

Investigation of dynamic quality changes and optimization of drying parameters of carrots (*Daucus carota* var. *laguna*)

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Abstract

The effect of air temperature and sample thickness on the color changes and total carotenoids content of carrot slices was investigated. Temperature, exposure time, and moisture levels significantly affected the dynamic changes of total carotenoids and color. A slow and linear decrease in total carotenoids was observed at higher moisture content until reaching an inflection point at around 0.45 g_w/g_{dm} for all temperatures studied. Thereafter, the retention in total carotenoids decreased rapidly. The highest retention for a final product was 66.2% when drying at 60°C while retention was between 42.2 and 51.1% when drying at 50 and 70°C. These changes occurred alongside a noticeable change in color at moisture contents below the inflection point of 0.45 g_w/g_{dm} for all drying temperatures. Design of experiment based optimization of the drying process resulted in an ideal temperature of 59.8°C and 3.5 mm slice thickness with the predicted values for $L^*a^*b^*$; ΔE of 62.18 ± 5.12 , 22.46 ± 1.98 , 40.35 ± 6.64 , 6.31 ± 4.74 ; rehydration ratio of 0.48 ± 0.07 ; and total carotenoids of $163.83 \pm 17.38 \mu\text{g/g}$ or 67.38%, respectively, all at a 95% prediction interval.

Practical applications

Convective drying is the most widely used drying technique for food preservation due to its easy application and readily available technology. However, the quality of the end product is currently lower than it would be achievable due to a lack of direct integration of quality characteristics into process design. Monitoring the quality changes as a function of moisture content throughout the drying process is essential to developing advanced process parameters with a view to increasing final product quality. This study describes the experimentally determined dynamic quality changes of carrots throughout the drying process in order to identify the critical points at which the process settings should be changed to increase the retention of valuable components and sensory quality attributes, and thus, to provide consumers with higher quality products.

1 | INTRODUCTION

Carrots are globally the second most consumed vegetable and have been identified as one of the healthiest vegetables due to their abundance of

phytochemical constituents such as beta-carotene, vitamin C, and minerals (Anon, 2011). These nutrients provide significant health benefits to humans in terms of antioxidant capability, anticancer, anti-inflammatory, and many other properties (Da Silva Dias, 2014). Fresh carrots are used

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in many dishes around the world such as stews, soups, curries, and salads, as well as in baked goods such as cakes and bread. The crop can also be processed into many nutritious goods such as puree, juice, oil, dried products, and baby food (Nguyen & Nguyen, 2015; Saidel et al., 2015).

In freshly harvested crops, such as carrot, the presence of water accelerates phytochemical degradation due to enzymatic and non-enzymatic processes. Thus, reducing the water content through drying is imperative. By doing so, the material becomes easier to handle and less prone to microbial degradation (Pittia & Antonello, 2016). Drying can also result in a loss of bioactive compound and flavors. Thus, the drying process must be carried out as quickly and evenly as possible (Chin, Siew, & Soon, 2015). Inadequate drying gives rise to microbial infection, whereas overdrying or unfavorable process settings result in drastic loss of quality. Drying at low temperatures between 30 and 50°C is recommended to preserve heat-sensitive active ingredients in medicinal plant or herbs (Müller & Heindl, 2006). However, different crops require different drying temperatures depending on their desired quality attributes and nutrient content. The most commonly applied temperatures for preserving food materials using convective air drying were reported to be in the range of 50 to 90°C (Krokida & Maroulis, 2000).

Minimizing quality changes of carrots after drying is imperative for quality assurance and final evaluation of the finished product. Many studies (Table 1) have analyzed convective drying of different varieties of carrots with diverse processing conditions, which have resulted in a variation of findings because different varieties of carrot respond differently to the drying process (Markowski et al., 2006). Drying behavior of different cultivars of the same crop may also vary due to the characteristics of the different varieties (Aboltins, Rubina, Palabinskis, & Jotautiene, 2016; Oke & Workneh, 2014). Furthermore, the experimental setup also impacts on the product response in terms of product quality. Therefore, more drying trials need to be undertaken for different varieties of carrots because the inadequacy of drying information related to the product quality of specific varieties of carrots generates quality-related problems for the industry, such as consumer and market acceptability. In light of this, there is a need to develop specific and

innovative drying strategies that simultaneously minimize the quality degradation of carrots, while maximizing the production efficiency under optimum operating conditions. Furthermore, drying is a nonlinear, dynamic, unsteady, and complex process that needs to be monitored with care because the process leads to different levels of quality degradation depending on factors such as properties of wet material, chemical composition, shapes, dimensions, and process parameters (Moscetti et al., 2017). Thus, monitoring the product quality throughout the entire drying process is crucial because it will influence the decision-making in selecting and developing proper drying strategies for carrots, as well as the information is needed for the development of noninvasive quality measurements for intelligent drying systems. Most of the previous research either reported on the quality of the product at the end of the drying period or described the quality degradation as a function of drying time rather than evaluating the influence of moisture content on quality changes throughout the drying process. This leads to a poor understanding of how the quality reacts to changes in moisture content and exposure time. Therefore, an intelligent approach needs to be explored, which optimizes the parameters throughout the entire drying process, in order to identify potential critical control points for parameter settings to realize the highest retention of the nutrients through optimized process control. Therefore, the aim of this study was to investigate the impact of drying settings and the influence of moisture content on drying behaviors and dynamic quality changes, such as color and total carotenoids content, throughout the entire drying process of carrots, as well as the optimization of the process parameters using response surface methodology (RSM). The results obtained will be fundamental in the designing of a quality-oriented innovative drying strategy for the improvement of the whole drying process in the future.

2 | MATERIALS AND METHODS

2.1 | Raw materials

Organic carrots (*var. laguna*) at optimum maturity of 3.5 months after planting were obtained from the University of Kassel's farm in

TABLE 1 Previous work on convective drying of different varieties of carrot

Variety	Type of dryer	Quality parameters	Reference
Not mentioned	Cabinet hot air dryer	Effective diffusivities, activation energy, and drying kinetics	Doymaz and Özdemir (2014)
Kazan, Maxima, Nandor, Nektarina, Simba, and Tito	Hot air dryer	Drying kinetics, rehydration capacity, color, water absorption	Markowski, Stankiewicz, Zapotoczny, and Borowska (2006)
Pusa Kesar	Solar cabinet hot air, fluidized bed dryer, and microwave dryer	Drying behavior, rehydration ratio, β -carotene	Prakash, Jha, and Datta (2004)
Nanco	Hot air dryer	Color, total carotenoids, nonenzymatic browning	Koca, Burdurlu, and Karadeniz (2007)
Chantenay	Hot air dryer	Mathematical modeling, effective diffusivities	Mulet, Berna, and Rossello (1989)
Nantes	Hot air dryer	Shrinkage, total carotenoids, total polyphenols, and antioxidant activity	Eim et al. (2013)

Frankenhausen, Kassel, Germany. The roots were stored in a low-temperature refrigerator at the commercially practiced storage temperature for carrots of $1^{\circ}\text{C} \pm 1$ (Liew & Prange, 1994). Prior to drying, the roots were washed with distilled water, peeled, and sliced to two different thicknesses (3 and 6 mm) using a food slicer (model E21EU, Graef, GmbH, Germany). The maximum thickness of 6 mm was chosen because severe browning occurs at greater thicknesses as a result of the longer drying time (Sra, Sandhu, & Ahluwalia, 2011). The outer diameter for each slice was kept constant at 2.5 ± 0.1 cm by using a custom-made rounded stainless steel cutter. The diameter of carrots was measured manually using a vernier caliper (Model 98618, Kinzo, Netherlands).

