Journal of Agriculture and Food Research 10 (2022) 100409

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Colour change kinetics of pumpkin (*Cucurbita moschata*) slices during convective air drying and bioactive compounds of the dried products

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ARTICLE INFO

Keywords:
Bioactive compounds
Colour change kinetics
Convective air drying
Effective moisture diffusivity
Pumpkin

ABSTRACT

The high contents of bioactive compounds make the pumpkin fruit an important crop for the development of novel functional foods for improving food security, nutrition and health. This study investigated the effect of drying air temperatures (50, 60 and 70 °C) and slice thicknesses (3 and 5 mm) on the drying behaviour, colour change kinetics and bioactive compounds content of the dried pumpkin slices. The effective moisture diffusivity of pumpkin increased from 2.860×10^{-10} to 9.815×10^{-10} m^2/s as drying temperature increased while activation energy values ranged between 47.14 and 51.60 kJ/mol. After the drying process, Lightness (L^*) and yellowness (b^*) values of pumpkin decreased from 74.61 ± 1.18 to 56.50–70.15 and 61.95 ± 2.03 to 51.90–56.10, respectively whereas redness (a^*) and total colour difference (ΔE) increased from 8.47 ± 0.09 to 9.98–11.07 and 0 to 10.01–17.12, respectively. Changes in L^* and b^* values during drying were adequately predicted by the first-order reaction kinetics while a^* and ΔE followed zero-order reaction kinetics ($R^2 = 0.9765$ to 0.9978). The reaction rate constants for colour change greatly depended on the drying air temperature. Contents of β-carotene, ascorbic acid, total phenols, flavonoids and antioxidant activity of the dried pumpkins varied between 43.80 and 58.15 μg g^{-1}, 37.62–50.13 mg/100g, 109.60–155.92 mg GAE/100g, 49.68–67.74 mg kaempferol/100g and 61.45–80.72%, respectively. Predominantly, an increase in pumpkin slice thickness prolonged drying time and caused a greater loss of bioactive compounds and antioxidant activity. Moreover, β-carotene and ascorbic acid contents were higher in 60 °C dried pumpkin than those dried at 50 °C and 70 °C. Nonetheless, increasing the drying air temperature increased the total phenolic compounds and flavonoid contents in dried pumpkin products. The study results could be useful for the food industry and further research work.

1. Introduction

Pumpkin (*Cucurbita* spp) is an important crop that is grown and consumed worldwide due to its nutritional and health benefits [1–3]. Pumpkin belongs to the Cucurbitaceae family and grows well under tropical and subtropical conditions. High-yielding and widely cultivated pumpkin species of commercial importance are the *Cucurbita pepo, Cucurbita moschata* and *Cucurbita maxima* [2]. The fruits vary greatly in size, shape and colour depending on the species. Mostly, the ripped fruits have tasty yellow-orange flesh which makes them very attractive to consumers. Pumpkin is a good and cheap source of carotenoids, phenolic acids, flavonols, vitamins, polysaccharides and minerals [1, 4–6]. The bioactive compounds profile of pumpkin reveals its great potential as a functional food or ingredient for the development of a diversity of innovative food products with health-promoting properties. Nevertheless, pumpkin fruits are seasonal and more susceptible to

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https://doi.org/10.1016/j.jafr.2022.100409
Received 17 June 2022; Received in revised form 9 September 2022; Accepted 26 September 2022
Available online 28 September 2022

microbial spoilage and quality changes after harvest because of their high moisture content [2,7]. Hence, pumpkin fruits need to be kept either frozen or dried [7].

Drying is one of the extensively used food processing techniques for preserving agricultural products [8,9]. As widely reported in the literature, drying extends the shelf life of agricultural products by reducing moisture content and, thus, reducing water activity to levels that greatly inhibit microbial, enzymatic and chemical deterioration [3,5]. Aside from extending the shelf life, drying reduces volume and weight which consequently decreased the cost of packaging, transportation and storage of agricultural food products [3,10], and diversifies their food applications [8,11]. The dried pumpkin can be rehydrated and used to prepare stews and soups [7]. Also, the dried pumpkin product can further be processed into flour and used as an ingredient for infant food, instant noodles, cookies, pasta and bread preparation [2]. Though several new drying technologies were developed in the past three decades for industrial drying [12], conventional air drying is the most widely used method for industrial drying of fruits and vegetables because it is cost-effective, versatile and easy to operate [5,9,13]. However, the drying process could adversely affect the quality characteristics of dried fruits and vegetables [13,14].

Colour is a vital quality characteristic that affects consumers' choices due to its association with freshness, nutritional value and safety of food products [15]. The exposure of fruits and vegetables to heat, oxygen and light during drying could lead to the degradation of pigments and the occurrence of non-enzymatic browning reactions that can result in undesirable colour changes in dried food products [15–18]. Nevertheless, the colour change kinetics of food products is a complex process [16]. Several factors such as varietal, the composition of food material, drying conditions and pre-drying treatments could influence colour change behaviour in different foods during drying. For example, drying fruits and vegetables at a higher temperature for a long time causes a greater degradation of heat-sensitive bioactive compounds like carotenoids and subsequently increases colour change in the dried products [14,19]. Conversely, higher drying temperatures and shorter processing times were found to increase the retention of colour and carotenoid food products [14]. Therefore, modelling colour changes in pumpkin during drying to obtain vital kinetic parameters such as reaction order, rate constant and activation energy is crucial for predicting and monitoring quality changes during processing and optimization of the drying process [16,20]. Moreover, from an engineering perspective, experimental data on quality changes of pumpkins during drying would be vital for the development of non-invasive quality monitoring and measurement techniques for smart drying systems [10].

CIELAB L^* (lightness/darkness), a^* (greenness/redness), and b^* (blueness/yellowness) and the combinations of L^*, a^* and b^* consisting of chroma or colour saturation (C^*), hue angle (H°) and total colour difference (ΔE) are largely used for modelling colour change kinetics of fruits and vegetables [14,21]. Studies were performed on colour change kinetics during hot-air drying of carrot slices [19,21], apple and banana [22], jackfruit [16], kiwifruit [23], American ginseng [24], and colour change kinetics of pumpkin puree during thermal treatment [20]. Most studies have shown that colour degradation in food products during thermal processing or storage followed zero-order or first-order reaction kinetics [20,21]. Although drying studies were performed on pumpkin fruit as shown in Table 1, a multitude of these studies focused on drying behaviour and physical properties of dried pumpkin. There is limited information on the influence of slice thickness and drying air temperature on colour change kinetics and retention of health-beneficial bioactive compounds during convective air drying of pumpkin. Therefore, this study aimed to investigate the influence of different pumpkin slice thicknesses and hot-air drying temperatures on the drying kinetics, effective diffusivity, colour change kinetics, contents of bioactive compounds and antioxidant properties of the dried pumpkin. Also, the relationship between the colour parameters and the bioactive compounds of the dried pumpkin was determined.

Table 1
Summary of previous drying experiments conducted on different varieties of pumpkin.

Pumpkin variety	Drying method	Investigated quality parameters	Reference
Cucurbita moschata	Hot-air drying	Drying kinetics, structural, thermal, viscoelastic and rehydration properties of dried pumpkin	[25]
C. moschata	Microwave multi-flash, microwave vacuum, conductive multi-flash, hot-air, and freeze-drying	Drying behaviour, apparent density, porosity, mechanical properties, structure and colour of dried pumpkin	[3]
C. moschata	Hot-air, hot-air-microwave drying	Drying behaviour, rehydration and structural properties of dried pumpkin	[5]
C. moschata	Hot-air drying	Drying pattern, colour change kinetics, brownness index, and total carotenoid content of dried pumpkin slices	[14]
C. pepo L.	Hot-air drying	Drying kinetics, effective diffusivity, and activation energy	[7]
C. maxima	Hot-air drying	Drying behaviour, effective diffusivity, activation energy, and colour of dried pumpkin	[26]
C. maxima	Microwave-vacuum drying	Carotenoids and colour degradation kinetics	[27]
C. moschata	Osmotic dehydration and hot-air drying	Water loss, sugar gain, effective diffusivity, moisture content, and shrinkage	[28]
C. maxima and C. pepo	Convective, vacuum, vacuum-microwave and freeze-drying	Drying kinetics and quality properties of dried pumpkin (cutting strength, shrinkage, bulk density, colour and total carotenoid content)	[29]
C. moschata	Hot-air, and freeze-drying	Total phenols content, physicochemical and antioxidant properties of flour	[30]
C. maxima	Convective air and freeze-drying	Textural profile (hardness, springiness, cohesiveness and chewiness) and colour of dried pumpkin	[31]

Summary of previous drying experiments conducted on different varieties of pumpkin.

2. Materials and methods

2.1. Material preparation

Fresh pumpkin (*Cucurbita moschata*) fruits were purchased from the central market of Tamale Metropolis of Ghana. The fruits were transported to the laboratory, and uniformly sized and non-damaged fruits were selected, washed with tap water and stored in a refrigerator at 4 ± 1°C for further use. Before the start of the experiment, the fruits were removed from the refrigerator and kept at room temperature (23 ± 1°C) for about 45 min to be accustomed to room temperature [10]. After which the fruits were washed, peeled and divided longitudinally into two halves with a stainless steel knife. The seeds and fibrous strands were then separated from the pulp. The CIELAB colour (L^*, a^*, b^*) values of the fruit pulp were measured with a colorimeter (CR-400 Minolta Konica Inc. Marunouchi, Japan) and fruits with similar colour values were selected and sliced into uniform sizes of 3 and 5 mm thicknesses and 15 mm length using a mechanical food slicer (E16, Ritterwerk GmbH, Gröbenzell, Germany). The initial moisture content of the fresh pumpkin was determined by oven drying at 105 °C for 24 h

using with electric oven (Memmert GmbH, Büchenbach, Germany) described in AOAC [32]. Three replicated measurements were performed and the average moisture content of the fresh pumpkin was 7.31 ± 0.06 on a dry basis (d.b.).

