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A novel approach for color degradation kinetics of paprika as a function of water activity

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Abstract

The influence of temperature and water activity on color degradation in paprika powders was investigated. The Hunter color parameters (L, a, b), hue angle (h), and total color difference (TCD) were used to estimate the color changes of paprika during thermal treatment at different temperatures (60, 80 and 99 °C) and water activities (0.459, 0.582 and 0.703). The changes in L, a, b and TCD values were significantly influenced by the processing time, temperature and water activity. The color changes during processing and storage were described by a first order kinetic model. The temperature dependence of the degradation followed the Arrhenius relation. Samples with a high water activity exhibited a high rate constant of the color degradation. The effect of water activity on activation energy was not significant. A linear relationship between the water activity and rate constant of the color parameters was found. By incorporating the linear relationship $k_{ref}a_w$ into the Arrhenius equation, a modified Arrhenius equation was proposed which was used to predict paprika color changes as influenced by temperature and water activity.
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Keywords: Paprika; Color; Kinetics; Water activity

1. Introduction

Paprika (the powder or flake processed from mature fruit of *Capsicum annuum* L.) is a spice with commercial importance in many countries. It is extensively consumed throughout the world because of its color, flavor and pungency. Since paprika is used as food colorant both for industrial and culinary purposes, the red color intensity is considered as the most important attribute of paprika (De Guevara et al., 2002; Ittah, Kanner, & Granit, 1993).

The attractive red-orange color of paprika is mainly due to the presence of keto-carotenoids, namely capsorubin and capsanthin. They comprise 70–80% of the total carotenoid content of paprika (Ittah et al., 1993). There are also some other carotenoids contributing to the paprika color, such as violaxanthin, capsanthin 5,6-epoxide, zeaxanthin, lutein, β-cryptoxanthin, and β-carotene (Levy et al., 1995; Minguez-Mosquera & Hornero-Mendez, 1993). As the visual color is the combination of attributes of specular reflectance, diffuse reflectance and diffuse transmittance, the color perception of paprika is also affected by surface texture (Martins & Silva, 2002).

During processing and storage, the color of paprika is substantially changed mainly due to carotenoids degradation and non-enzymatic browning reactions. These degradation reactions accelerate at higher temperatures and water activities (De Guevara et al., 2002; Gogus & Eren, 1998; Jaren-Galan & Minguez-Mosquera, 1999; Minguez-Mosquera & Hornero-Mendez, 1994; Osuna-Garcia & Wall, 1998; Ramesh, Wolf & Jung, 2001; Scala & Crapiste, in press; Topuz & Ozdemir, 2003). However, since the water molecules cover the active site of the dry solid against oxidation as a protective film, some moisture content may be required in paprika for carotenoid stabilities (Lee, Chung, & Yam, 1992; Osuna-Garcia & Wall, 1998).

For color description, tristimulus colorimetry has been used as a rapid and simple method to specify visual perception of food products (Rocha, Lebart, & Marty-Audouin, 1993). Several color systems have been developed to describe the actual

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color of foods (Garcia-Esteban, Ansorena, Gimeno, & Astiasaran, 2003; Giese, 1995; Giese, 2000). Due to its simplicity, the Hunter *Lab* color scale is among the most widely used to characterize color changes in foods. Several mathematical combinations of the color co-ordinates, such as; $L \times a \times b$, *La*/*b*, hue angle (*h*) and total color difference (TCD) are also used in food color evaluation (Ahmed, Kaur, & Shivhare, 2002; Ahmed & Ramaswamy, 2005; Barreiro, Milano, & Sandoval, 1997; Martins & Silva, 2002; Shin & Bhowmik, 1995).

From an industrial point of view, kinetic parameters of color degradation have great importance. Studies on color changes in foods have generally focused on paste and puree products (Ahmed, Kaur, et al., 2002; Ahmed & Ramaswamy, 2005; Ahmed & Shivhare, 2001; Ahmed, Shivhare, & Ramaswamy, 2002; Avila & Silva, 1999; Barreiro et al., 1997; Shin & Bhowmik, 1995). A few kinetic studies similar in nature have been conducted to determine paprika discoloration during thermal treatment and storage (Ahmed, Shivhare, et al., 2002; Carbonell, Pinaga, Yusa, & Pena, 1986; De Guevara et al., 2002; De Guevara, Parra-Lopez, Pardo-Gonzalez, Saus, & Varon-Castellanos, 1998; Ismail & Revathi, 2006). However, no effort was devoted to the development of a kinetic model taking into consideration the effect of water activity to predict paprika color degradation during thermal processing and storage.