2.2 | Drying procedure

Drying experiments were conducted in a pilot-scale cabinet hot air dryer. The dimensions of the dryer are $50 \times 40 \times 60$ cm ($L \times W \times H$) and the air velocity of the dryer was kept constant at 0.6 m/s. For every drying trial, about 200 g of sliced carrots was placed as a single layer on the drying shelves of the cabinet dryer. Trials were performed at 50, 60, and 70°C . The temperature range used in this trial was selected in order to simulate the industrial drying of carrots (60°C), and because drying at temperatures higher than 70°C causes decomposition of flavors due to volatilization of valuable components (Correia, Loro, Zanatta, Spoto, & Vieira, 2015; Rawson, Tiwari, Tuohy, O'Donnell, & Brunton, 2011). Before each drying run, the dryer was started 1 hr in advance to attain steady-state conditions. The initial moisture content of the carrots was determined according to the AOAC method (Association Official Analytical Chemists, 2019) by drying the sample in an oven at 105°C for 24 hr (ULM 400, Mermert GmbH, Germany). The initial moisture content was recorded to be around $7.02 \text{ g}_w/\text{g}_{dm}$. The weight of the samples prior to moisture content determination was recorded in 30 min intervals during drying by weighing the samples manually using an electronic balance (model E2000D, Sartorius, Göttingen, Germany, readability 0.001 g) until the samples reached a final moisture content of $0.14 \pm 0.02 \text{ g}_w/\text{g}_{dm}$. It was decided to dry at this level because drying below $0.11 \text{ g}_w/\text{g}_{dm}$ (10% wet basis) accelerates the Maillard reaction causing brown discoloration in carrots (Eichner, Laible, & Wolf, 1985). Moreover, final moisture contents between 0.11 and $0.14 \text{ g}_w/\text{g}_{dm}$ are common in the industrial drying of carrots (Kowalski, Szadzińska, & Łechtańska, 2013). Water activity was measured at the end of the drying process using a water activity meter (Novasina, LabSwift model, Novasina AG, Switzerland) in order to ensure that the moisture content of the final product was safe for subsequent storage. For quality analysis, a total of four slices from four roots were withdrawn from the dryer at every measurement point of 30 min in order to ensure the consistency and traceability of the total carotenoid content throughout the drying period. A total of 12 slices from 12 roots were used for each setting in this experiment. All slices were vacuum packed, sealed, and kept at -30°C for further chemical analysis. All the drying experiments were

performed in triplicate and around 1,000 slices of carrot were chemically analyzed for total carotenoids content to ensure the accuracy of the results obtained.

2.3 | Total carotenoids

Total carotenoids content was determined according to the method reported by Moschetti et al. (2017), with minor modification, by extracting 100 mg of carrot tissue in 10 mL of solvent mixture of hexane, acetone, and ethanol (2:1:1). The solution mixture was homogenized for 2 min at 8000 rpm using a laboratory homogenizer (Model T25, IKA, Staufen, Germany) and incubated inside a refrigerator for 1 hr at 4°C , until the sample turned completely white, in order to ensure all the total carotenoids were fully extracted. Then, 5 ml of distilled water was added to the extracted sample to allow phase separation. The upper layer was separated from the aqueous phase and consequently subjected to assessment for total carotenoids by measuring the absorbance at a wavelength of 450 nm using a UV/Vis spectrophotometer (model Genesys™ 10 series, Thermo Electron Co). The total carotenoids content was determined using Equation (1).

$$\text{Total carotenoids mL}^{-1} = \frac{A \times V_1}{A_{1\%}} \times C^{1\%}, \quad (1)$$

where A is the absorbance reading of the sample, V_1 is the dilution factor, $A_{1\%}$ is the extinction coefficient of the 1% solution (i.e., 2500 AU), and $C^{1\%}$ is the concentration of the 1% solution (10 mg/ml). The total carotenoids content was converted to mg/g_{dm} based on dry matter content, and the concentration was expressed as a percent retention in this study.

2.4 | Degradation kinetics of total carotenoids

The degradation of total carotenoids during drying at 50, 60, and 70°C was modeled by applying Equations (2) and (3) for zero- and first-order reaction, respectively (Fратиanni et al., 2013):

$$C = C_0 - K_0 t, \quad (2)$$

$$\ln C = \ln C_0 - K_1 t, \quad (3)$$

$$\text{RMSE} = \frac{1}{N} \sum_{i=1}^n (\text{MR}_{\text{exp},i} - \overline{\text{MR}}_{\text{exp},i})^{1/2}, \quad (4)$$

where C is the concentration (%) at time t ; C_0 is the concentration (%) at time zero; K_0 is the zero-order rate constant (hr^{-1}); K_1 is the first-order rate constant (hr^{-1}); t is the drying time (hr). The efficiency of the fitted model was determined by the highest correlation coefficient (R^2) and the lowest root mean square error (RMSE). The reaction rate constant (K) for both models can be obtained from the slope of the linear Equations (2) and (3).

The activation energy (E_a) for total carotenoids degradation was calculated using the Arrhenius equation (Equation 5).

$$K = k_0 \exp\left(-\frac{E_a}{RT}\right), \quad (5)$$

where R is the universal gas constant (8.3142 kJ/mol), T is the absolute drying temperature in kelvin, and k_0 is the frequency factor or the Arrhenius constant (time^{-1}). The activation energy, E_a , can be obtained from the slope of $\ln K$ versus $1/T$, where K was obtained from Equations (2) and (3) for both zero- and first-order models.

2.5 | Calculation of the moisture ratio

The following equation was used to determine the moisture ratio (MR) of the carrot slices during the drying process (Botelho et al., 2011):

$$\text{MR} = \frac{M - M_e}{M_0 - M_e} \quad (6)$$

$$\text{MR} = \frac{M_t}{M_0} \quad (7)$$

where M (g_w/g_{dm}) is the moisture content at any given time t , M_0 is the initial moisture content, and M_e is the equilibrium moisture content. The MR was simplified to M_t/M_0 as in Equation (7) because the values of M_e are relatively small when compared with M_t or M_0 for long drying times (de Jesus Junqueira, Corrêa, de Oliveira, Avelar, & Pio, 2017; Doymaz, 2017).

2.6 | Calculation of effective moisture diffusivity and activation energy

The effective moisture diffusivity and activation energy are critical parameters for modeling and simulation of drying processes, and greatly depend on temperature and moisture content of the material (Darvishi, Farhudi, & Behroozi-Khazaei, 2017). The value of effective moisture diffusivity can be obtained from the Fick's second law of diffusion equation for a slab as described by Doymaz and Özdemir (2014) (Equation 8):

$$\text{MR} = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 Dt}{4L^2}\right). \quad (8)$$

A plot of $\ln \text{MR}$ versus time gives a straight line with a slope of $\pi^2 D_{\text{eff}}/4L^2$ where L is half the thickness of the slab in meters. The diffusivity coefficient can be obtained from the slope of Equation (8). The activation energy (E_a), which is the function of temperature, was calculated using the Arrhenius equation as in Equation (9), and the value can be obtained from the slope of $\ln D_{\text{eff}}$ versus $1/T$ as in Equation (10) (Doymaz & Özdemir, 2014):

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right), \quad (9)$$

$$K_1 = \frac{E_a}{R}. \quad (10)$$

2.7 | Measurement of color

Color measurements were performed using a Minolta chroma meter (model CR-400, Minolta Camera Co. Ltd. Osaka, Japan). The chroma meter was calibrated against a standard white reference tile prior to sample measurements. The color was measured on four slices from four roots at each measurement point for each replicate. Measurements were taken two times for each slice, and the values were averaged over the slice. The color measurements were performed based on the 3D color space of CIE $L^*a^*b^*$ scales where L represents the brightness of the color, a^* is the redness, and b^* is the yellowness (de Mendonça et al., 2017). From the color values, the total color change of ΔE was calculated using Equation (11), which is based on changes in color parameters of L , a^* , and b^* during the drying process.

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}, \quad (11)$$

where subscript "0" refers to the color reading of fresh carrot slices. Fresh carrots were used as a reference and a larger ΔE denotes a greater color change from the reference material (Akoy, 2014).