2.2. Drying equipment and procedure

The drying experiments were conducted at three different air temperatures (50, 60 and 70 °C) using a "Hohenheim HT mini" cabinet dryer (Innotech-Ingenieursgesellschaft mbH, Altdorf Germany). The cabinet dryer was described previously by Korese et al. [9]. Before the drying experiment, the dryer was powered and run for 30 min to achieve steady-state conditions. Fresh pumpkin slices (250 ± 2 g) were evenly distributed on a perforated tray in a single layer. The tray and samples were then placed in the drying chamber and dried to a final moisture content of 0.11 ± 0.002 (d.b.). The sample weight and CIELAB colour coordinates (L^*, a^* and b^*) were measured with a precision weighing scale (PCB 10000-1, KERN & SOHN GmbH, Balingen, Germany) and colorimeter (CR-400 Minolta Konica Inc. Marunouchi, Japan) respectively at regular intervals of 30 min until the drying process was terminated. Each drying experiment was replicated three times. At the end of each drying process, the dried pumpkin slices were removed from the dryer and cooled for 15 min at room temperature (24 ± 1°C). The dried pumpkins were then packed into high-density polyethylene bags and stored in a refrigerator (4 ± 1°C) for further analyses.

2.3. Measurement of moisture content

Before the drying process, the moisture and dry matter contents of the fresh pumpkin sample were determined as described in section 2.1. The moisture content of the pumpkin slices during the drying process was calculated using Eq. (1), [33].

$$M_t = \frac{X_t - X_g}{X_g} \tag{1}$$

where M_t and X_t represent the moisture content (d.b.) and sample mass (g) at any drying time t and X_g is the absolute dry matter of the sample (g).

2.4. Modelling of drying curves

The moisture ratio (MR) and drying rate (DR) of pumpkin slices during drying were calculated using Eqs. (2)–(4), respectively [9,33]. Eq. (2) was reduced to Eq. (3) because for long drying times the value of M_e is too small compared with M_o and M_t values [34].

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{2}$$

$$MR = \frac{M_t}{M_o} \tag{3}$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{4}$$

where M_o is the initial moisture content of the fresh pumpkin (d.b.), M_t is the moisture content at drying time t, M_e represents equilibrium moisture content (d.b.), M_{t+dt} is moisture content at time t + dt (d.b.), dt is the small increase in time t (min).

The experimental drying data were used to develop drying curves and fitted to three thin-layer drying kinetic models (Table 2). The goodness of fit of the drying models was evaluated using five statistical parameters including the coefficient of determination (R^2), reduced Chi-square (χ^2), root mean square error (RMSE), mean absolute percentage error (PE) and the corrected Akaike Information Criterion (AICc). The R^2, χ^2 and RMSE values were calculated using Eqs. (5)–(7), respectively [34] while Eqs. (8) and (9) were respectively used for the determination of PE [35] and AICc [38]. The selection of the best-fitted model was based on the highest value for R^2, and the lowest χ^2, RMSE, PE and AICc values.

Table 2
Thin-layer drying models.

Model name	Model	Reference
Page	$MR = \exp(-kt^n)$	[7]
Henderson & Pabis	$MR = a\exp(-kt)$	[35]
Midilli et al.	$MR = a\exp(-kt^n) + bt$	[36,37]

Where a, b, n and k are the model coefficients and t is the drying time (min).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre} - MR_{exp,i}\right)^2} \tag{5}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - K} \tag{6}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{0.5} \tag{7}$$

$$PE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{MR_{exp,i} - MR_{pre,i}}{MR_{exp,i}}\right| \tag{8}$$

$$AICc = \left[N.\ln\left(\frac{SSE}{N}\right) + 2K\right] + \frac{2K\,(K+1)}{N - K - 1} \tag{9}$$

where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, SSE is the sum of squared error, N represent the number of observations and K is the number of coefficients of the model.

2.5. Determination of effective moisture diffusivity

Fick's second law of diffusion defined for slab geometry as illustrated in Eq. (10) was used to calculate the effective moisture diffusivity of the pumpkin slices during drying [39]. However, for long drying periods, the drying characteristics can be described by the first term of the diffusion equation. Therefore, Eq. (10) was simplified to Eq. (11) [7].

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(\frac{-(2n-1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{10}$$

$$MR = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff}t}{4L^2}\right) \tag{11}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is the half-thickness of the pumpkin slice (m), n is a positive integer and t is the drying time (s). The effective diffusivity was determined from Eq. (11) by plotting a graph of lnMR against drying time (s) followed by calculation of the effective diffusivity by the slope method using Eq. (12) [39].

$$Slope\ (K) = \frac{\pi^2 D_{eff}}{4L^2} \tag{12}$$

2.6. Calculation of activation energy

Temperature dependency of the effective moisture diffusivity is defined by the Arrhenius relationship illustrated in Eq. (13) [40]. The activation energy was calculated from the slope of the straight line of the graph of $\ln D_{eff}$ against the reciprocal of the temperature (1/(T+273.15)) indicated in Eq. (14).

$$D_{eff} = D_o \exp\left(\frac{-E_a}{R(T + 273.15)}\right) \quad (13)$$

$$Slope = \frac{E_a}{R} \quad (14)$$

where D_0, E_a, R and T represent the pre-exponential factor (m^2s^{-1}), activation energy (kJ/mol); universal gas constant (8.314 $Jmol^{-1}K^{-1}$), and the drying air temperature (°C), respectively.

2.7. Colour measurement

The CIELAB colour parameters of the pumpkin slices were measured using a colorimeter (CR-400 Minolta Konica Inc. Marunouchi, Japan). Calibration of the equipment and colour measurement procedures used were described in a previous study by Korese et al. [9]. The colour values were taken from six pumpkin slices and the average values were computed. The chroma (C^*) and hue angle (H°) were calculated from CIELab colour coordinates of a* and b* following Eq. (15) and Eq. (16), respectively [31]. The total colour difference (ΔE) was also determined from L^*, a^*, and b^* by Eq. (17) [41].

$$C^* = \sqrt{a^* + b^*} \quad (15)$$

$$H^\circ = tan^{-1}\left(b^*/a^*\right) \quad (16)$$

$$\Delta E = \sqrt{\left(L_0^* - L_t^*\right)^2 + \left(a_0^* - a_t^*\right)^2 + \left(b_0^* - b_t^*\right)^2} \quad (17)$$

Where L^*, a^* and b^* represent lightness, redness, and yellowness respectively. L_0^*, a_0^*, b_0^* are the CIELab colour parameters of the fresh pumpkin slices before drying and L_t^*, a_t^*, b_t^* are the colour parameters of the pumpkin slices during the drying process at time t.

2.8. Modelling colour change kinetics

Colour changes in the pumpkin slices of 3 and 5 mm thicknesses during hot air drying at 50, 60, and 70 °C were modelled using the zero-order reaction and the standard first-order reaction models indicated in Eqs. (18) and (19), respectively [21]. A non-linear regression analysis was performed to determine the kinetic parameters. The adequacy of the fitness of the models for predicting the experimental colour data was evaluated using the R^2 and RMSE values.

$$C = C_0 \pm k_0 t \quad (18)$$

$$\ln C = \ln C_0 \pm k_1 t \quad (19)$$

where C is the colour value measured at drying time t, C_o is the initial colour value of the fresh sample before drying, k_o and k_1 are the reaction rate constants for zero-order and first-order reactions (h^{-1}), respectively, and t is the drying time (h). The signs (+) indicate formation/synthesis while (−) means degradation of the colour/pigment.

2.9. Determination of activation energy and temperature coefficient

The activation energy for colour change in the pumpkin slices during drying was calculated using the Arrhenius-type expression shown in Eq. (20) described previously by Demiray & Tulek [21]. Additionally, the influence of increasing drying temperature by 10 °C on colour change was evaluated using the temperature coefficient (Q_{10}) value calculated using Eq. (21) [21].

$$k = k_0 \exp\left(\frac{-E_a}{RT}\right) \quad (20)$$

$$Q_{10} = \left(\frac{k_2}{k_1}\right)^{\frac{10}{(T_2 - T_1)}} \quad (21)$$

where E_a is the activation energy (kJ/mol), k is the reaction rate constant, k_0 is the pre-exponential factor, R is the universal gas constant (8.314 $Jmol^{-1}K^{-1}$), T is the drying temperature (°K), Q_{10} is the temperature coefficient, k_1 and k_2 are reaction rate constants for temperature T_1 and T_2, respectively.