In the current study, the color degradation of paprika expressed by *L*, *a*, *b*, hue angle (*h*) and total color difference (TCD) was fitted to a fractional first order kinetic model and an effort was made to incorporate the effect of both temperature and water activity into kinetic parameters rate constant (k_{ref}) and activation energy (E_a).

2. Materials and methods

2.1. Material

Paprika powders, free of additives, were obtained from a local spice processor in Antalya, Turkey.

2.2. Moisture adjustment

Paprika samples were equilibrated at three different moisture levels (4.86, 7.45 and 12.55 g/100 g, wet basis) which corresponded to a_w values of 0.418, 0.567 and 0.725 at 25 °C, respectively. After being moisturized with a spray of distilled water, the samples were placed in glass containers for 4 days and shaken periodically to achieve the water activity values. The time for equilibration was determined by preliminary experiments. Then each sample was passed through a 35 mesh (500 μm aperture) laboratory test sieve (Retsch, Germany) to break up lumps, and each 80 g sample was put into a 660 mL glass jar, and then capped to maintain the moisture level.

2.3. Heat treatment and sampling

The samples in air-tight glass jars were kept in ovens at 60, 80 and 99 °C, with a maximum temperature fluctuation of ±1 °C. Jars were vigorously shaken for thorough mixing both at the beginning and again in the middle of each sampling time interval.

Sampling was carried out at the beginning of the heat treatment and then at geometrically increasing time intervals (0, 2, 4, 8, 16, 32, 64, 128 and 256 h). At each sampling, 3 g of duplicate samples were immediately taken out from the jar, put into polyethylene bags and placed in a refrigerator until analysis of color and water activity was carried out. Care was taken to keep the moisture levels of the samples as stable as possible.

2.4. Water activity analysis

The water activities of the samples were measured at 25 °C with a water activity meter (Testo 650, Testo Inc., NJ, USA). For this purpose, approximately 3 g of each sample was put into the sample holder which was equipped with a meter having a relative humidity and temperature sensor. After equilibration, a_w values were recorded.

2.5. Color measurement

A chromameter (Model CR 400, Conica Minolta Corp., Japan) was used to measure the apparent color of the samples in terms of "*L*" (degree of lightness to darkness), "*a*" (degree of redness to greenness) and "*b*" (degree of yellowness to blueness). The instrument was calibrated with a tile ($L = 97.02$, $a = 0.08$, $b = 1.75$) before measurements. The samples were placed above the light source in the sample holder of the instrument (the minimum height of the samples in the sample holder was 1 cm). Hunter *L*, *a* and *b* values were recorded as the mean of triplicate measurements from three different spots.

The total color difference (TCD) and hue angle (*h*) were calculated from the *L*, *a* and *b* values according to Eqs. (1) and (2), respectively.

$$\mathrm{TCD} = \left[(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2\right]^{1/2} \quad (1)$$

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

where *L* is degree of lightness to darkness, L_o is initial value of *L*, *a* is degree of redness to greenness, a_o is initial value of *a*, *b* is degree of yellowness to blueness, and b_o is initial value of *b*.

2.6. Kinetics consideration

Color changes of selected vegetables and fruits in growth or under post harvest storage conditions have been reported to be sigmoid in nature, and have been modeled by a logistic function (Calligaris, Falcone, & Anese, 2002; Jacobi, MacRae, & Hetherington, 1998; Tijskens & Evelo, 1994). For color changes during thermal processing and subsequent storage, however, the first order kinetic models better described the color alterations (Ahmed, Kaur, et al., 2002;

Gunawan & Barringer, 2000; Ismail & Revathi, 2006; Shin & Bhowmik, 1995; Wagner & Warthesen, 1995). The fractional (irreversible) first order kinetic model (Eq. (3)) is employed for color degradation kinetics since a considerable color values are recorded at the end of a long processing time (Levenspiel, 1974; Martins & Silva, 2002; Zimerri & Tong, 1999).

$$\frac{C - C_\infty}{C_0 - C_\infty} = \exp(-kt) \tag{3}$$

where C is the measured value of color variables at time t (dimensionless), C_0 the initial value of color variables at time zero (dimensionless), t the heating time (h), k reaction rate constant (h^{-1}), and C_∞ is the value of color variables at infinite time (dimensionless).