2.8 | Rehydration ratio

Dried samples from the same roots, which were used in the chemical analyses, were soaked in a water bath at 95°C for 10 min, removed from the water bath, and drained on a metal sieve for 5 min. Then, the excess water was carefully removed by blotting on filter paper for 2 min to ensure that all remaining water was fully drained before weighing. The weight of the drained carrots was recorded and the rehydration ratio was calculated as in Equation (12), which is based on the differences of the weight of the rehydrated sample (W_r) to the weight of the fresh samples before drying (W_0) (Lewicki, 1998):

$$\text{RR} = \frac{W_r}{W_0}. \quad (12)$$

2.9 | Statistical analysis for optimization of process parameter

A general multilevel factorial design with two continuous independent factors and several dependent responses was statistically analyzed using the RSM (Design-Expert® Software Version 9 [DX9], Stat-Ease, Inc., MN). The drying temperature was set at three levels of 50, 60, and 70°C, and the sample thickness was set at two levels of

thicknesses, 3 and 6 mm. The same experimental design was reported by Ogolla et al. (2019) for spray drying of camel milk. To obtain the regression coefficients, the experimental data were fitted to a second-order polynomial model indicated by Equation (13), with the general linear model approach:

$$y = \beta_0 + \beta_1 x_i + \beta_{ij} x_i x_j + \beta_{ii} x_{ii}^2 + \varepsilon, \quad (13)$$

where β_0 , β_1 , β_{ij} , and β_{ii} are the regression coefficients for the intercept and the linear, quadratic, and interaction terms, respectively, while y is the response, x_i and x_j are the independent variables, and ε is the non-explainable portion of variation (Gamboa-Santos, Soria, Fornari, Villamiel, & Montilla, 2013; Myers, Montgomery, Vining, Borror, & Kowalski, 2004). The coefficient of determination (R^2) was chosen to fit the polynomial equation. The robustness of the fitted equation was obtained by controlling the difference between adjusted R^2 and predicted R^2 (desirable diff < 0.2) via an iterative manual backward model selection with only significant terms considered for a final model. The significance of the regression coefficients was confirmed by multifactorial analysis of variance (ANOVA) and Fisher's F test at $\alpha = 0.05$ (Bruns, Scarminio, & de Barros Neto, 2006). The interactions between drying air temperatures, slice thickness, and the responses were derived from the regression models and visualized using 3D response surface plots. The coefficient estimates are shown for coded factors. The actual factor levels are standardized in a range from -1 for the lowest actual level to $+1$ for the highest actual level of a certain factor (Table 7). As the second step, the multiresponse goal conflict was optimized using Derringer's desirability function. The settings of the factors leading to the highest desirability D represent the best operation point of the drying process achieved in the experiment (Sturm, Hofacker, & Hensel, 2012; Sturm, Vega, & Hofacker, 2014; Yolmeh, Najafi, & Farhoosh, 2014).

3 | RESULTS AND DISCUSSION

3.1 | The effect of drying temperature and thickness on drying time and drying rate

The results from Figures 1 and 2 indicate that the drying time to achieve the desired level of moisture content as in Table 2 is greatly dependent on slice thickness and temperature. These are commonly known facts that have been reported by other researchers for carrot drying and many other products, with results depending on shape, dimension, drying methods, and parameter settings (Zielinska & Markowski, 2012; Eim et al., 2013; Koca et al., 2007). However, these previous works were based on different varieties of carrots that were sourced from different locations across the world. Markowski et al. (2006) reported that different varieties of carrots with the same dimensions responded differently during drying treatments causing a variation in drying characteristics. The differences are due to divergence in the varieties, food matrix, structure, tissue, and chemical composition within the crop as explained further by Capuano,

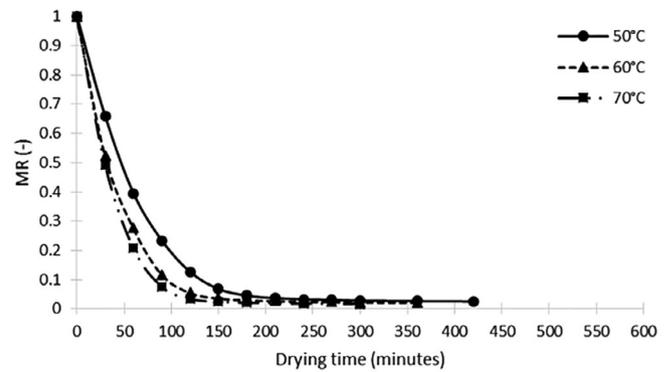


FIGURE 1 Moisture ratio (MR) versus drying time at different temperatures of carrot for 3 mm of slice thickness

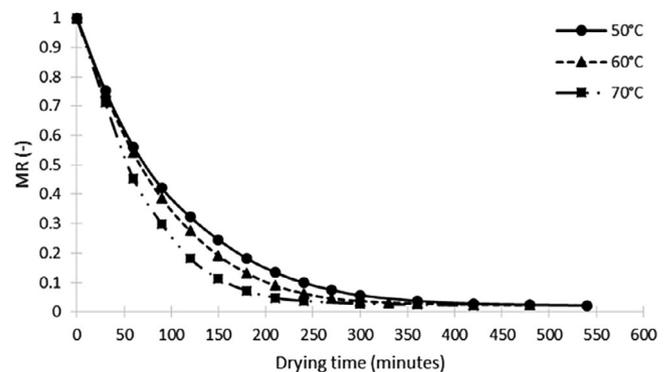


FIGURE 2 Moisture ratio (MR) versus drying time at different temperatures of carrot for 6 mm of slice thickness

TABLE 2 Final moisture content and water activity of carrot at different temperatures and thicknesses

Drying temperature (°C)	Thickness (mm)	Final moisture content (g_w/g_{dm})	Water activity
50	3	0.144	0.346
	6	0.142	0.351
60	3	0.138	0.361
	6	0.144	0.361
70	3	0.139	0.366
	6	0.141	0.342

Oliviero, and van Boekel (2017). The authors explained in detail that all the variations will generate different levels of chemical reactions within the food matrix when subjected to thermal treatments, such as drying, which consequently may influence the drying behavior due to changes in thermal properties. Water activity of the final product was also measured at the end of drying experiments in order to ensure a safe level of water activity for subsequent storage. The values of water activity were between 0.342 and 0.361 (Table 3), which is a recommended level for storage stability of carrots (Lavelli, Zanoni, & Zaniboni, 2007). The results obtained were contradictory with

TABLE 3 Correlation between total color changes (ΔE) and total carotenoids of carrots at different temperatures and thicknesses presented by polynomial equations

Drying temperature ($^{\circ}\text{C}$)	Thickness (mm)	Polynomial equations	R^2
50	3	$\Delta E = -0.0003C^3 + 0.0607C^2 - 3.9862C + 95.125$	0.9693
	6	$\Delta E = -7E - 07C^5 + 0.0003C^4 - 0.0371C^3 + 2.5406C^2 - 85.399C + 1,135$	0.9115
60	3	$\Delta E = -0.0067C^2 + 0.9627C - 27.506 - 0.144$	0.9093
	6	$\Delta E = -0.0005C^3 + 0.1051C^2 - 8.1171C + 215.12$	0.9662
70	3	$\Delta E = -0.0005C^3 + 0.1061C^2 - 7.4442C + 180.99$	0.8088
	6	$\Delta E = -7E - 06C^4 + 0.002C^3 - 0.1843C^2 + 7.3064C - 92.958$	0.9527

Notes: ΔE is the total color change and C is the total carotenoid amounts.

TABLE 4 Retention of total carotenoids at the end of drying process

Drying temperature ($^{\circ}\text{C}$)	Thickness (mm)	Final moisture content (g_w/g_{dm})	Retention of total carotenoids (%)
50	3	0.14	47.5
	6	0.14	51.1
60	3	0.14	66.2
	6	0.14	62.7
70	3	0.14	46.4
	6	0.14	42.2

TABLE 5 Kinetics parameters for thermal degradation of total carotenoids at different temperatures

Degradation models	K (hr^{-1})	R^2	RMSE
Zero-order kinetics			
50 $^{\circ}\text{C}$, 3 mm	0.060	0.98243	0.267666
60 $^{\circ}\text{C}$, 3 mm	0.072	0.98772	0.000181
70 $^{\circ}\text{C}$, 3 mm	0.108	0.97985	0.000403
50 $^{\circ}\text{C}$, 6 mm	0.048	0.97446	0.001132
60 $^{\circ}\text{C}$, 6 mm	0.054	0.97852	0.000738
70 $^{\circ}\text{C}$, 6 mm	0.078	0.98366	0.000920
First-order kinetics			
50 $^{\circ}\text{C}$, 3 mm	0.012	0.98594	0.001201
60 $^{\circ}\text{C}$, 3 mm	0.072	0.99331	0.000181
70 $^{\circ}\text{C}$, 3 mm	0.162	0.98597	0.000786
50 $^{\circ}\text{C}$, 6 mm	0.048	0.95361	0.006222
60 $^{\circ}\text{C}$, 6 mm	0.108	0.97686	0.024196
70 $^{\circ}\text{C}$, 6 mm	0.120	0.98218	0.001325

previously published study on sorption isotherms, which show that moisture content of 0.14 g_w/g_{dm} results in a water activity of >0.6 (Kaya, Aydın, & Demirtaş, 2009). The present study, however, shows decidedly lower water activity at these moisture contents. This can be explained by the fact that water activity is a function of chemical

components, physicochemical state, porosity, temperature, and surface tension (Rahman and Labuza, 2007). Therefore, the same level of moisture content at the same temperature will result in different levels of water activity due to differences in varieties and/or chemical composition within one variety caused by different growing conditions (Bajaj, Kaur, & Sukhija, 1980; Brunsgaard, Kidmose, Sørensen, Kaack, & Eggum, 1994).