2.10. Measurement of bioactive compounds

2.10.1. Analysis of β–carotene and ascorbic acid

About 50 g of each dried pumpkin sample was milled into powder with a Kenwood blender (BL400A, Kenwood Ltd, India). β-carotene content of pumpkin powder was determined following the protocol described by Rodriguez-Amaya & Kimura [42]. The extraction and partition of β-carotene in the sample were carried out in petroleum ether and the absorbance was measured at 450 nm with a spectrophotometer (UV-Vis Excellence UV5, Mettler Toledo, Switzerland). For ascorbic acid analysis, the 2,6-dichlorophenolindophenol titrimetric method was used [43]. Briefly, 5 g of pumpkin powder was thoroughly mixed with 10 ml of 5% metaphosphoric acid and titrated with 0.21% 2,6-dichlorophenolindophenol. Ascorbic acid content was expressed as mg per 100 g of sample on a dry matter basis. All analyses were replicated three times.

2.10.2. Determination of total phenolics and flavonoids

The pumpkin samples were extracted in acidified methanol following the procedure described previously by Li et al. [44] with modification. About 10 g of the pumpkin powder was added to 80 ml of 80% methanol acidified with 1% HCl, stirred thoroughly and incubated in the dark under room conditions for 6 h with regular shaking on a mechanical shaker to facilitate extraction of antioxidants. The mixture was then centrifuged at 4000 rpm for 30 min with a Rotofix 32A centrifuge (Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany). The supernatant was carefully collected and the residue was extracted twice following the same extraction procedure. The supernatants from the three extractions were pooled together and filtered with a Whatman grade 1 filter paper (Whatman Int., Maidstone, U.K).

The total phenolic content was determined following the Folin–Ciocalteu method [45]. Gallic acid was used as standard and absorbance was measured at 745 nm with a spectrophotometer (UV-Vis Excellence UV5, Mettler Toledo, Switzerland). Total phenols content was expressed as mg gallic acid equivalent per 100g (d.b.) of the sample. For flavonoid determination, the colourimetric procedure described by Li et al. [44] was used and absorbance was read at 415 nm with a spectrophotometer. Kaempferol was used for the standard curve calibration and flavonoid content was expressed as mg kaempferol equivalent per 100g (d.b.) of the sample.

2.10.3. Analysis of antioxidant activity

The antioxidant activity of the pumpkin extract was determined following the 2,2,-di-phenyl-2-picryl-hydrazyl (DPPH) protocol described by Turkmen et al. [46]. Extract (0.5 ml) was added to 1.5 ml of 0.1 mM DPPH radical in methanol, vortexed for 5 min and kept in the dark for 1 h at room temperature (23 ± 1 °C). This was followed by the measurement of absorbance of the reaction mixture at 517 nm using a spectrophotometer (UV-Vis Excellence UV5, Mettler Toledo, Switzerland). Methanol without sample extract was used as a control. Antioxidant activity was expressed as a percentage of scavenging activity of DPPH using Eq. (22).

$$\text{Antioxidant activity } (\%) = \frac{\text{Control}_{Abs} - \text{Sample}_{Abs}}{\text{Control}_{Abs}} \times 100 \quad (22)$$

2.11. Statistical analysis

The dried pumpkin quality data measured were subjected to analysis of variance in a full factorial design using SPSS software (IMB SPSS Statistics, version 25). Means were compared by Tukey's test at a 5% significance level. The effects of the slice thickness, drying air temperature and interactions on the response variables were determined by regression analysis using the response surface methodology (RSM) of the Design-Expert software version 11.1.2.0 (Stat-Ease Inc., Minneapolis, United States). The experimental data were fitted to the quadratic model described in Eq. (23) to determine the regression coefficients using the coded factors where the lower and upper limits of the actual factors were coded as −1 and +1, respectively [47].

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \varepsilon \quad (23)$$

where Y is the response variable, β_o, β_i, β_{ii}, and β_{ij} are the regression coefficients for model intercept, linear, quadratic and interaction terms respectively, X_i and X_j are continuous independent variables, respectively, k is the number of variables and ϵ is the error term.

Principal Component Analysis (PCA) was performed with XLSTAT software (Version 2018.1, Addin-soft, 2018) to establish the correlation between the CIELAB (L^*, a^* and b^*), ΔE, bioactive compounds and antioxidant activity of the dried pumpkin slices as well as to discriminate between the dried pumpkin samples.

3. Results and discussion

3.1. Drying behaviour of pumpkin slices

Fig. 1a and b shows the drying curves of the pumpkin slices as influenced by the drying air temperature and slice thickness. The effective drying time to reduce the initial pumpkin moisture content from 7.31 ± 0.06 (d.b.) to a final moisture content of 0.11 ± 0.002 (d.b.) at drying air temperatures of 50, 60, and 70 °C were 330, 270, and 210 min, respectively for the 3 mm slice thickness and 480, 360 and 300 min for the 5 mm slice thicknesses. From the results, a decrease in pumpkin slice thickness and an increase in drying air temperature from 50 to 70 °C shortened the drying time by 25.0–41.7%. This was expected because the heat transfer rate increase as the drying temperature increases resulting in an increased drying rate and decreased drying duration [9,48]. Similar observations were reported for hot-air drying of pumpkin [5,7,8], carrot [19,34], eggplant [49] and palmyra seed sprout [9]. As indicated in Fig. 1c and d, the drying rate of the pumpkin slices was higher when the moisture ratio was high at the initial drying phase but decreases continuously with decreased moisture ratio as drying progressed. The whole drying process of the pumpkin slices happened at a falling rate since no visible constant rate of drying was detected from the drying rate curves (Fig. 1c and d). This was in agreement with previous findings by Refs. [5,7,8]. However, increasing the drying air temperature from 50 to 70 °C results in an increased drying rate in both slice thicknesses (Fig. 1c and d). This phenomenon is normal because during drying moisture movement from the interior of food products to the surface and subsequent evaporation is temperature-dependent [6]. The final moisture content and water activity of the final dried pumpkin samples varied from 0.107 to 0.113 (d.b.) and 0.270 to 0.281 (d.b.), respectively (Table 4). The drying process lowered the moisture content and water activity greatly which could inhibit or minimize microbial growth and chemical reactions and subsequently enhance product quality stability and shelf life during storage [50].

3.2. Modelling of drying curves

The pumpkin drying data were fitted to three drying models (Table 2). The coefficients and statistics of the drying models are presented in Table 3. The statistics for the three models ranged from 0.9896 to 0.9999 for R^2, 0.00001 to 0.00151 for χ^2, 0.0294 to 0.03313 for RMSE, 0.31 to 22.96 for PE and −144.40 to −61.53 for AICc (Table 3). The Midilli et al. model had the highest R^2 value and lowest values for

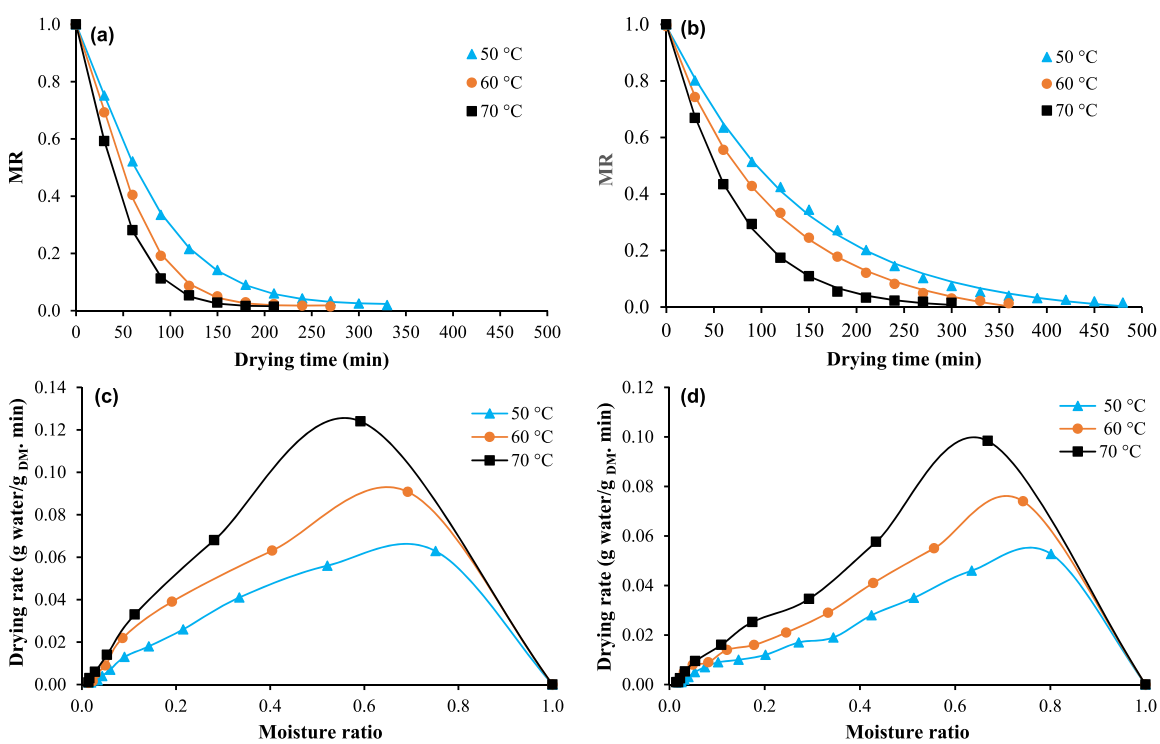

Fig. 1. Effect of slice thickness and drying air temperature on the moisture ratio (MR) and drying rate (DR) of pumpkin slices. (a) and (b) MR of 3 mm and 5 mm slice thickness fitted with Midilli et al. model (solid lines), respectively, (c) and (d) are DR of 3 mm and 5 mm slice thicknesses respectively.