The dependence of the degradation rate constant on temperature can be represented by the Arrhenius equation (Eq. (4)),

$$k = k_{\text{ref}} \exp\left(\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right) \tag{4}$$

where E_a is the activation energy (J/mol), R is the universal gas constant (8.314 J/mol K), T is temperature (K), T_{ref} is the reference temperature (K), and k_{ref} is the reaction rate constant at reference temperature.

2.7. Analysis of data

The experiments were conducted using a factorial design (*three water activities* × *three temperatures* × *nine processing times*) with two replicates. Variance analyses were performed to determine whether there were significant differences among color variables. Non-linear regression analysis for model fitting was performed on all data of color variables in a one-step optimization procedure (Arabshahi & Lund, 1985), by maximizing the likelihood function for all the temperature levels. The kinetic parameters were estimated by Sigma Plot (For windows, version 8.0) using the first order model (Eq. (3)) taking into account the temperature effect with the Arrhenius model (Eq. (4)) or derived Arrhenius model (Eq. (5)). The estimation of the kinetic parameters was carried out at a reference temperature of 75 °C.

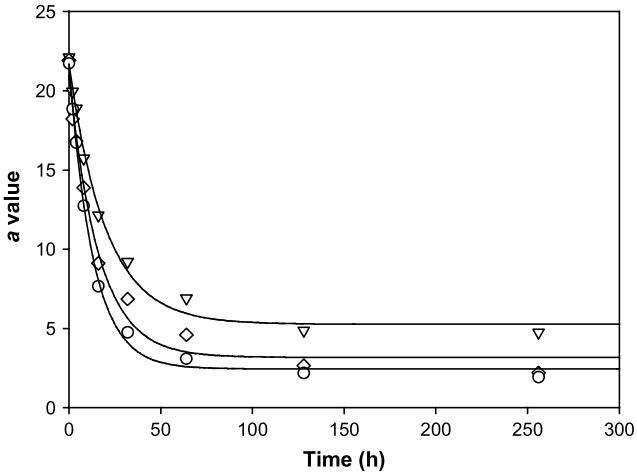


Fig. 2. Change in color variable of a of paprika depends on water activity [0.459 (▽), 0.582 (◇), 0.703 (○)] at 80 °C.

3. Results and discussion

3.1. Color degradation kinetics

The color of paprika is featured by a mix of yellowness and redness due to the presence of carotenoids. These color components are represented by Hunter a and b color co-ordinates. Since any change in a and b values is accompanied by a simultaneous change in the L value (Ahmed, Shivhare, et al., 2002), the color co-ordinates of L, a and b and the combination of h and TCD were selected to represent the color change in paprika. These parameters were also used to evaluate color changes in previous color degradation studies (Ahmed &

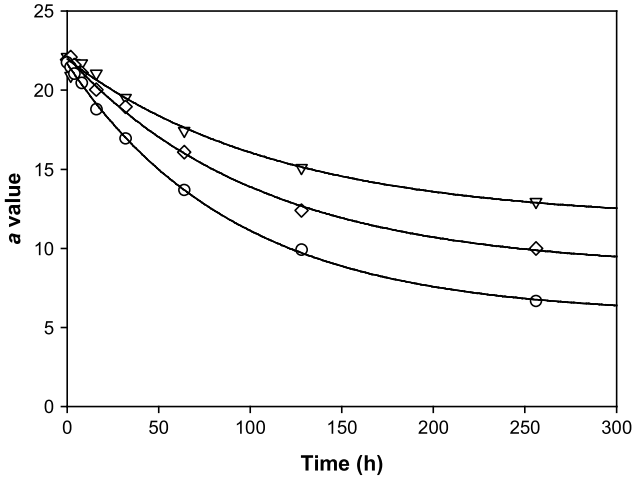


Fig. 1. Change in color variable of a of paprika depends on water activity [0.459 (▽), 0.582 (◇), 0.703 (○)] at 60 °C.