Drying characteristics of carrots can be obtained from the drying curves as displayed in Figures 1 and 2. When drying at 50, 60, and 70 $^{\circ}\text{C}$, the time taken to reach the desired moisture content for 3 mm slice thickness was 420, 360, and 300 min, respectively. The required time is significantly increased for 6 mm slice thickness with total drying times of 540, 480, and 420 min. The increment of 2 hr drying time for all temperatures studied, when the thickness is doubled from 3 to 6 mm, was similar to those reported by Sonmete, Mengeş, Ertekin, and Özcan (2017). The authors observed that the increment in total drying time for 6 mm thickness, as compared with 3 mm thickness, was not higher than 2 hr when drying at 55, 65, and 75 $^{\circ}\text{C}$ with an airflow of 2.0 m/s. The authors reported total drying times of approximately 4.3, 3.3, and 2 hr for 3 mm thickness when dried at 55, 65, and 75 $^{\circ}\text{C}$ with an airflow of 2.0 m/s and around 6, 4, and 3 hr when drying under the same conditions for 6 mm. The increase in drying time with an increase in slice thickness must be due to the lower surface area-to-volume ratio, and the longer distance for the moisture to travel from the inside of the material to the surface (Kek, Chin, & Yusof, 2014). In other words, the drying rate will increase as the temperature increases, and the slice thickness decreases due to shorter transport distance and an increased relative of heat and mass transfer (Figure 3). Furthermore, the thermal gradient between drying air and drying material increases with increasing temperatures, causing an increase in heat transfer and drying rates (Sturm et al., 2012). The differences in energy consumption for heat and mass transfer cause thicker samples to require more energy to evaporate internal moisture to the surface as explained by Wang and Xi (2005). This reflects the longer drying time for thicker samples with lower drying rates when compared with high drying rates in thinner samples. Thicker samples also have a higher level of dry solid than thinner samples leading to longer drying times because, according to Geankoplis

(2018), drying time is always proportional to weight of the dry solid.

The graph for both thicknesses for all drying temperatures (Figure 3) showed that there is no constant drying rate period observed in this experiment, and drying takes place in the falling rate period, which indicates that the liquid diffusion is controlling the drying process as described by Aghbashlo, Kianmehr, and Samimi-Akhlijahani (2008). Similar findings were reported by previous studies where only the first and second falling rate periods occurred (Bobic, Bauman, & Curic, 2001; Hatamipour & Mowla, 2002; Planinić, Velić, Tomas, Bilić, & Bucić, 2005; Prakash et al., 2004). Dynamic changes in moisture transport mechanisms, such as surface diffusion, pore diffusion, capillary flow, evaporation, and thermodiffusion, influence the rate of moisture removal throughout the drying process as mentioned by Aboltins et al. (2016).

3.2 | Effect of drying on effective diffusivity and activation energy

The effect of drying temperature on the effective diffusivity and activation energy was described by Fick's law and the Arrhenius

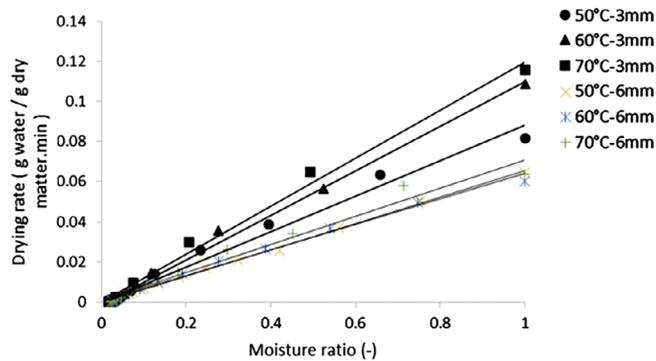


FIGURE 3 Effect of drying temperature on drying rate for 3 and 6 mm of slice thicknesses

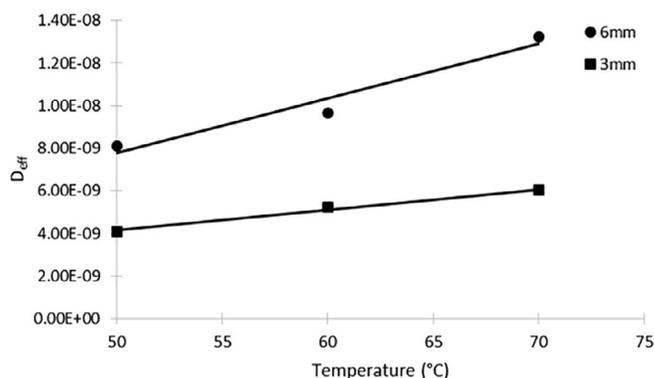


FIGURE 4 Coefficient of effective diffusivity, D_{eff} (m^2/s), obtained for the drying of carrot

relationship as shown in Equations (9) and (10). The plot of effective diffusivity in Figure 4, D_{eff} versus temperature was a straight line, which indicates the temperature dependence for all investigated temperatures. The values of effective diffusivity as displayed in Figure 4 were found to be in the range of 2.705×10^{-10} to $4.011 \times 10^{-10} m^2/s$ for 3 mm thickness and 5.409×10^{-10} to $8.813 \times 10^{-10} m^2/s$ for 6 mm thickness. The values were comparable with the previous findings reported by other researchers at varying temperatures, such as on apple slices at 1.79×10^{-9} to 4.45×10^{-9} (Velic, Planinic, Tomas, & Bilic, 2004), carrot cubes at 0.776×10^{-9} to $9.335 \times 10^{-9} m^2/s$ (Doymaz, 2005), and sliced carrots at $1.371 \times 10^{-7} m^2/s$ (Markowski, 1997). According to Sacilik and Elicin (2006), the differences among the values could be due to the different crops and varieties, as well as different parameter settings and drying equipment or other uncontrollable parameters during drying.

The values of effective diffusivity (D_{eff}) were found to increase with increased temperature (Figure 4) for both thicknesses. Drying at $70^\circ C$ for 6 mm thickness gave the highest D_{eff} value of $8.813 \times 10^{-10} m^2/s$ as compared with drying at 50 and $60^\circ C$ with D_{eff} values of $5.409 \times 10^{-10} m^2/s$ and $6.442 \times 10^{-10} m^2/s$, respectively. This might be due to a higher volume-to-surface ratio, which results in a higher moisture distribution in thicker samples and, consequently, increases the rate of moisture movement as explained by Wang and Xi (2005). Similar results were obtained for apples (Meisamiasl, Rafiee, Keyhani, & Tabatabaeefar, 2010), garlic (Rasouli, Seiedlou, Ghasemzadeh, & Nalbandi, 2011), papaya (Sairam, Kumar, Edukondalu, & Kumar, 2017), and tomato (Akhijani, Arabhosseini, & Kianmehr, 2016). It was documented that the overall effective moisture diffusivity rate for agricultural products was in the range of 10^{-7} to $10^{-11} m^2/s$ (Aghbashlo et al., 2008; Babilis & Belessiotis, 2004).

The activation energy, which is temperature dependent, can be obtained from the slope of the straight line of the Arrhenius equation as displayed in Figure 5. The activation energy for carrots calculated from this study is 16.386 and 20.292 kJ/mol for 3 and 6 mm thickness, respectively. Higher activation energy values were observed in thicker samples due to longer distances for moisture transport, causing higher energy requirements for heat transfer. The range of

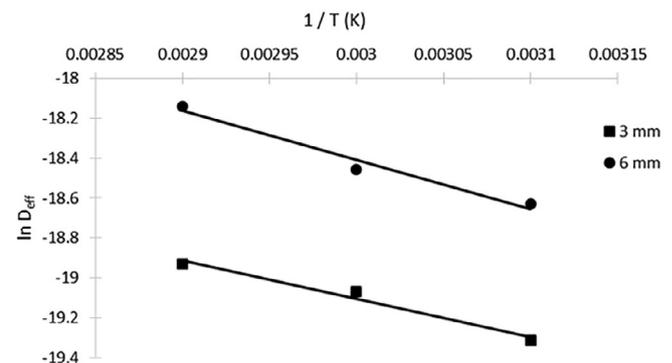


FIGURE 5 The Arrhenius representation of the natural logarithmic coefficient of diffusivity as a function of drying temperature of carrot

activation energy for agricultural produce was reported to be from 12.7 to 110 kJ/mol (Zogzas, Maroulis, & Marinos-Kouris, 1996). Thus, the results obtained in this study were still within the acceptable range of documented data.

