L^* , (b) a^* , (c) b^* , (d) ΔE^* , (e) C^* , (f) H^* , and (g) BI^* curves as a function of power density (microwave power/ vacuum level), — predicted model.

of microwave power to applied vacuum levels during VAM drying. Table 2 shows estimated coefficients and statistical values of the quadratic model for final L^* , a^* , b^* , ΔE^* , C^* , H^* , and BI^* as a function of the ratio of microwave power to vacuum level (D ratio). For GBP samples, the final values of L^* and b^* decreased while the final value of a^* and ΔE^* increased as D ratio increased (Figures 4a – 4d). Considering for derived color parameters, final value of C^* and H^* decreased while final value of BI^* increased as the D ratio increased (Figures 4e – 4g).

ΔE^* and BI^* had a sharp increase in their value after D ratio of 1, indicating that at higher microwave power, there was considerable change in total color difference and the product had undergone more browning, probably making it less acceptable to consumers. Similar results were obtained for pineapple (Chutintrasri and Noomhorm, 2007) and okra (Dadali *et al.*, 2007b).

Estimation of E_a

The dependence of power density (microwave power / sample weight) on estimated kinetic rate constants of all color parameters were well described by Arrhenius-type model ($R^2 > 0.9$). Kinetic rate constants from the zero-order kinetic model of L^* , ΔE^* , H^* and kinetic rate constants from the first-order kinetic model of a^* , b^* , C^* , and BI^* were adequately fitted to Eq. 9. Table 2 shows the calculated E_a value for each color parameters. The activation energy values were calculated and found within the range of 3.20 – 13.58 Wg^{-1} , except for b^* ($E_a = 26.708 \text{ Wg}^{-1}$) and C^* value ($E_a = 20.4105 \text{ Wg}^{-1}$). The color parameters having higher values of E_a are more sensitive to color degradation during drying process (Chutintrasri and Noomhorm, 2007; Swain *et al.*, 2014). E_a values of b^* and C^* were higher than the other color parameters, hence they could be considered as the most heat sensitive color parameter for GBP. To get a quality product, the

changes in the values of b^* and C^* must be taken care of during drying of GBP. Similar results were obtained for E_a values in the study of yellow sweet pepper (Swain *et al.*, 2014) and okra (Dadali *et al.*, 2007b), which changed within the range of 5 – 15 Wg^{-1} .

CONCLUSIONS

Quantitative changes in the color of VAM dried samples, expressed in terms of L^* , a^* , b^* , ΔE^* , C^* , H^* and BI^* were found to be influenced significantly by microwave power and applied vacuum levels. Total variation of ΔE^* , C^* , H^* , and BI^* at the end of drying was between 4.14 – 8.65, 21.8 – 24.8, 114.98 – 116.15, and 68.19 – 77.33, respectively for the range of microwave power (100 – 300 W) and vacuum level (200 – 600 mm Hg). VAM drying of GBP at higher microwave power and lower vacuum level caused more browning in the final dried product. L^* , ΔE^* , and H^* were found to fit well to zero-order kinetic model, while it was a first-order kinetic model that fit suitably with the variation in a^* , b^* , C^* and BI^* . A developed quadratic equation predicted the relationship between microwave power to vacuum level ratio and all color parameters. a^* , ΔE^* , and BI^* were found to be positively correlated while L^* , b^* , H^* and C^* were found to be negatively correlated with the ratio of microwave power to vacuum level. The dependence of power density (microwave power / sample weight) on estimated kinetic rate constants of all the color parameters were well described by Arrhenius-type model and were used to calculate activation energy for respective color change kinetics.

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سینتیک تغییر رنگ فلفل دلمه ای خشک شده در سامانه میکروویو با کمک خلاء

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چکیده

این آزمایش با هدف بررسی سینتیک تغییرات رنگ فلفل دلمه ای در طی خشک شدن در سامانه میکروویو به کمک خلاء (VAM) در سه سطح قدرت میکروویو (۱۰۰، ۲۰۰، و ۳۰۰ وات (W) و خلاء (۲۰۰، ۴۰۰، و ۶۰۰ میلیمتر جیوه) انجام شد. تغییرات رنگ با استفاده از دستگاه رنگ سنج tristimulus اندازه گیری شد. در قدرت های کمتر میکروویو همراه با سطوح خلاء بالاتر، نمونه های خشک شده با VAM در وضع بهتری بودند و کمترین نشانه های سوختگی (browning) را داشتند. پارامترهای L^* ، ΔE^* ، و H^* برازش خوبی با مدل سینتیکی صفر داشت در حالی که پارامترهای a^* ، b^* ، C^* ، و BI^* از مدل سینتیکی درجه اول تبعیت می کردند. همه این پارامترهای رنگ به یک معادله درجه دوم به صورت تابعی از نسبت قدرت میکروویو به سطح خلاء برازش شد. هردو پارامتر ΔE^* و BI^* با افزایش قدرت میکروویو و کاهش سطح خلاء، زیاد شدند، در حالی که دیگر پارامترهای رنگ در همین شرایط کاهش یافتند. چنین فرض شد که وابستگی ضریب نرخ (rate constant) به تراکم قدرت (power density) از نوع Arrhenius بود. انرژی فعال سازی برای پارامترهای سینتیک تغییر



رنگ با استفاده از یک معادله نمایی مبتنی بر معادله Arrhenius محاسبه شد. مقادیر انرژی فعال سازی محاسبه شده در محدوده $3.20 - 13.58 \text{ Wg}^{-1}$ بودند به جز برای b^* ($E_a = 26.708 \text{ Wg}^{-1}$) و C^* ($E_a = 20.4105 \text{ Wg}^{-1}$). مقادیر E_a به دست آمده برای b^* و C^* نسبتاً بیشتر بود، به این قرار پارامترهای مزبور سنجه های حساستری از تغییر رنگ بودند. از این رو برای به دست آوردن محصول با کیفیت، لازم است در خشک کردن فلفل دلمه ای بعد از برداشت محصول مراقبت بیشتری معمول داشت.