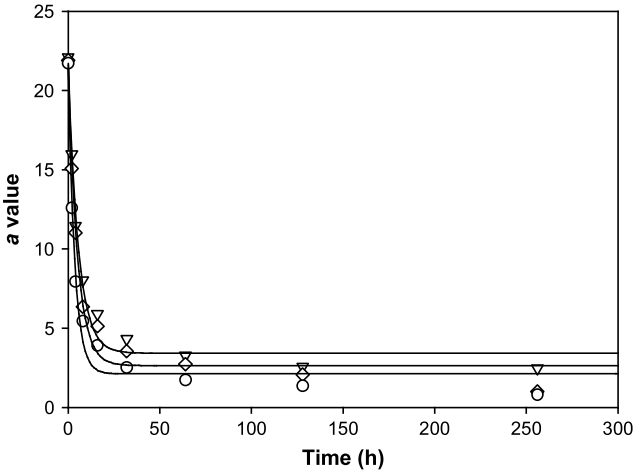


Fig. 3. Change in color variable of a of paprika depends on water activity [0.459 (▽), 0.582 (◇), 0.703 (○)] at 99 °C.

Table 1
Kinetic parameters of the color degradation of paprika as a function of water activity

Water activity	Kinetic parameters	Color variables			
		L	*a*	*b*	TCD
0.459	C_o	37.49 + 0.14	21.51 + 0.26	13.56 + 0.17	0.80 + 0.32
	C_∞	29.16 + 0.17	3.93 ± 0.30	2.74 ± 0.22	22.98 ± 0.38
	$k_{75\ °C}$	0.015 + 0.001	0.019 ± 0.001	0.015 ± 0.002	0.018 ± 0.001
	E_a	124.8 + 4.2	109.0 ± 3.1	108.5 ± 3.6	110.7 ± 3.2
	R^2_{adj}	0.970	0.977	0.972	0.977
	SEE	0.597	1.077	0.736	1.365
0.582	C_o	37.43 + 0.18	21.33 + 0.32	13.48 + 0.20	0.82 + 0.40
	C_∞	28.21 + 0.20	2.86 ± 0.34	1.80 ± 0.24	24.29 ± 0.43
	$k_{75\ °C}$	0.022 + 0.002	0.025 ± 0.002	0.021 ± 0.002	0.024 ± 0.002
	E_a	113.0 + 4.0	101.9 ± 3.3	98.8 ± 3.4	104.1 ± 3.3
	R^2_{adj}	0.962	0.971	0.968	0.972
	SEE	0.743	1.285	0.845	1.604
0.703	C_o	36.76 + 0.12	21.37 + 0.25	13.46 + 0.18	0.50 + 0.32
	C_∞	27.56 + 0.11	2.37 ± 0.24	1.42 ± 0.18	24.76 ± 0.31
	$k_{75\ °C}$	0.034 + 0.002	0.037 ± 0.002	0.034 ± 0.002	0.036 ± 0.002
	E_a	108.7 + 2.4	99.0 ± 2.4	97.1 ± 2.7	99.9 ± 2.4
	R^2_{adj}	0.985	0.984	0.979	0.984
	SEE	0.458	0.966	0.703	1.238

Units of the $k_{75\ °C}$ and E_a are h^{-1} and kJ/mol, respectively.
R^2_{adj}: adjusted coefficient of determination, SEE: *standard error of estimate*.
Number of observation for each color variables is 54, $T_{ref} = 75$ °C.

Ramaswamy, 2005; Ahmed, Shivhare, et al., 2002; Barreiro et al., 1997; Martins & Silva, 2002; Shin & Bhowmik, 1995).

During thermal processing of paprika, the values of the color variables, except hue angle (*h*), were significantly ($P < 0.01$) decreased. Rapid color degradation can be relatively observed at the beginning of the treatments. Afterwards, the color changes were slowed down until they reached a constant value (Figs. 1–3).