3.3 | Dynamic quality changes of carrot during drying

3.3.1 | Color characteristics

Color characteristics are the most common parameter measured in dried food products as they are one of the first quality attributes that could be visualized by a consumer (Chua, Mujumdar, Chou, Hawlader, & Ho, 2000). The dynamic changes in color throughout the drying process could be observed by total color changes of ΔE . The results from the experiment showed that minimal ΔE (Figure 6) was obtained for 3 mm sample thickness when drying at 60°C. Changes in ΔE were related to changes in L , a^* , and b^* values during drying. Maximum total color changes of the final product were observed for 6 mm samples when dried at 50°C and followed by 3mm sample dried at 70°C (Figure 7) with values of ΔE being 14.2 and 10.8, respectively. Drying at 50°C led to greater color changes for both thicknesses than at the other temperatures. This is most likely due to the longer drying time at lower temperatures leading to longer exposure time to hot air and, consequently, causing an increase in color degradation.

The changes in ΔE values were more noticeable at reduced moisture content of less than 0.45 g_w/g_{dm} for a thicker sample of 6 mm when dried at 50 and 60°C and also for a thinner sample of 3 mm when dried at 70°C (Figure 6). The trends were apparent for all process settings, especially when drying at 50 and 60°C where the changes were slow and almost linear at a higher moisture content until it reaches the inflection point at the lower moisture content of 0.45 g_w/g_{dm} . The greater changes in color are due to the increase in absolute values of L with a decrease in values of a^* due to longer drying times or higher drying temperature. The results

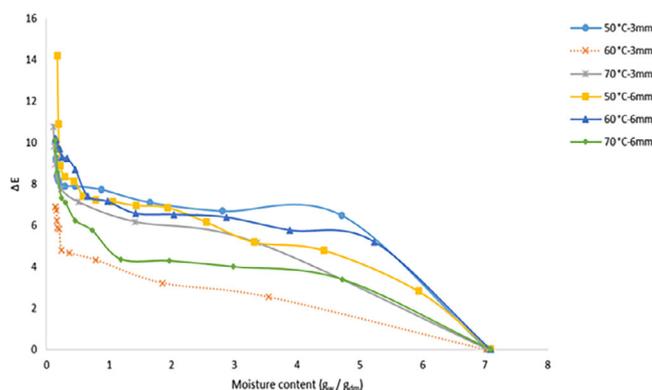


FIGURE 6 Total color difference of ΔE value of carrot at different drying temperatures

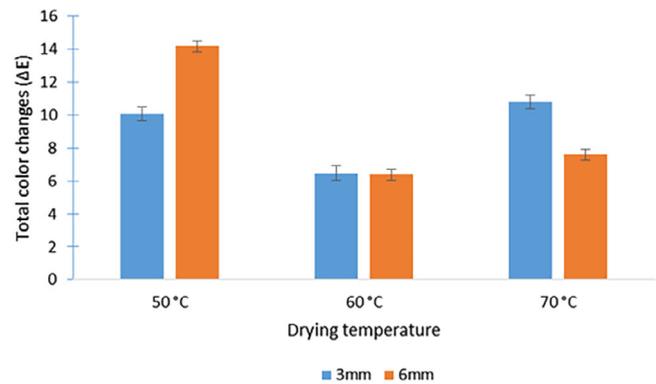
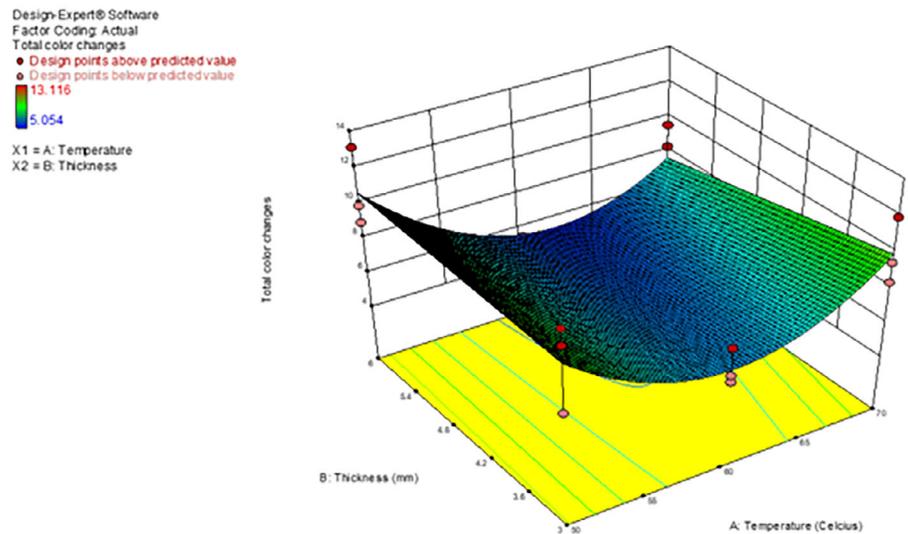


FIGURE 7 Total color changes (ΔE) of the final product for carrot at different drying temperatures and thicknesses

indicate that the orange color of the final product gets lighter, or decreases in brightness, due to longer drying times for thicker samples. The degradation of color in terms of L , a^* , and b^* in carrots might correspond to the degradation of thermolabile components of carotenoids, which will be discussed in the next section on dynamic changes of total carotenoids. The degradation is very likely due to autoxidation of total carotenoids under the influence of rigorous operating conditions (Zielinska & Markowski, 2012). Additionally, the oxidation of carotenoids causes losses in color and flavors due to formation of colorless lower molecular weight reaction products such as β -ionone and β -damascenon, which leads to pigment degradation in carrots (Sturm & Hensel, 2017). Samples dried at 50 and 70°C for both thicknesses showed lower color retention while drying at 60°C resulted in minimal color degradation (Figure 8). The results confirm that drying temperature significantly ($p < .05$) affected the color parameters L , a^* , and ΔE values of carrots, while the b^* value was affected by both drying temperature and thickness, as shown in Table 6.

Many studies with different results reported on the effect of drying temperature and thicknesses on color changes of agricultural crops. It was observed that color retention of the dried product greatly depends on cultivars, preprocessing treatments, and process parameters as reported by Onwude, Hashim, and Chen (2016) on pumpkin, Akoy (2014) on hot air-dried mango, (Hafezi, Sheikhdavoodi, & Sajadiye, 2016) on sliced potato, Kulshreshtha, Singh, and Vipul (2009) on mushroom, Joshi, Orsat, and Raghavan (2009) on sliced tomato, and Sturm et al. (2012 and 2014) on apples. The obtained results from this experiment confirm that both temperature and duration of exposure time during drying greatly affect the color retention of sliced carrots and can be correlated with chemical instability of total carotenoids as influenced by moisture content and process parameters. This will be discussed further in the next section on dynamic changes of total carotenoids during drying. The findings are similar to those of Zielinska and Markowski (2012) who demonstrated that changes in the color of carrots during processing are related to degradation of total carotenoids. Sturm and Hensel (2017) also reported that pigment discoloration could be linked to

FIGURE 8 Response surface of total color changes (ΔE) at different temperatures and thicknesses**TABLE 6** Color parameters, rehydration ratio and total carotenoids of dried carrot as influenced by drying temperature and thickness

Regression coefficient (β)	L^*	a^*	b^*	ΔE	Rehydration ratio	Total carotenoids
Intercept β	61.76	22.34	39.33	5.99	0.45	159.02
Linear						
Temperature (A)	-1.28	-0.73*	1.39	-0.82	-0.023*	4.03
Thickness (B)	-0.56	-0.50	-1.57	-0.45	-0.032**	-7.28
Quadratic						
Temperature (A^2)	3.04*	-2.42***	0.42	3.57*	-0.011	-48.20***
Thickness (B^2)	-	-	-	-	-	-
Cross product (2F1)						
Temperature*	0.24	-0.019	-0.96*	-0.72	-0.026**	-2.51
Thickness (AB)						
R^2	0.5085	0.7663	0.435	0.5548	0.7692	0.7443
F value (model)	3.36*	9.29**	2.50	3.43*	10.83**	9.46**
F value (lack of fit)	0.8568	0.2213	0.5283	0.9369	0.4595	0.2574

Notes: * $p < .05$; ** $p < .001$; *** $p < .0001$.