Table 3
The coefficients and statistics of the thin-layer drying models for different drying air temperatures and pumpkin slice thicknesses.

Model	Slice thickness (mm)	Drying temp. (°C)	Coefficients				Statistical values				
			a	k	n	b	R^2	χ^2	RMSE	PE (%)	AICc
Page	3	50		0.0055	1.1689		0.9995	0.00008	0.00814	1.25	−110.13
		60		0.0039	1.3364		0.9993	0.00017	0.01098	7.63	−85.07
		70		0.0074	1.2569		0.9997	0.00007	0.00744	5.07	−93.86
	5	50		0.0051	1.0809		0.9980	0.00021	0.01362	9.81	−141.22
		60		0.0079	1.0437		0.9983	0.00020	0.01268	8.58	−107.46
		70		0.0101	1.0765		0.9995	0.00006	0.00725	2.12	−102.88
Henderson & Pabis	3	50	1.0315	0.0124			0.9959	0.00050	0.02049	6.68	−87.96
		60	1.0365	0.017			0.9896	0.00151	0.03313	12.96	−61.53
		70	1.0201	0.0213			0.9942	0.00094	0.02651	17.72	−68.43
	5	50	1.014	0.0078			0.9971	0.00035	0.01746	21.20	−132.77
		60	1.0043	0.0098			0.9982	0.00025	0.01413	22.96	−104.81
		70	1.0106	0.0144			0.9988	0.00017	0.01781	13.18	−92.15
Midilli et al.	3	50	1.0004	0.0046	1.2150	0.000056	0.9999	0.00001	0.00294	0.63	−125.22
		60	0.9987	0.0033	1.3845	0.000068	0.9997	0.00005	0.00561	0.31	−91.66
		70	1.0000	0.0064	1.2972	0.000071	0.9999	0.00002	0.00296	1.80	−101.45
	5	50	0.9932	0.0058	1.0469	−0.000044	0.9985	0.00017	0.01153	3.85	−144.40
		60	0.9979	0.0105	0.9717	−0.000110	0.9993	0.00009	0.00780	3.51	−120.69
		70	0.9983	0.0102	1.0736	−0.000007	0.9995	0.00008	0.00718	1.95	−103.16

Where R^2, χ^2, RMSE, PE and AICc represent the coefficient of determination, reduced Chi-square, root means square error, mean absolute percentage error and corrected Akaike Information Criterion respectively.

Table 4
Effective moisture diffusivity, moisture content and water activity of dried pumpkin slices.

Slice thickness (mm)	Drying air temperature (°C)	Effective diffusivity ($m^2.s^{-1}$)	Moisture content (d.b.)	Water activity
3	50	2.860×10^{-10a}	0.111 ± 0.002^{ab}	0.275 ± 0.001^{a}
	60	4.593×10^{-10b}	0.109 ± 0.001^{ab}	0.272 ± 0.002^{a}
	70	7.961×10^{-10c}	0.107 ± 0.001^{a}	0.270 ± 0.002^{a}
5	50	3.209×10^{-10d}	0.113 ± 0.003^{b}	0.281 ± 0.001^{b}
	60	6.083×10^{-10e}	0.112 ± 0.001^{ab}	0.279 ± 0.001^{b}
	70	9.815×10^{-10f}	0.110 ± 0.001^{ab}	0.273 ± 0.002^{a}

Values that have no common letter are significantly different ($p < 0.05$).

χ^2, RMSE, PE and AICc as compared with Page's model and Henderson and Pabis model for all the drying experiments. Therefore, the Midilli et al. model was considered the most appropriate for describing the drying behaviour of the pumpkin slices.

3.3. Effective moisture diffusivity and activation energy

The effective diffusivity (D_{eff}) values of the pumpkin slices are shown in Table 4. An increasing trend for D_{eff} values from 2.860×10^{-10} to 7.961×10^{-10} m^2/s for 3 mm slice thickness and 3.209×10^{-10} to $9.815 \times 10^{-10} m^2/s$ for 5 mm slice thickness was observed as the drying air temperature increase from 50 to 70 °C. A similar pattern of D_{eff} values was reported previously for convective drying of pumpkin [7], carrot [19] and Monukka seedless grapes [6]. According to Xiao et al. [6] and Zhu & Shen [33], an increase in drying temperature increase the heating energy and activity of water molecules which consequently results in increased moisture diffusivity. The D_{eff} values of the pumpkin slices were within the range of D_{eff} values (10^{-12} m^2/s to 10^{-8} m^2/s) reported for agricultural food products previously [51]. Moreover, the pumpkin slices of 5 mm thickness had higher D_{eff} values as compared with the values estimated for the 3 mm slice thickness at all drying air temperatures (Table 4). The higher volume-to-surface ratio and greater moisture distribution within the thicker samples perhaps increase the moisture transfer rate during drying [19].

The average activation energy (E_a) values of the pumpkin slices during convective drying as calculated from the slope of the Arrhenius plot (Fig. 2) using Eq. (12) were 47.14 and 51.60 kJ/mol for the 3 and 5 mm slice thicknesses respectively. The thinner pumpkin slices had a lower E_a as compared with thicker slices. This observation can be attributed to the lower energy demand for heat transport in thinner slices due to the shorter distance that moisture travels from the inside to the surface of the material [19]. The E_a values for the pumpkin slices were within the range of 12.7–110.0 kJ/mol for most agricultural food products [51]. The E_a values determined for pumpkin slices in this study were higher than the 24.49–43.27 kJ/mol reported for hot-air drying of pumpkin by Falade & Shogaolu [26] but lower than 78.93 kJ/mol mentioned in the study performed by Doymaz [7]. The variations in the E_a could be associated with differences in variety, chemical composition, physical structure, pre-drying treatment and drying conditions [6].

3.4. Colour changes in pumpkin slices during drying

Figs. 3 and 4 show the variations in CIELAB colour parameters of the pumpkin slices as a function of drying time and moisture content respectively. Changes in the colour of the pumpkin were observed from the initial phase of the drying process when the moisture content was

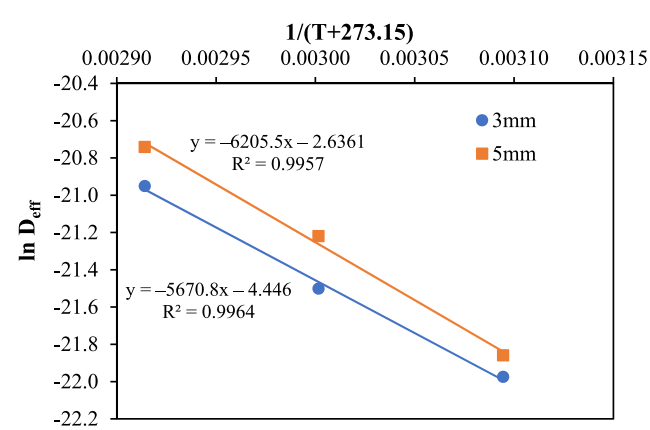

Fig. 2. Arrhenius plot of effective moisture diffusivity of pumpkin slices in relation to drying temperature.

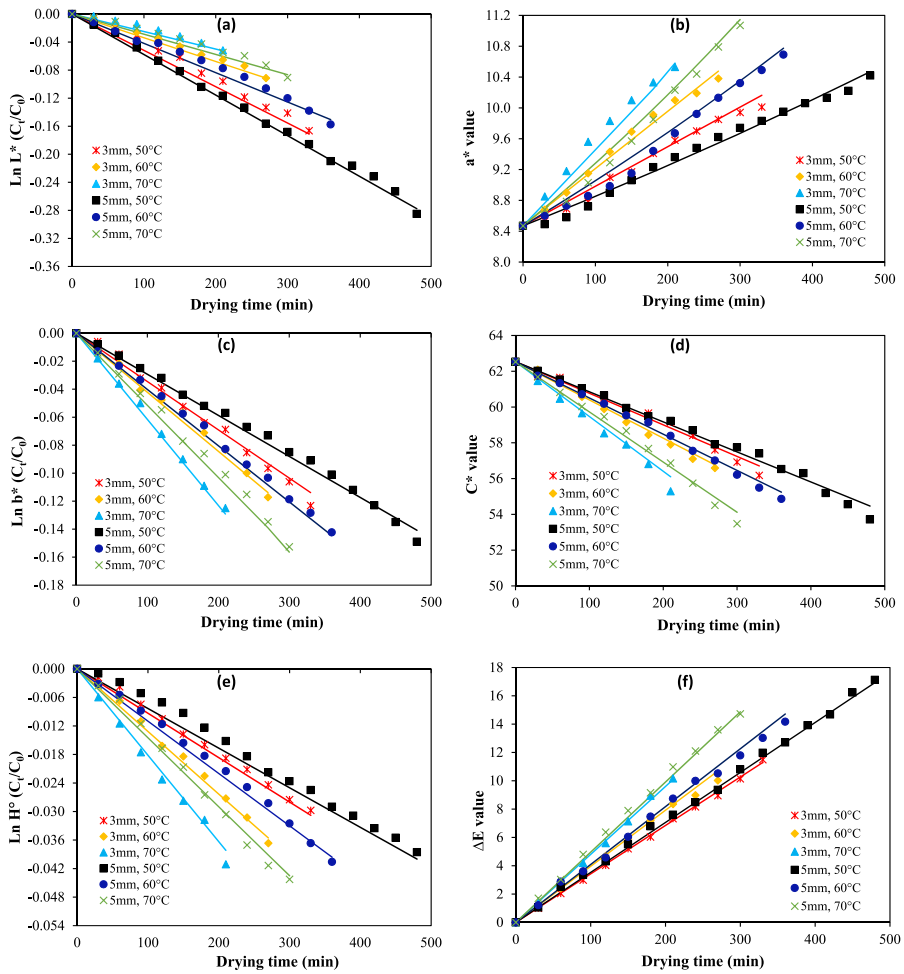

Fig. 3. Colour changes in pumpkin slices during drying as influenced by drying air temperature and slice thickness. Where (a) L^* is lightness, (b) a^* is redness, (c) b^* is yellowness, (d) C^* is chroma, (e) H° is hue angle, and (f) ΔE is the total colour difference. The solid lines represent the predicted data by the first-order kinetic model for L^*, b^*, H° and the zero-order kinetic model for a^*, C^* and ΔE. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

high and continuous as moisture levels in the samples reduced drastically to the level that could inhibit enzyme activity. This suggests that the changes in the colour attributes of the pumpkin slices could be attributed to enzymatic activities, non-enzymatic reactions and thermal degradation of natural pigments in pumpkin during the convective air drying [17,18].