The first order fractional kinetic model was used to estimate the kinetic parameters of paprika color degradation with *L*, *a*, *b* and TCD color variables. The color variable of *h* was excluded from kinetic models for all samples since no significant changes in *h* value were observed throughout the thermal processing.

Table 2
Variation of a_w values of the samples throughout the heat treatments

Moisture level	Temperature (°C)	Initial	Isothermal[a]	Overall[b]
Low	60	0.418	0.450 ± 0.035	0.459 ± 0.037
	80	0.418	0.469 ± 0.046	
	99	0.418	0.459 ± 0.029	
Moderate	60	0.567	0.576 ± 0.026	0.582 ± 0.034
	80	0.567	0.579 ± 0.047	
	99	0.567	0.589 ± 0.029	
High	60	0.725	0.714 ± 0.012	0.703 ± 0.030
	80	0.725	0.684 ± 0.036	
	99	0.725	0.710 ± 0.031	

[a] Data are the mean of nine determinations at sampling times ± standard deviation for the specific temperature.
[b] Data are the mean of 27 determinations ± standard deviation for overall temperature.

The kinetic parameters of the color degradations were estimated with non-linear regression methods by using first order model (Eq. (3)) after introducing the effect of temperature with the Arrhenius model (Eq. (4)) (Arabshahi & Lund, 1985). This method provided more reliable results by both increasing the degree of freedom and narrowing the confidence interval.

The rate constant (*k*) at reference temperature (75 °C), the activation energy (E_a), and the initial (C_0) and infinite values (C_∞) of the color variables of paprika are presented in Table 1. The kinetic parameters in Table 1 for all color variables have a high correlation coefficient ($R^2 > 0.96$) and low standard error between the predicted and the experimental data. It indicates that the kinetic equations for the color variables well presented the color changes in paprika, and hence can be used to describe the color degradation during thermal processing and storage. Since the *a* value is an indication of the characteristic color of paprika, the color variable of *a* may be a better parameter in monitoring the color alteration of paprika.

3.2. Effect of temperature on rate of color degradation

It is well known that dependence of the rate constant on absolute temperature obeys the Arrhenius relationship (Eq. (4)). A higher E_a value indicates a greater heat sensitivity for color degradation during a thermal process (Chutintrasri & Noomhorm, 2006). It can be seen from Table 1 that all color variables, except *L*, exhibited almost the same heat sensitivity. The E_a values of *L* color parameter were found to be higher in comparison to those of the other color parameters. Hence, *L* can be considered to be the most heat sensitive color variable of paprika.

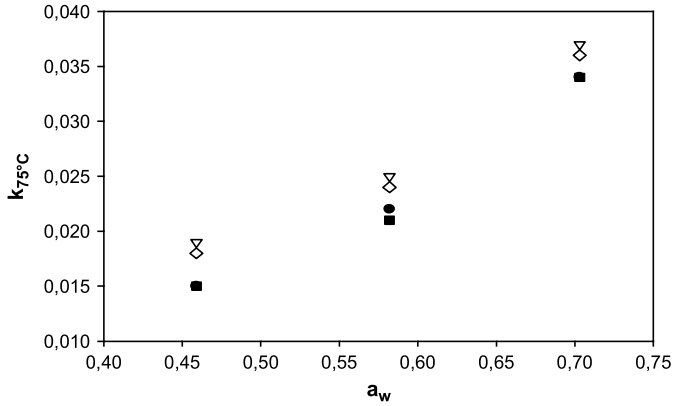


Fig. 4. Change in rate constants of the color variables [L (●), a (▽), b (■), TCD (◇)] as a function of water activity.

3.3. Effect of water activity on rate of color degradation and activation energy

The water activity of paprika varies with industrial processing methods and during storage, and has a considerable effect on paprika color. In the current study, the stability of the initial equilibrated a_w values were monitored throughout the heating processes (Table 2). Generally, the paprika samples with a higher water activity experienced a marked change in color variables in a short processing time. However, the color parameters of the samples at low water activity were found to be more stable. Usually, the carotenoids present in the structure of fatty acid esters in paprika are more stable (Minguez-Mosquera & Perez-Galvez, 1998). The discoloration effect of a_w on paprika may thus be caused by hydrolysis of the fatty acid ester. The color degradation can also be caused by non-enzymatic browning reactions which are closely related to the water activity of paprika (Gogus & Eren, 1998; Lee et al., 1992; Osuna-Garcia & Wall, 1998). Both reactions are accelerated at higher water activities (Ramesh et al., 2001; Scala & Crapiste, in press).