TABLE 7 Conditions and outputs of the numerical optimization of the responses for drying of carrot

Factor/parameter	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
Temperature ($^{\circ}C$)	Is in range	50	70	-1	+1	3
Thickness (mm)	Is in range	3	6	-1	+1	3
L^*	58.16	56.368	67.403	-1	+1	1
a^*	23.10	18.438	24.095	-1	+1	5
b^*	40.351	34.96	46.613	-1	+1	1
ΔE	Minimize	5.054	13.116	-1	+1	5
Rehydration ratio	Maximize	0.3297	0.509	-1	+1	1
Total carotenoids (%)	Maximize	31.138	79.622	-1	+1	5

degradation of carotenoids due to enzymatic and nonenzymatic browning, which increased with increasing temperatures. Other authors also confirmed that a strong correlation was found between color and

total carotenoids content in pumpkin and squash (Itle & Kabelka, 2009), pequi (Ribeiro, Fernandes, Alves, & Naves, 2014), and apricot (Ruiz, Egea, Tomás-Barberán, & Gil, 2005). Therefore, from this study,

we can conclude that color changes during drying can be a good indicator for carotenoids retention in carrots. The correlations for color and total carotenoids (Table 3) are best described by polynomial equations with a high accuracy of R^2 between 0.81 and 0.97, and it can be used to predict the retention of color and total carotenoids at any given time during drying. A similar trend was reported by Saxena, Maity, Raju, and Bawa (2012) on color degradation of jackfruit. The authors reported that polynomial equations were found adequate to model the relationship between visual color and total carotenoids content of jackfruit.

3.3.2 | Dynamics of total carotenoids' changes during drying

Figures 9 and 10 show the retention of total carotenoids as a function of moisture content for the tests undertaken in this study. The results show that drying at 60°C for both thicknesses retained a higher level of total carotenoids as compared with drying at 50 and 70°C. The retention of total carotenoids at the end of the drying period was 66.2 and 62.7% when dried at 60°C for 3 and 6 mm thickness, respectively (Table 4). The retention of total carotenoids for 3 mm and 6 mm

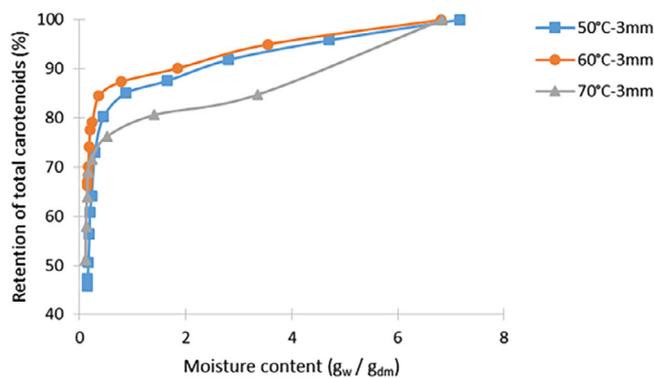


FIGURE 9 Retention of total carotenoids in carrot at different temperatures as a function of moisture content for 3 mm thickness

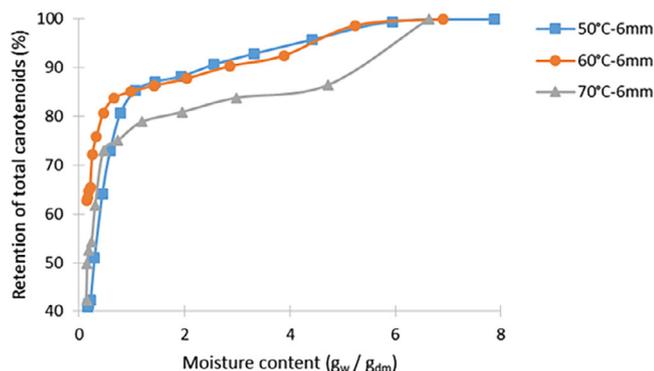


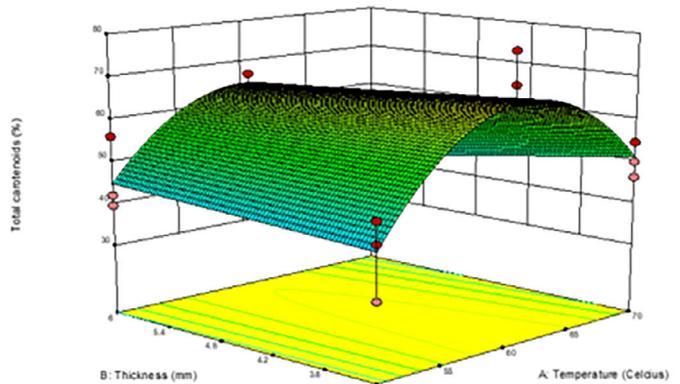
FIGURE 10 Retention of total carotenoids in carrot at different temperatures as a function of moisture content for 6 mm thickness

thickness at 70°C was 46.4 and 42.2% while drying at 50°C retained 47.5% of total carotenoids for 3 mm thickness and 51.1% for 6 mm thickness. The observed degradation was greater for samples dried at 70 and 50°C for both thicknesses. The high losses of total carotenoids must be due to thermal degradation at an elevated temperature of 70°C and long exposure time at 50°C as explained by Karabulut, Topcu, Duran, Turan, and Ozturk (2007). Moreover, thermal damage of carotenoids occurs at elevated temperature due to severe cellular destruction that could speed up the losses via oxidation (Kaimainen, 2014; Schwartz, Elbe, & Giusti, 2008). According to Zielinska and Markowski (2012), carotenoid degradation can be caused by lipid peroxidation, which may affect the color due to nonenzymatic browning. Nonenzymatic browning occurs due to the reactions of food components such as amines with carbonyl groups of reducing sugars (aldehydes and ketones), which participate in the chain of Maillard reactions and lead to the formation of brown pigments or colored polymers such as melanoidins resulting in the loss of carotenoids (Potes, Lim, & Roos, 2017). Carbonylic compounds are a chemically organic functional group of a carbon atom double bonded to an oxygen atom formed through oxidation, which leads to degradation of total carotenoids (Boon, McClements, Weiss, & Decker, 2010). The results from Figures 9 and 10 also show that linear degradation of total carotenoids could be observed at higher moisture contents of more than 0.45 g_w/g_{dm} , which demonstrates slow degradation of total carotenoids at the early stage of drying for samples dried at 50 and 60°C. At this point, the membrane integrity of the tissue was still intact and consequently reduced degradation of nutrients, such as total carotenoids, from thermal damage, which has been explained further by Karim and Adebawale (2009) and Kaimainen (2014). It is also possible that the endogenous water-soluble antioxidative components, such as ascorbic acid, amino acids, bioflavonoids, and other polyphenolic compounds, present in carrots protect the total carotenoids from thermal degradation at the initial stage of drying when the moisture content is still high (Arya, Natesan, Parihar, & Vijayaraghavan, 1979; Karim & Adebawale, 2009). However, rapid losses of total carotenoids were observed for samples dried at 70°C at the early stage of drying for both thicknesses. This is probably due to rapid heating at high temperature that could speed up the moisture losses on the surface and ultimately promote the degradation of total carotenoids as a result of exposure to hot air (Pan, Wu, Li, Mujumdar, & Kudra, 1997).