The average colour values for L^*, a^* and b^* of the fresh pumpkin slices were 74.61 ± 1.18, 8.47 ± 0.09, and 61.95 ± 2.03, respectively. The values of L^* and b^* of pumpkin decrease progressively with increasing drying time (Fig. 3a and c) and decreasing moisture content (Fig. 4a and c). The change in L^* and b^* was somehow gradual at lower moisture content but intensified as the moisture content decreased below 2.0 (d.b.) for all drying experiments (Fig. 4a and c). The reduction in L^* and b^* values can be attributed to the degradation of carotenoids and other pigments due to exposure to heat, light and oxygen during drying [15,18,21] and non-enzymatic browning reactions accelerated by high drying temperatures and lower moisture content [15,18]. Similar findings were made during hot-air drying of pumpkins [14,31], carrots [21,34] and jackfruit [16]. After the drying process, the L^* value of dried pumpkin slices ranged between 63.17–70.15 and 56.50–65.93 for the 3 and 5 mm slice thicknesses, respectively (Fig. 5a). Mostly, reducing the slice thickness and increasing the drying air temperature increased the L^* value of the dried pumpkin slices (Fig. 5a). For example, the highest L^* value (70.15 ± 1.75) was found in 3 mm slices dried at 70 °C air temperature while the lowest L^* value (56.90 ± 1.03) was observed in 5 mm slice thickness dried at 50 °C (Fig. 4a). Drying thicker food materials at a lower temperature prolongs drying time and causes greater degradation of pigments [19]. In terms of yellowness, the value of b^* of the dried pumpkin slices varied between 54.32 and 56.10 for 3 mm slices and 51.90–54.81 for 5 mm slice thicknesses dried between 50 and 70 °C air temperatures (Fig. 5c). It was found that the 3 mm slice thickness had a slightly higher b^* value than the 5 mm slice thickness (Fig. 5c). Also, the b^* value of the dried pumpkin slices increased as the drying air temperature increased from 50 to 60 °C after which an increase in temperature to 70 °C led to a reduction in b^* (Fig. 5c). Previous studies suggested that prolonged drying time and higher drying temperature cause increased degradation of carotenoids [19,52].

The variations in a^* values during drying as against drying time and moisture content of pumpkin as illustrated in Figs. 3b and 4b, respectively. The values of a^* of pumpkin slices increased gradually with drying time and decreasing moisture content. Mostly, polyphenol oxidase (PPO)-induced enzymatic browning [48] and non-enzymatic browning reaction [24] occur during the drying of fruits and vegetables and consequently increased the redness of the dried products. The dried pumpkin slices had similar values for a^* which measured between 9.98 and 11.07 (Fig. 5b). The pattern of a^* values observed is in line with the previous finding in hot-air dried pumpkin [31] and jackfruit [16]. However, the current results differed from the result of Onwude et al. [14] and Demiray & Tulek [21] for pumpkin and carrot respectively. This could be associated with differences in variety, composition, sample preparation, drying methods and settings [53].

Fig. 3d and e shows the evolution of chroma or colour saturation (C^*) and hue angle (H°) values of the pumpkin slices during drying. The C^* and H° exhibited decreasing trends throughout the drying process. The initial values of C^* (62.53 ± 1.0) and H° (82.21 ± 0.14) decreased to 52.40–57.01 and 78.67–79.85, respectively in the final dried pumpkin

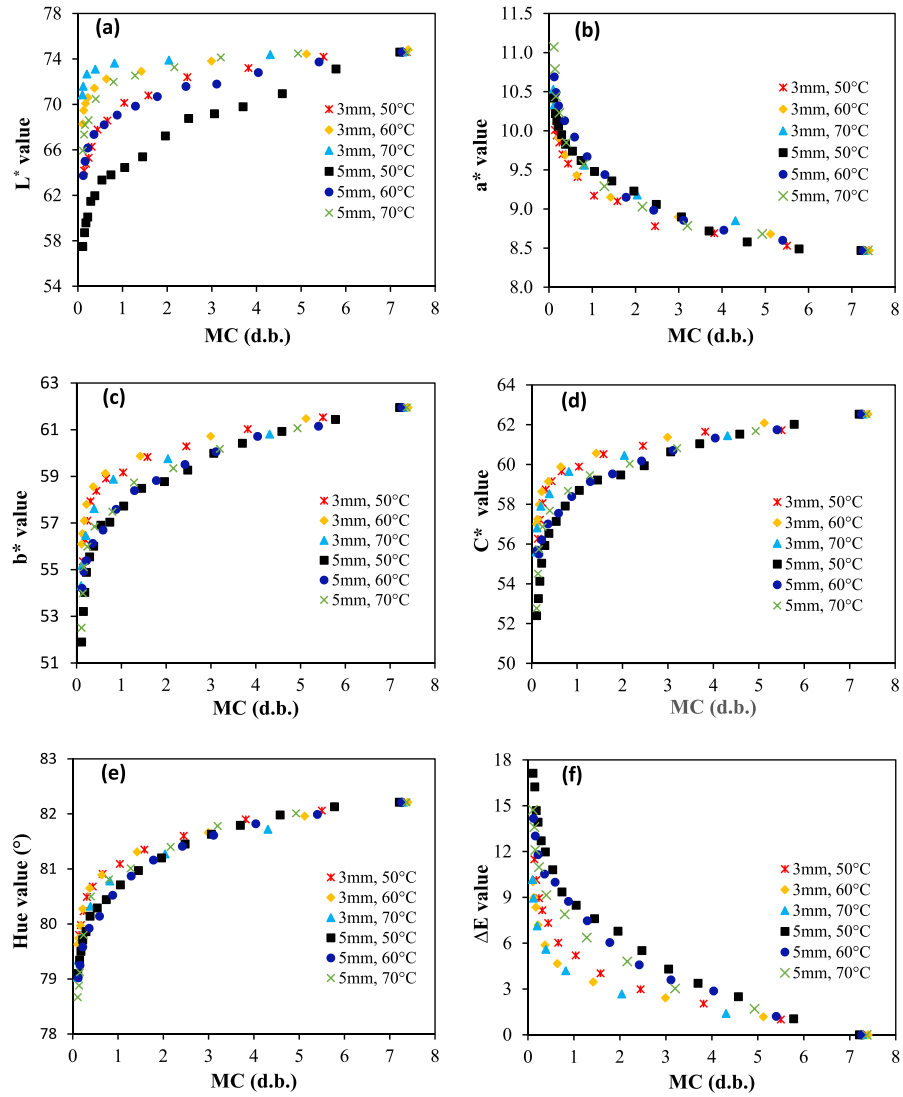

Fig. 4. Variations in colour values of pumpkin slices as a function of moisture content (MC) at different drying air temperatures. Where (a) L^* is lightness, (b) a^* is redness, (c) b^* is yellowness, (d) C^* is chroma, (e) hue angle and (f) ΔE is the total colour difference. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

slices. The C^* values varied significantly ($p < 0.05$) between the dried pumpkins samples and the pattern was similar to the b^* value. However, the dried pumpkin slices did not differ significantly in their H° values (Fig. 5e). Despite, there being a shift from the yellow hue towards the direction of the red hue, the values were still within the yellow-orange hue similar to the findings of Onwude et al. [14].

Figs. 3f and 4f describe the ΔE values of the pumpkin slices during drying as a function of drying time and moisture content respectively. Similar to the previous observations in dried pumpkin [14,31], carrots [10,19,21] and jackfruit [16], ΔE values of pumpkin slices increased progressively as the drying process advanced with decreasing moisture content in the pumpkin. Fig. 5f compares the ΔE values of the dried pumpkin samples. It was found that the 3 mm slice thickness dried at 60 °C had the least value for ΔE (10.01 ± 0.21) while the highest value of ΔE (17.12 ± 0.56) was observed in the 5 mm processed at 50 °C air temperature (Fig. 5f). Despite the rate of change of ΔE increased with increasing drying air temperature as discussed in section 3.5, the relatively shorter drying time for higher temperature drying resulted in a lower ΔE in the final dried pumpkin products as compared with drying at a lower air temperature of 50 °C which increased the exposure of the samples to oxidation and thermal degradation of pigments thereby increasing colour change in the final products. This result was in agreement with the findings on convective air drying of carrots [19].