A few studies have documented the effect of water activity on quality changes of selected food products (Goula, Adomopoulos, Chatzitakis, & Nikas, 2006; Guevara, Yahia, Cedeno, & Tijskens, 2006; Prachayawarakorn et al., 2004). However, no study has been reported in the literature that considered the effect of water activity on paprika discoloration kinetics. In this work, the kinetic parameters of paprika color degradation (k_{ref}, and E_a) were examined at three a_w levels.

The current experimental results reveal that the color degradation rate of paprika significantly ($P < 0.01$) increased with increasing a_w, which also concurred with human eye perception. A decrease in the activation energy of paprika color degradation with an increase in a_w can also be observed values although it is not statistically significant. In all the color parameters, the k_{ref} values showed almost linear relationship as a function of a_w (Fig. 4). A linear relationship ($k_{ref}a_w$) was thus introduced into the Arrhenius model (Eq. (4)), and the following modified equation (Eq. (5)) was obtained.

$$k = (k_{ref}a_w)\exp\left(\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right) \quad (5)$$

Where k_{ref} is the rate constant at reference temperature (K) and water activity (a_w) is measured at 25 °C. The changes in the color variables of the paprika were fitted to the kinetic equation (Eq. (3)) using the modified Arrhenius model (Eq. (5)) by a non-linear regression of all data (processing time, temperature and water activity). Results are presented in Table 3. These kinetic parameters can be used to predict paprika color changes at any water activity level.

4. Conclusions

In the present study, the color parameters L, a, b and TCD were used to investigate the changes in the color of paprika, using the fractional conversion kinetics model. The kinetic parameters were estimated with a one-step non-linear regression method. The temperature dependence of color degradation for all the color parameters can be described with the Arrhenius model. The degradation of color was also dependent on water activity. As the water activity of paprika increased, the rate constant of the color degradation at the reference temperature linearly increased, whereas the activation energy decreased but not significant. By incorporating $k_{ref}a_w$ into the Arrhenius model, a new model was proposed which can be used to predict the color parameters of paprika at different temperatures and water activities. The proposed model reveal that the color variables of a and L had the highest k_{ref} and E_a values, respectively. They can be used for practical purposes in controlling the unique color characteristics of paprika.

Table 3
Kinetic parameters of the color degradation of paprika estimated with proposed model

Kinetic parameter	L	a	b	TCD
C_∞	28.25 + 0.14	3.00 + 0.19	1.94 + 0.15	24.08 + 0.24
C_0	37.25 + 0.13	21.41 + 0.18	13.51 + 0.14	0.70 + 0.23
$k_{75\ °C}$	0.040 + 0.002	0.046 + 0.002	0.039 + 0.002	0.043 + 0.002
E_a	113.3 + 2.9	102.5 + 1.9	100.1 + 2.3	104.1 + 1.9
R^2_{adj}	0.942	0.971	0.958	0.972
SEE	0.905	1.275	0.960	1.599

Units of the $k_{75\ °C}$ and E_a are h^{-1} and kJ/mol, respectively.
R^2_{adj}: adjusted coefficient of determination, SEE: *standard error of estimate*.
Number of observation for each color variables is 162, $T_{ref} = 75$ °C.

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References

Ahmed, J., Kaur, A., & Shivhare, U. (2002). Color degradation kinetics of spinach, mustard leaves, and mixed puree. *Journal of Food Science, 67*(3), 1088–1091.

Ahmed, J., & Ramaswamy, H. S. (2005). Effect of temperature on dynamic rheology and colour degradation kinetics of date paste. *Food and Bioproducts Processing, 83*(C3), 198–202.

Ahmed, J., & Shivhare, U. S. (2001). Thermal kinetics of colour degradation and storage characteristics of onion paste. *LWT - Food Science and Technology, 34*(6), 380–383.