The results from this study have proven that total carotenoids, which are fat-soluble pro-vitamin A, are stable in high moisture system at optimum temperature of 60°C because the presence of sufficient water on the surface of sliced carrots at the early stage of drying provides maximum resistance from oxidation as described by Ramakrishnan and Francis (1979). However, drying at 70°C causes degradation of total carotenoids due to thermal damage at elevated temperature. It could be observed that a distinct reduction in retention occurred at lower moisture contents of 0.45 g_w/g_{dm} and less for all temperatures studied, showing that the critical degradation lies in this area at the point where appropriate process and parameters settings need to be employed. During this period, it could be assumed

FIGURE 11 Response surface of total carotenoids at different temperatures and thicknesses

Design-Expert® Software
Factor Coding: Actual
Total carotenoids (%)
● Design points above predicted value
● Design points below predicted value
79.622
31.138
X1 = A: Temperature
X2 = B: Thickness



that the internal temperature of the slices increased as the drying proceeds, causing a reduction in moisture content that could possibly disrupt the cellular structure leading to rapid degradation of nutrients (Karim & Adebawale, 2009). The degradation of total carotenoids at this point may be correlated with the phase transition from the second phase to the third phase of drying at which point the rate of water evaporation inside the samples decreases due to depletion of moisture, causing a lower transfer of water to the surface area and, ultimately, nutrient losses. Karim and Adebawale (2009) also mentioned that degradation of nutrients depends on moisture content and temperature. Similar results were reported by (Pan et al., 1997) who found that the degradation of β -carotene, which is the major carotenoid in carrots, was observed to be higher at the final drying stage, in other words at a lower moisture content, due to the overheating of the surface layers when subjected to vibro fluidized bed drying. Similar findings were reported by Suvarnakuta, Devahastin, and Mujumdar (2007) on drying of carrots under an oxygen-free environment using a low pressure superheated steam dryer, where the retention of β -carotene was greater at a higher MR and reduced dramatically at a lower MR of roughly around 0.22. The trend was similar to the changes in ΔE , as discussed in the previous section, which indicates that the color changes during drying of carrots are highly correlated with degradation in total carotenoids and the level of degradation is highly dependent on the moisture content in question. Ramakrishnan and Francis (1979) found that the moisture content greatly influenced the color deterioration of the carotenoid pigments of a model food in a cellulose system where minimal degradation rate of color and carotenoids was found in high moisture samples. The optimization results from ANOVA (Table 6) also showed that the thickness of the samples did not significantly affect the degradation of carotenoids. However, drying temperature and exposure time to the hot air were found to have the most dominant effect on degradation of carotenoids, which directly affected the color retention in carrot. Previous studies by Zielinska and Markowski (2012) also reported on degradation of carotenoids at different drying times on carrot cubes and Goula and Adamopoulos (2010) on blanched carrot. Both studies found that degradation of total carotenoids was greatly affected by high

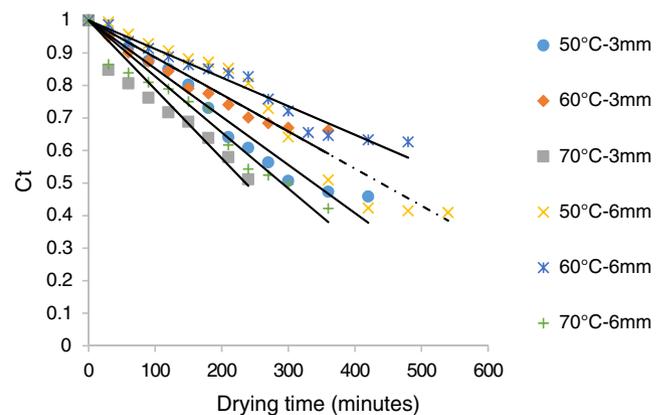


FIGURE 12 Zero-order degradation kinetics of total carotenoids at different temperatures and thicknesses

temperatures and duration of the drying process. Although many researchers have reported on losses of total carotenoids during drying, the knowledge on dynamic changes of total carotenoids as a function of moisture content along the drying process, which has been described in this study, is not mentioned in other studies. Therefore, from the results, it could be concluded that drying at 60°C leads to highest retention of carotenoids (Figure 11).

3.3.3 | Degradation kinetics of total carotenoids

In general, the degradation kinetics of nutrients in food is influenced by moisture content and temperature in the food system. Since food products are exposed to a wide range of temperatures and different levels of moisture removal during drying, kinetic models are needed to predict the evolution of nutrients of interest with time (Karim & Adebawale, 2009). Degradation kinetics of total carotenoids in carrots, shown in Figures 12 and 13, were modeled using Equations (2) and (3) because quality degradation of food, as affected by thermal processes, normally followed zero- and first-order reaction kinetics (Maiti, Raju, & Bawa, 2012). The linear plots showed that degradation of total

carotenoids for thinner samples (3 mm) followed first-order kinetics, and thicker samples (6 mm) were best represented using zero-order kinetics for all temperatures studied. The selection of the best model is based on the R^2 value and RMSE as in Table 5. The activation energy values for degradation of carotenoids for the first-order model were 35.61 kJ/mol for 6 mm and 40.60 kJ/mol for 3 mm. The higher activation energy for 3 mm thickness indicated that the degradation of total carotenoids is more temperature sensitive (Dutta, Dutta, Raychaudhuri, & Chakraborty, 2006) than at the higher thickness. The results demonstrated that the activation energy for degradation of carotenoids obtained from this experiment was adequate

to cause discoloration of the product as stated by Lee and Kim (1989). The authors stated that the activation energy for degradation of carotenoids between 32.2 and 114.5 kJ/mol will most likely cause the discoloration of the product, which can be correlated with losses of color in carrots as explained in the previous section. Different levels of kinetics parameters for degradation of carotenoids particularly β -carotene were documented in the literature (Pénicaud, Achir, Dhuique-Mayer, Dornier, & Bohuon, 2011). These variations may be due to different processing conditions, chemical composition of different crops, and the presence of acids, iron, free radicals, and metal catalysis, which influence the degradation kinetics (Boon et al., 2010). Modeling quality degradation along the drying process is important in order to predict the retention of total carotenoids at any given time of drying, so that better process control could be developed in order to improve the process efficiency and quality retention.

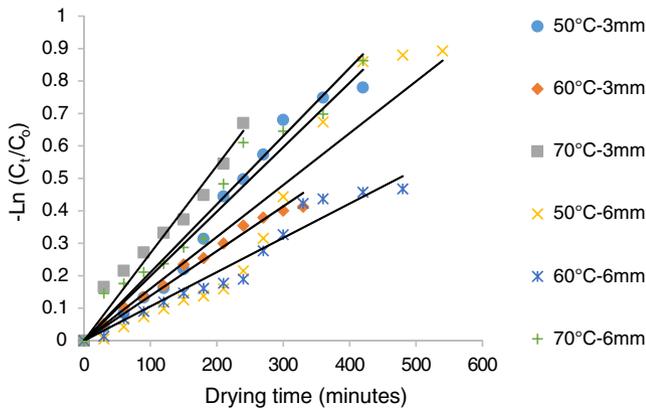


FIGURE 13 First-order degradation kinetics of total carotenoids at different temperatures and thicknesses

3.4 | Rehydration ratio

Rehydration ratio is one of the most important quality attributes in dried materials because most of the dehydrated products must be rehydrated for their final use (Akoy, 2014). The ratio indicates the capability of the material to restore to its original state by absorbing water after drying. The results obtained showed that drying at a high temperature of 70°C for 6 mm slice thickness reduced the rehydration ratio significantly ($p < .05$) when compared to drying at 50 and 60°C