3.5. Modelling colour changes in pumpkin slices

Table 5 shows the colour change kinetics parameters and statistics of pumpkin slices during drying at air temperatures of 50, 60 and 70 °C. The changes in L^*, b^* and H° values of the pumpkin slices for all drying experiments followed the first-order kinetic model (Table 5). However, changes in a^* values for the 3 mm slice thickness and C^* value for both slice thicknesses at all drying temperatures were satisfactorily predicted by the zero-order kinetic model. Nonetheless, the values of a^* for the 5 mm slice thickness could be suitably defined by both the zero-order and first-order kinetics models since the R^2 values are similar (R^2 = 0.9897–0.9941 and 0.9900–0.9946, respectively). However, based on the easiness of application, the zero-order kinetic model was selected for fitting the experimental data for a^* (Fig. 3b). Similarly, the degradation of L^* during microwave-vacuum drying of pumpkin slices [27] and thermal degradation of L^* and b^* in peach puree [54] followed the first-order kinetic model. Also, Xiao et al. [24] found the zero-order reaction model as the most appropriate for the prediction of changes

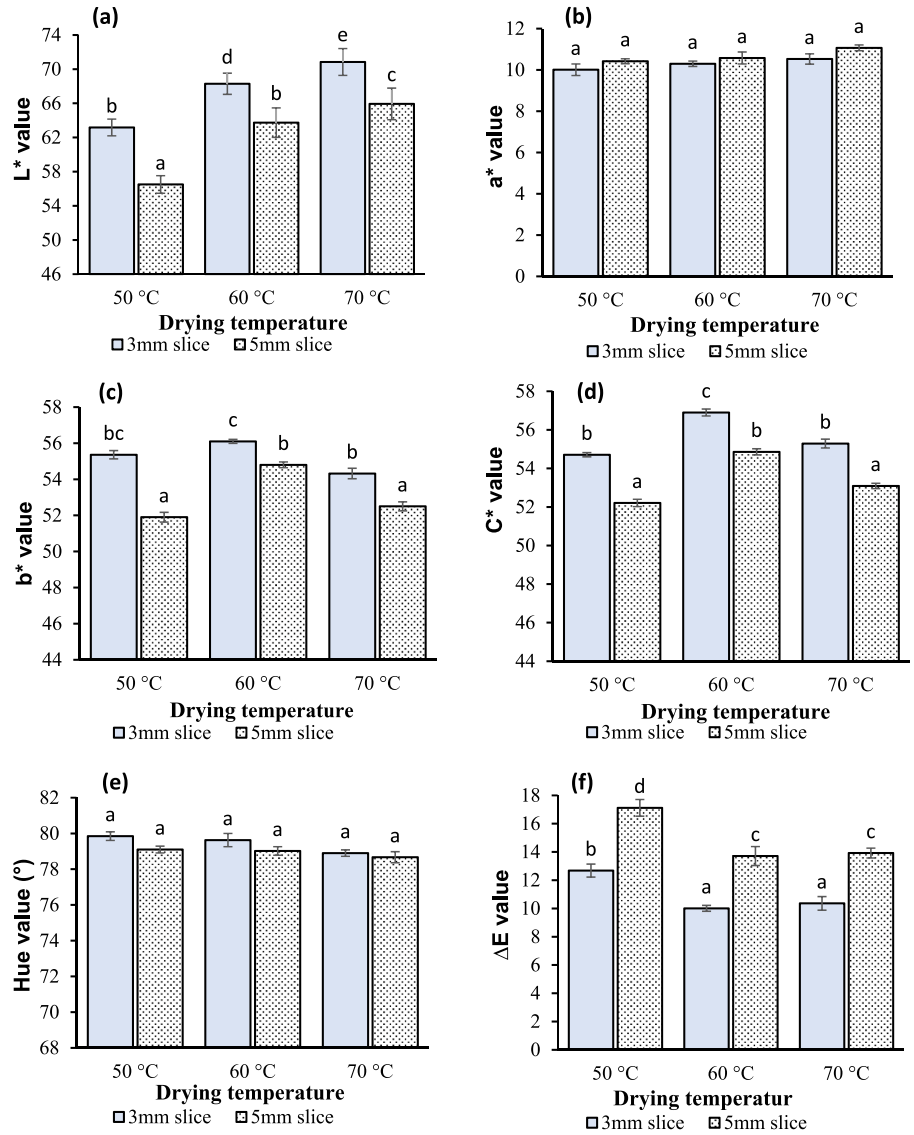

Fig. 5. Colour values of the dried pumpkin slices processed at different temperatures. Colour data are averages ± standard deviation (n = 3). Where (a) L^* is lightness, (b) a^* is redness, (c) b^* is yellowness, (d) C^* is chroma, (e) Hue and (f) ΔE is the total colour difference. Values having no common letter are significantly different ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in a^* values of American ginseng dried between 35 and 55 °C. However, Demiray & Tulek [21] reported that the degradation of L^*, a^* and b^* in carrot slices during hot air drying could be predicted by both the zero-order kinetic and first-order kinetic models. The modelling results in Table 4 showed that values of ΔE for the pumpkin slices during convective drying followed the zero-order reaction model. This result was in agreement with the findings of previous studies on pumpkin [27], carrot [21] and jackfruit [16].

The values of the reaction rate constants for the colour parameters increased as the drying temperature increased, except for L^* (Table 5). This suggests colour change occurred faster at a higher drying temperature than at a lower temperature. However, the reaction rate constants for the L^* decrease with an increase in drying temperature (Table 5). This implies the darkening of pumpkin slices slows down as the drying temperature increase which could be linked to the speedy inhibition of oxidative enzymes like PPO due to the faster removal of moisture at higher drying temperatures [17,48]. During the drying process, L^* and ΔE values change slowly while a^*, b^* and H° values change more quickly in the 3 mm slice thickness than in the thicker slices of 5 mm (Table 5). Therefore, aside from the drying temperature, the thickness of pumpkin slices had a significant influence on the reaction rate constants of colour change probably due to the effect of the thickness of food material on heat transfer during thermal processing.

3.6. Activation energy for colour change and temperature coefficient

Fig. 6 exemplifies the graphs of the reaction rate constants of colour change in the pumpkin slices as a function of drying time. The temperature dependency of reaction rate constants followed the Arrhenius relationship, similar to the findings in previous colour degradation kinetics studies of fruits and vegetables [14,16,19,21,24]. The values of E_a for colour changes in pumpkin slices of 3 mm thickness were 33.66 kJ/mol for L^*, 30.14 kJ/mol for a^*, 26.56 kJ/mol for b^*, 25.64 kJ/mol for C^*, 27.10 kJ/mol for H° and 16.54 kJ/mol for ΔE. However, the values of E_a for colour change in the 5 mm slices were 32.05, 34.89, 32.16, 23.13, 26.19 and 15.59 kJ/mol for L^*, a^*, b^*, C^*, H° and ΔE respectively. It was clear that the 3 mm slice thickness had lower E_a for a^*, b^* and H° but higher energy values L^*, C^* and ΔE as compared with the 5 mm slice thickness. A lower E_a value suggests less energy is needed for the colour change, therefore, colour change can occur easily and at a

Table 5
Colour change kinetics parameters of pumpkin slices at different drying temperatures.

Colour parameter	Slice thickness (mm)	Drying temperature (°C)	Zero-order reaction				First-order reaction			
			K_o (h^{-1})	R^2	RMSE	Q_{10} value	K_1 (h^{-1})	R^2	RMSE	Q_{10} value
*L**	3	50	2.1464	0.9929	0.6338	0.68	0.0311	0.9942	0.6159	0.65
		60	1.4527	0.9933	0.3075	0.75	0.0203	0.9950	0.2513	0.74
		70	1.0917	0.9750	0.3552		0.0150	0.9765	0.3281	
	5	50	2.2628	0.9968	0.1408	0.77	0.0347	0.9976	0.1359	0.72
		60	1.7349	0.9901	0.3427	0.71	0.0251	0.9950	0.2630	0.69
		70	1.2389	0.9812	0.4105		0.0173	0.9837	0.4089	
*a**	3	50	0.3079	0.9862	0.0716	1.45	0.0334	0.9838	0.0733	1.42
		60	0.4459	0.9915	0.0640	1.33	0.0473	0.9875	0.0929	1.32
		70	0.5917	0.9883	0.1241		0.0622	0.9817	0.1668	
	5	50	0.2493	0.9915	0.0735	1.53	0.0265	0.9918	0.0724	1.51
		60	0.3805	0.9897	0.1475	1.40	0.0401	0.9900	0.1173	1.37
		70	0.5311	0.9941	0.1671		0.0549	0.9946	0.1162	
*b**	3	50	1.2557	0.9941	0.0691	1.19	0.0207	0.9960	0.0639	1.22
		60	1.4978	0.9906	0.1456	1.43	0.0253	0.9928	0.1418	1.46
		70	2.1448	0.9929	0.2197		0.0369	0.9945	0.1986	
	5	50	1.1521	0.9834	0.2681	1.20	0.0176	0.9877	0.2130	1.35
		60	1.3845	0.9845	0.4269	1.45	0.0237	0.9862	0.2815	1.49
		70	2.0078	0.9794	0.3043		0.0354	0.9831	0.1529	
*C**	3	50	1.1266	0.9806	0.3941	1.21	0.0190	0.9769	0.4270	1.21
		60	1.3681	0.9981	0.1401	1.44	0.0230	0.9982	0.1754	1.45
		70	1.9686	0.9934	0.1839		0.0334	0.9913	0.2103	
	5	50	1.0462	0.9900	0.2992	1.21	0.0180	0.9862	0.3884	1.20
		60	1.2670	0.9961	0.1756	1.40	0.0216	0.9936	0.2495	1.41
		70	1.7685	0.9919	0.3271		0.0305	0.9877	0.4353	
Hue°	3	50	0.4512	0.9953	0.0512	1.38	0.0055	0.9958	0.0429	1.42
		60	0.6238	0.9948	0.0640	1.27	0.0078	0.9964	0.0586	1.24
		70	0.7943	0.9929	0.1014		0.0097	0.9938	0.0894	
	5	50	0.4071	0.9951	0.2443	1.34	0.0050	0.9956	0.1570	1.36
		60	0.5439	0.9928	0.2150	1.32	0.0068	0.9960	0.1961	1.32
		70	0.7204	0.9942	0.2486		0.0090	0.9957	0.1637	
ΔE	3	50	2.0527	0.9977	0.1229	1.16				
		60	2.3751	0.9969	0.2734	1.24				
		70	2.9440	0.9984	0.1958					
	5	50	2.1173	0.9978	0.2210	1.16				
		60	2.4520	0.9972	0.3206	1.21				
		70	2.9737	0.9975	0.3077					