Ahmed, J., Shivhare, U. S., & Ramaswamy, H. S. (2002). A fractional conversion kinetic model for thermal degradation of color in red chilli puree and paste. *LWT - Food Science and Technology, 35*(6), 497–503.

Arabshahi, A., & Lund, D. B. (1985). Considerations in calculating kinetic parameters from experimental data. *Journal of Food Process Engineering, 7*, 239–251.

Avila, I. M. L. B., & Silva, C. L. M. (1999). Modelling kinetics of thermal degradation of colour in peach puree. *Journal of Food Engineering, 39*(2), 161–166.

Barreiro, J. A., Milano, M., & Sandoval, A. J. (1997). Kinetics of colour change of double concentrated tomato paste during thermal treatment. *Journal of Food Engineering, 33*(3–4), 359–371.

Calligaris, S., Falcone, R., & Anese, A. (2002). Color changes of tomato purees during storage at freezing temperatures. *Journal of Food Science, 67*(6), 2432–2435.

Carbonell, J. V., Pinaga, F., Yusa, V., & Pena, J. L. (1986). The dehydration of paprika with ambient and heated air and the kinetics of colour degradation during storage. *Journal of Food Engineering, 5*(3), 179–193.

Chutintrasri, B., & Noomhorm, A. (2006). Color degradation kinetics of pineapple puree during thermal processing. *LWT - Food Science and Technology, 40*(2), 300–306.

De Guevara, R. G. L., Gonzalez, M., Garcia-Meseguer, M. J., Nieto, J. M., Amo, M., & Varon, R. (2002). Effect of adding natural antioxidants on colour stability of paprika. *Journal of the Science of Food and Agriculture, 82*(9), 1061–1069.

De Guevara, R. G. L., Parra-Lopez, V., Pardo-Gonzalez, J. E., Saus, M. L., & Varon-Castellanos, R. (1998). Influence of storage conditions on pigment degradation in paprikas from different greenhouse pepper cultivars. *Journal of the Science of Food and Agriculture, 78*(3), 321–328.

Garcia-Esteban, M., Ansorena, D., Gimeno, O., & Astiasaran, I. (2003). Optimization of instrumental color analysis in dry-cured ham. *Meat Science, 63*(3), 287–292.

Giese, J. (1995). Measuring physical properties of foods. *Food Technology, 49*(2), 54–63.

Giese, J. (2000). Color measurement in foods as a quality parameter. *Food Technology, 54*(2), 62–63.

Gogus, F., & Eren, S. (1998). Effect of temperature and pH on nonenzymic browning in minced dried pepper during storage. *Turkish Journal of Engineering and Environmental Sciences, 22*, 33–38.

Goula, A. M., Adomopoulos, K. G., Chatzitakis, P. C., & Nikas, V. A. (2006). Prediction of lycopene degradation during a drying process of tomato pulp. *Journal of Food Engineering, 74*, 37–46.

Guevara, J. C., Yahia, E. M., Cedeno, L., & Tijskens, L. M. M. (2006). Modeling the effects of temperature and relative humidity on gas exchange of prickly pear cactus (*Opuntia* spp.) stems. *LWT - Food Science and Technology, 39*(7), 796–805.

Gunawan, M. I., & Barringer, S. A. (2000). Green color degradation of blanched broccoli (*Brassica oleracea*) due to acid and microbial growth. *Journal of Food Processing and Preservation, 24*(3), 253–263.

Ismail, N., & Revathi, R. (2006). Studies on the effects of blanching time, evaporation time, temperature and hydracolloid on physical properties of chili (*Capsicum annum var kulai*) puree. *LWT - Food Science and Technology, 39*(1), 91–97.

Ittah, Y., Kanner, J., & Granit, R. (1993). Hydrolysis study of carotenoid pigments of paprika (*Capsicum annuum* L. variety Lahava) by HPLC/Photodiode Array Detection. *Journal of Agricultural and Food Chemistry, 41*(6), 899–901.