Design-Expert® Software

Factor Coding: Actual
Rehydration ratio

- Design points above predicted value
- Design points below predicted value



X1 = A: Temperature
X2 = B: Thickness

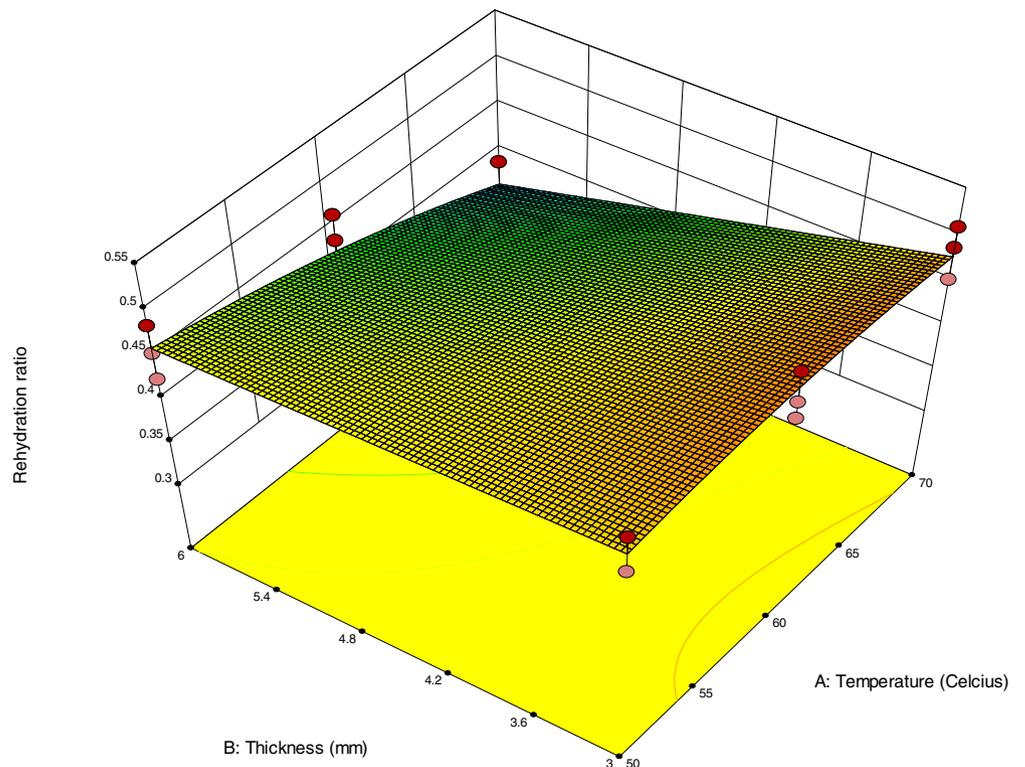


FIGURE 14 Response surface of rehydration ratio at different temperatures and thicknesses

(Figure 14; Table 6). Drying at a lower temperature of 50 and 60°C had shown better rehydration capacity for 3 mm thickness of dried samples. This must be due to minimal cellular destruction and dislocation, which occur at lower temperatures, so that the material is capable of absorbing more water (Nour, Trandafir, & Ionica, 2011). However, the rehydration capacity was decreased for thicker samples of 6 mm when drying at 70°C because the structural damage and shrinkage are more severe when dehydrated at high temperatures causing lower rehydration ratios for thicker samples. Furthermore, drying at 70°C causes higher drying rates at the initial stage, which might lead to case hardening of the product surface that results in the formation of dense structure (Krokida & Maroulis, 2000). This will limit the water migration from the solution into the dried samples due to decreased ability of the dried materials to absorb water. Additionally, substantial amounts of soluble solids might be leached into the external water during rehydration, hence affecting the nutritional quality of the products and, simultaneously, its ability to absorb water (Vega-Gálvez et al., 2015). It may be noted that a higher rehydration ratio indicates a better product. The results also proved that slice thickness greatly affected the rehydration ratio of carrots (Table 6). Similar results were observed for potato (Hafezi et al., 2016), apples (Sturm, 2010), and mushrooms (Kumar, Lalmani, & Singh, 2014; Nour et al., 2011).

3.5 | Optimization of process parameters

The optimum conditions for drying of organic carrots were determined from the following RSM in order to obtain optimal color parameters ($L^*a^*b^*$) with minimal ΔE , a maximum rehydration ratio, and also the highest retention of total carotenoids. These target-dependent variables were categorized according to their importance (Table 7). The most important was categorized as an importance of 5 while the independent variables were automatically categorized as an importance of 3. In the case of the color parameters L , a^* , and b^* , the target values were set to similar values of the fresh carrot. The settings for all goals for the best solutions of the optimization resulted in a

TABLE 8 Desirable solutions for the optimization of organic carrot drying

Factors	Optimal conditions
Temperature (°C)	59.77
Thickness (mm)	3.48
Parameters	Predicted values
L^*	62.177
a^*	22.455
b^*	40.351
ΔE	6.310
Rehydration ratio	0.476
Total carotenoids (%)	67.38
Desirability	0.781

TABLE 9 Fitted second-order polynomial and linear equations for the quality parameters of dried carrot in terms of coded factor

Response	Model
L^*	$61.76 - 1.28A + 3.04A^2$
a^*	$22.34 - 0.73A - 2.42A^2$
b^*	$39.33 - 1.57B$
ΔE	$5.99 - 0.82A + 3.57A^2$
Rehydration ratio	$0.45 - 0.023A - 0.032B - 0.026AB$
Total carotenoids	$159.02 + 4.03A - 48.2A^2$

Notes: A is the drying temperature (°C), B is the slice thickness (mm), and AB is the interaction between temperature and thickness.

desirability value of 0.781, as presented in Table 8. Gamboa-Santos et al. (2013) and Eim et al. (2013) also reported on the optimization of carrot drying using different setting parameters, shapes, dimensions, and quality attributes. However, those authors used different designs of experiment and processing software resulting in different desirability values for optimization.

The drying temperature of 59.8°C and slice thickness of 3.5 mm were found to be the most desirable solutions for the optimum parameters for drying of carrots when all response variables were set as important. Under optimized conditions (Table 8), the predicted values for L , a^* , b^* , ΔE , rehydration ratio, and total carotenoids at 95% prediction interval were 62.18 ± 5.12 , 22.46 ± 1.98 , 40.35 ± 6.64 , 6.31 ± 4.74 , 0.48 ± 0.07 , and $163.83 \pm 17.38 \mu\text{g/g}$ or 67.38%, respectively. All the quality parameters can be modeled mathematically using linear and polynomial functions as in Table 9. The optimization results indicate that the drying temperature significantly influences the color parameters, total color changes (ΔE), rehydration ratio, and retention of total carotenoids (Table 6). It is also possible that the experimental setup during drying also influences the quality retention of dried materials. However, optimizing the quality of the final product in this study, which is based on the black box concept, can only predict the quality of the product at the end of the process without considering the quality transformation along the drying process. The optimization should include information of the quality changes as a function of moisture content, which can be advantageous for the industry because it could potentially be applied to online measurement that could provide more reliable and faster results when performing routine analysis for quality assurance than existing conventional laboratory methods, which are always laborious and time consuming. Therefore, this study demonstrates the importance of monitoring the quality changes of carrots throughout the drying process because it has a significant impact on the quality of the end product.

4 | CONCLUSION

The study has shown that the drying characteristics and final quality of dried organic carrot are highly dependent on process parameters.

The effective diffusivity increased with an increase in drying temperature and decreased with a reduction in slice thickness. The values of effective diffusivity were in the range of 2.705×10^{-10} to 4.011×10^{-10} m²/s for 3 mm thickness and 5.409×10^{-10} to 8.813×10^{-10} m²/s for 6 mm thickness for all temperatures studied. The activation energy of carrots was found to be 16.386 and 20.292 kJ/mol for 3 and 6 mm thickness, respectively. The outputs from RSM with regard to quality resulted in optimal operating conditions of 59.8°C with a slice thickness of 3.5 mm.

The results from this study proved that the dynamic changes of color and total carotenoids throughout the drying process are dependent on temperature, time, and moisture levels of the material. Evaluating the changes in total carotenoids as a function of moisture content in this study provides a better understanding of stability of total carotenoids when subjected to different process conditions at varying exposure times, and this information is valuable for process design and optimization. This experiment showed that knowing the exact dynamics of moisture removal is critical for the process control and simulation of different drying strategies, particularly when attempting to correlate physicochemical and thermodynamic aspects. The study clearly indicates that monitoring the dynamic changes of quality degradation throughout the drying process is essential for the future development of real-time noninvasive quality measurements and, consequently, the development of smart drying technologies.

Future research needs to focus on maximizing the quality retention through smart drying techniques and minimizing the production cost of dried carrots so that premium quality products at an affordable price could be produced. The data from this experiment can be used as a reference and baseline for further research in developing novel drying techniques, as well as upgrading the existing technologies, so that suitable, energy saving, and cost-effective drying strategies can be developed.

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NOMENCLATURE

K_0, K_1, K	empirical coefficients in degradation kinetic models
n	number constants
N	number of observations
dm	dry matter of the product
g	weight of the product (gram)
M_{db}	moisture content (g/g) in dry basis
M_e	equilibrium moisture content (dry basis)
M_0	initial moisture content (g/g) in dry basis
M_t	moisture content at time, t (g/g) in dry basis
MR	moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
R^2	correlation coefficient
RMSE	root mean square error
t	time (min)

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