faster rate [15,21,24]. The E_a values for L^*, b^* and ΔE of the pumpkin slices were lower while E_a for a* was higher than the values reported for pumpkin [14]. Also, the E_a for changes in L^*, a^* and b^* obtained for pumpkin slices were lower than values reported for American ginseng [24], carrot [21], and peach puree [54]. The difference in the activation energy values for colour change in the pumpkin slices of the present study and values reported in other agricultural products could be ascribed to variations in the food composition, pre-drying processes, the method and conditions of drying [14,53].

The temperature coefficient (Q_{10}) values calculated using Equation (19) are shown in Table 5. Generally, an increase in drying temperature from 50 to 60 °C resulted in a higher Q10 value than a change from 60 to 70 °C for L^* of the 5 mm slice thickness, a^* and hue angle of both slices thicknesses (Table 5). This means the reaction rate constants of these colour attributes were more affected when the temperature was increased from 50 to 60 °C than 60–70 °C. This could be explained by the rapid inhibition of PPO enzyme activity at higher drying temperatures [48]. Contrariwise, the b^*, chroma and ΔE values were greatly affected when drying air temperature increased from 60 to 70 °C as indicated by the higher Q_{10} values than an increase from 50 to 60 °C which gave lower Q_{10} values for both slice thicknesses. This may be due to an upsurge in thermal degradation of carotenoids and non-enzymatic browning reactions as drying temperature increases [21]. Similar trends of results were noticed for L^*, a^* and b^* values of carrots dried at 45, 55 and 65 °C air temperatures [21].

3.7. Nutritional and antioxidant properties of dried pumpkin

Table 6 shows the contents of β-carotene, ascorbic acid, total phenolics and flavonoids of the fresh and dried pumpkin slices on a dry matter basis. The fresh pumpkin had a β-carotene content of 76.30 ± 2.17 $\mu g.g^{-1}$. The β-carotene content of the dried pumpkin slices decreased by 23.8–33.9% and 33.3–42.6% in the 3 and 5 mm slice thicknesses respectively. The reduction in β-carotene content in dried pumpkins could be attributed to oxidative and thermal degradation as well as isomerization of carotenoids due to exposure to oxygen, heat and light during drying [15,18,20]. The results of the regression analysis indicated the pumpkin slice thickness and drying air temperature had significant ($p < 0.05$) influences on the β-carotene content of the dried pumpkins (Table 6). The β-carotene content of the dried pumpkin decreased as the slice thickness increased (Fig. 7), possibly due to extended exposure of the pumpkin slices to heat, oxygen and light which could cause greater loss of β-carotene [9,19]. The β-carotene content of the dried pumpkin increased as the drying air temperature increased from 50 to 60 °C while further increased in drying temperature to 70 °C caused a significant ($p < 0.05$) reduction in β-carotene content (Fig. 7). The lower β-carotene values in pumpkin dried at air temperatures below and above 60 °C could be associated with the prolonged drying time for lower drying temperature and thermal degradation at high temperatures. Similar results were reported for thermally treated pumpkin puree [20], hot air-dried carrot slices [19] and pre-cooked palmyra seed-sprout fleshy slices [9].

The ascorbic acid content of the fresh pumpkin was 63.82 ± 1.20 mg/100g whereas the values in the dried pumpkin slices varied between 41.06 and 53.10 mg/100g and 37.62– 44.38 mg/100g for the 3 and 5 mm slice thicknesses respectively (Table 6). A reduction in ascorbic acid of about 21.5– 41.1% was observed in the dried pumpkin slices. This could be ascribed to oxidative and thermal degradation of ascorbic acid during the drying process [52,55,56]. Similarly, a decrease in the ascorbic acid content was reported in hot air-dried tomatoes [57] and

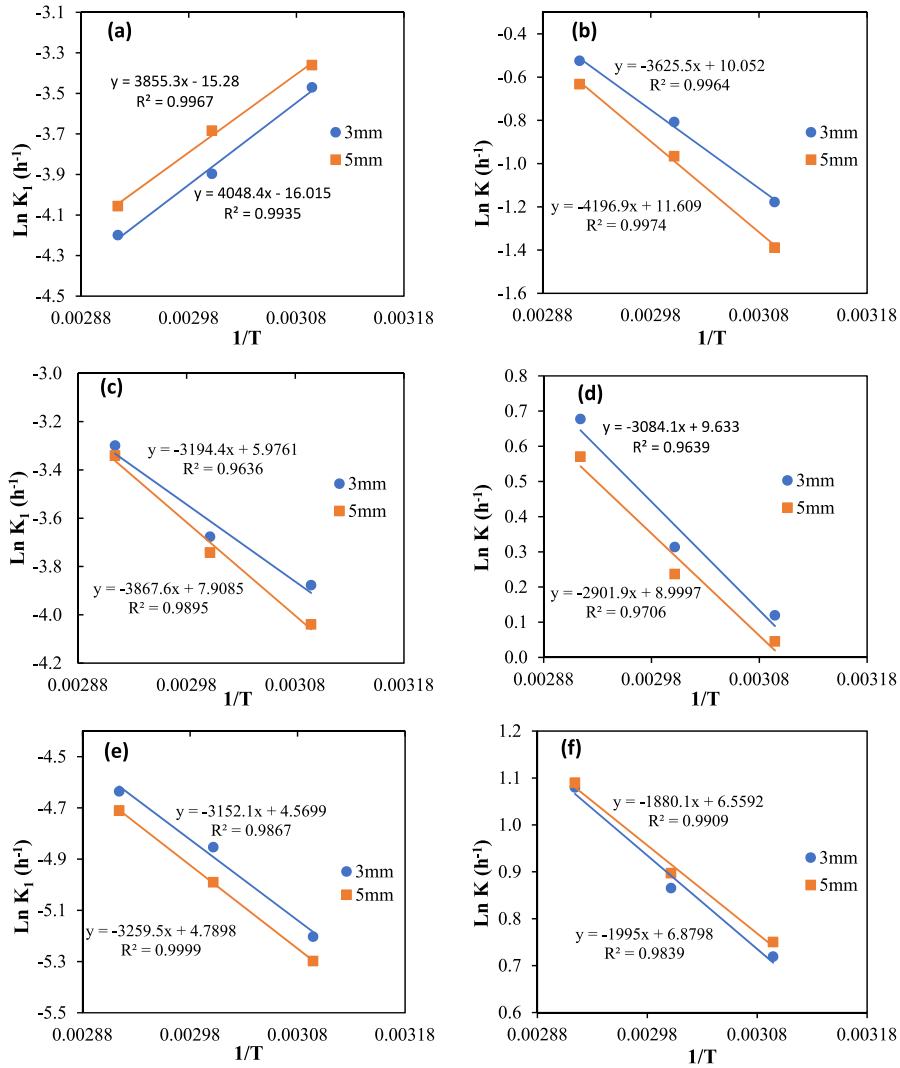

Fig. 6. Arrhenius plots of reaction rate constants of the colour change of the fitted kinetic model as a function of drying temperature. (a) Lightness, L^*, (b) redness, a^*, (c) yellowness, b^*, (d) chroma, C^* (e) hue angle, H° and (f) total colour difference, ΔE. Where K and K_1 represent the reaction rate constants of the zero-order and first-order kinetic models respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 6
Contents of bioactive compounds on a dry matter basis and antioxidant activity of fresh and hot-air dried pumpkin slices as influenced by the drying parameters.