Jacobi, K. K., MacRae, E. A., & Hetherington, S. E. (1998). Early detection of abnormal skin ripening characteristics of 'Kensington' mango (*Mangifera indica* Linn). *Scientia Hortuculturae, 72*(3–4), 215–225.

Jaren-Galan, M., & Minguez-Mosquera, M. I. (1999). Effect of pepper lipoxygenase activity and its linked reactions on pigmnents of peper fruit. *Journal of Agricultural and Food Chemistry, 47*(11), 4532–4536.

Lee, D. S., Chung, S. K., & Yam, K. L. (1992). Carotenoid loss in dried red pepper products. *International Journal of Food Science and Technology, 27*(2), 179–185.

Levenspiel, O. (1974). *Chemical reaction engineering*. New Delhi, India: Wiley Eastern Publication.

Levy, A., Harel, S., Palevitch, D., Akiri, B., Menagem, E., & Kanner, J. (1995). Carotenoid pigments and β-carotene in paprika fruits (*Capsicum* spp.) with different genotypes. *Journal of Agricultural and Food Chemistry, 43*, 362–366.

Martins, R. C., & Silva, C. L. M. (2002). Modelling colour and chlorophyll losses of frozen green beans (*Phaseolus vulgaris* L.). *International Journal of Refrigeration, 25*(7), 966–974.

Minguez-Mosquera, M. I., & Hornero-Mendez, D. (1993). Separation and quantification of the carotenoid pigments in red peppers (*Capsicum annuum* L.), paprika, and oleoresin by reverse-phase HPLC. *Journal of Agricultural and Food Chemistry, 41*, 1616–1620.

Minguez-Mosquera, M. I., & Hornero-Mendez, D. (1994). Comparative study of the effect of paprika processing on the carotenoids in papers (*Capsicum annuum*) of the *Bola* and *Agridulce* varieties. *Journal of Agricultural and Food Chemistry, 42*(7), 1555–1560.

Minguez-Mosquera, M. I., & Perez-Galvez, A. (1998). Study of lability and kinetics of the main carotenoid pigments of red pepper in the de-esterification reaction. *Journal of Agricultural and Food Chemistry, 46*, 566–569.

Osuna-Garcia, J. A., & Wall, M. M. (1998). Prestorage moisture content affects color loss of ground paprika (*Capsicum annuum* L.) under storage. *Journal of Food Quality, 21*(3), 251–259.

Prachayawarakorn, S., Sawangduanpen, S., Saynampheung, S., Poolpatarachewin, T., Soponronnarit, S., & Nathakarakule, A. (2004). Kinetics of color change during storage of dried garlic slices as affected by relative humidity and temperature. *Journal of Food Engineering, 62*(1), 1–7.

Ramesh, M. N., Wolf, W., & Jung, D. T. G. (2001). Influence of processing parameters on the drying of spice paprika. *Journal of Food Engineering, 49*(1), 63–72.

Rocha, T., Lebart, A., & Marty-Audouin, C. (1993). Effect of pre-treatments and drying conditions on drying rate and color retention in basil. *LWT - Food Science and Technology, 26*, 456–463.

Scala, K. D., & Crapiste, G. Drying kinetics and quality changes during drying of red pepper. *LWT - Food Science and Technology*, in press. doi:10.1016/j.lwt.2007.06.007.

Shin, S., & Bhowmik, S. R. (1995). Thermal kinetics of color changes in pea puree. *Journal of Food Engineering, 24*(1), 77–86.

Tijskens, L. M. M., & Evelo, R. G. (1994). Modelling colour of tomatoes during postharvest storage. *Postharvest Biology and Technology, 4*(1–2), 85–98.

Topuz, A., & Ozdemir, F. (2003). Influence of γ irradiation and storage on the carotenoids of sun dried and dehydrated paprika. *Journal of Agricultural and Food Chemistry, 51*(17), 4972–4977.

Wagner, L. A., & Warthesen, J. J. (1995). Stability of spray-dried encapsulated carrot carotenes. *Journal of Food Science, 60*(5), 1048–1053.

Zimerri, J., & Tong, C. H. (1999). Degradation kinetics of (−)-epigallocatechin gallate as a function of pH and dissolved oxygen in a liquid model system. *Journal of Food Science, 64*(5), 753–758.