Pumpkin sample	β-carotene (μg.g^{-1})	Ascorbic acid (mg/100g)	TPC (mg GAE/100g)	Flavonoids (mg Kaempferol/100g)	Antioxidant activity (%)
Fresh	76.30 ± 2.17^{e}	63.82 ± 3.45^{d}	178.65 ± 2.19^{g}	69.70 ± 2.05^{e}	83.02 ± 2.16^{d}
3mm/50°C	54.20 ± 1.13^{c}	49.24 ± 2.84^{c}	123.51 ± 3.46^{b}	56.12 ± 1.32^{bc}	70.93 ± 1.87^{b}
3mm/60°C	58.15 ± 1.75^{d}	50.13 ± 2.03^{c}	146.43 ± 2.70^{e}	62.30 ± 1.48^{d}	80.72 ± 1.59^{c}
3mm/70°C	50.42 ± 1.82^{b}	41.06 ± 1.51^{b}	155.92 ± 3.14^{f}	67.74 ± 1.65^{e}	79.26 ± 2.05^{c}
5mm/50°C	43.80 ± 1.91^{a}	43.91 ± 1.15^{b}	109.60 ± 2.92^{a}	49.68 ± 1.82^{a}	61.45 ± 1.31^{a}
5mm/60°C	50.91 ± 1.34^{b}	44.38 ± 2.79^{b}	137.28 ± 3.83^{c}	53.40 ± 2.17^{b}	70.52 ± 1.88^{b}
5mm/70°C	45.20 ± 1.69^{a}	37.62 ± 1.07^{a}	142.39 ± 2.12^{d}	57.90 ± 1.40^{c}	69.90 ± 1.23^{b}
Regression coefficient (β)					
Intercept	54.497	47.338	140.297	57.798	75.310
Slice thickness (A)	−3.799***	−2.448**	– 6.579**	– 4.256**	– 4.740***
Drying temperature (B)	– 0.595*	−3.618**	16.300***	4.960**	4.200**
A^2					
B^2	– 6.092***	– 4.380*	−7.442**	0.062	– 4.920**
Factor interaction (A*B)	1.295**	0.473	0.095	– 0.849*	0.025
R^2	0.9981	0.9952	0.9983	0.9986	0.9974
F-value (model)	853.065***	104.624**	894.779***	318.850***	188.870***
F-value (lack-of-fit)	35.11^{ns}	40.14^{ns}	7.58^{ns}	24.47^{ns}	1.06^{ns}

Values of bioactive compounds represent an average ± standard deviation (n = 3). Means within a column that have no common letter are significantly different ($p < 0.05$). where TPC is total phenolic content, *$p < 0.05$, **$p < 0.001$, ***$p < 0.0001$, and ns means not significant ($p > 0.05$).

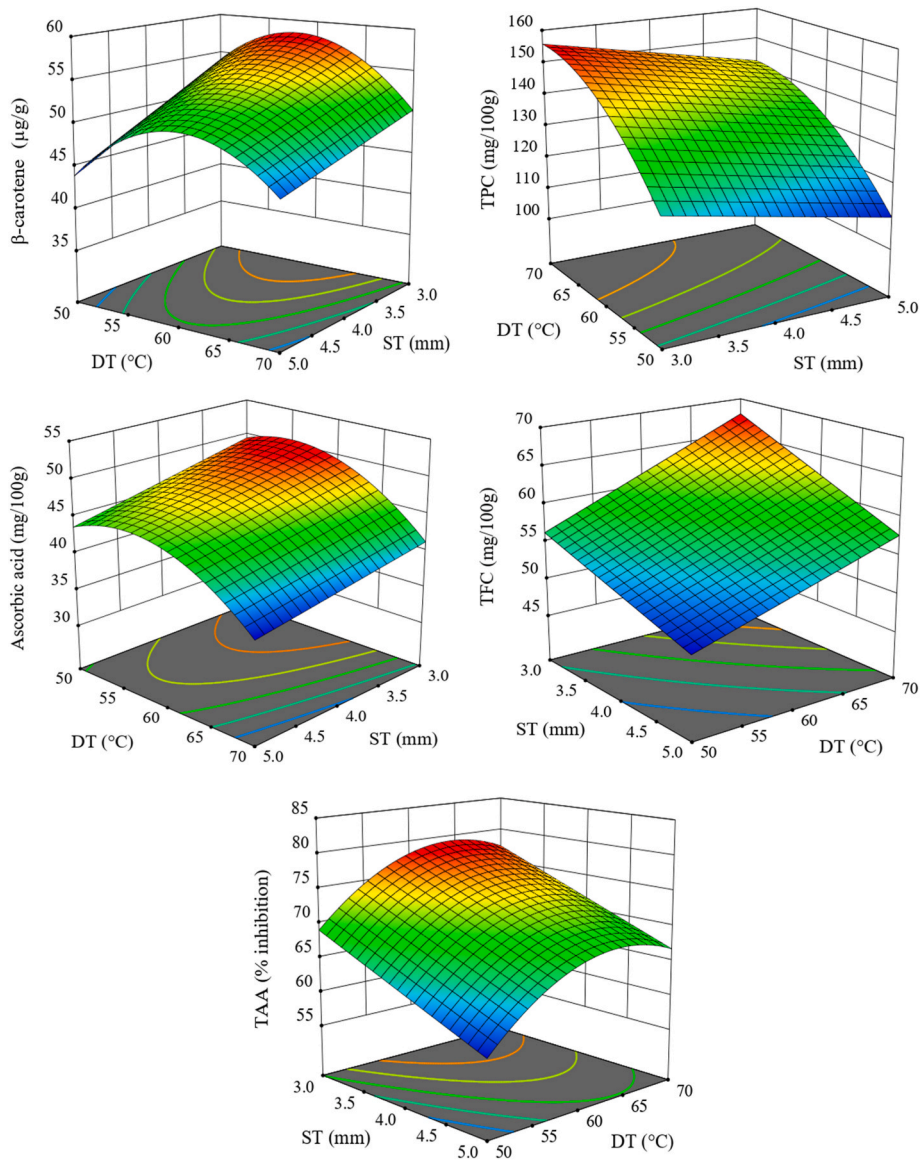

Fig. 7. Response surface plots showing the effect of slice thickness (ST) and drying air temperature (DT) on β-carotene, ascorbic acid, total phenol content (TPC), total flavonoid content (TFC) and total antioxidant activity (TAA) of dried pumpkin slices.

red bell pepper [52], boiled and microwaved broccoli [58] and dried palmyra seed-sprout fleshy slices [9]. Losses of ascorbic acid were higher in the 70 °C dried pumpkins than in samples dried at 50 and 60 °C drying air temperatures (Table 6). According to Korese et al. [9] and Vega-Gálvez et al. [52], ascorbic acid is highly susceptible to heat and breaks down easily at elevated temperatures.

The content of total phenols and flavonoids of the fresh pumpkin was 178.65 ± 2.19 mg GAE/100 g and 69.70 ± 2.05 mg kaempferol/100g, respectively. The contents of total phenols and flavonoids determined in the dried pumpkins varied greatly from 109.60 to 155.92 mg GAE/100g and 49.68 to 67.74 mg kaempferol/100g, respectively (Table 6). The reduction in the levels of total phenols and flavonoids in dried pumpkins can be associated with the degradation of phenolic compounds by the activities of endogenous enzymes such as PPO and the processing heat [17,58–60]. Also, a reduction in total phenolic content was observed in boiled and stir-fried pumpkin [61], boiled and microwaved broccoli [59], and boiled, steamed and microwaved leek, peas and squash [46]. According to Crozier et al. [60], boiling, frying and microwaving caused a reduction in the flavonoid content of tomatoes, onions, lettuce and celery. Mostly, the retention of total phenols and flavonoids in dried pumpkins increased as the slice thickness decreased and drying air temperature increased from 50 to 70 °C (Fig. 7). This might be due to the rapid inhibition of PPO at high drying temperatures due to faster moisture removal and consequently reduce enzymatic degradation of phenolic and flavonoids compounds during the drying process [17,48, 58]. Additionally, higher drying temperatures causes disintegration of plant cell wall which could increase the release of bound phenols and subsequently increase the availability of free phenolic compounds [57, 62]. The values of total phenols measured for dried pumpkins in the present study were lower than the 164.0 mg/100g reported for hot air-dried pumpkin powder but higher than the 39 mg/100g for freeze-dried pumpkin powder [30]. The variations in the contents of total phenols could be attributed to differences in the composition of pumpkins, process settings and processing methods. Largely, the antioxidant activities of fruits and vegetables depend on the composition of the secondary metabolites namely carotenoids, phenolic, ascorbic acid, and flavonoid compounds [56,57,62–64]. The results in Table 6, revealed a decline in antioxidant activity in the pumpkin slices after drying. This was expected due to the adverse effect of the drying process on the antioxidant components. The highest antioxidant activity was

determined in the 3 mm slices thickness dried at 60 °C (80.72 ± 1.59%) and the 5 mm slices dried at 50 °C obtained the least value for antioxidant activity (61.45 ± 1.31%). Higher antioxidant activities of 92.4% and 86.1% were reported for hot-air and freeze-dried pumpkin flour respectively [30] and 81.2–94.6% for boiled and stir-fried pumpkins [61] as compared with the results obtained in this study (Table 6).

3.8. Correlation between the quality attributes of the dried pumpkins

Fig. 8 represents a PCA biplot of dried pumpkin products and the investigated quality properties. Two principal components (PC1 and PC2) discriminated between the dried pumpkin samples where 63.75% and 32.48% of the variability in the raw data was explained by PC1 and PC2 respectively. The wide spread of dried pumpkin samples in the four quadrants of the PCA biplot revealed the variations in the dried pumpkins in terms of the CIELAB colour parameters, bioactive compounds and antioxidant activity as influenced by the drying air temperatures and slice thicknesses. The positive axis of PC1 was described by quality characteristics like a^* and ΔE which are dominant attributes in dried pumpkin samples of 5 mm slice thickness dried at 70 °C (PB_6) and 50 °C (PB_4), respectively (Fig. 8). While the negative axis of PC1 and PC2 were both defined by L^*, total phenols, flavonoids and antioxidant activity, major attributes of Sample PA_2 (3 mm/60 °C) and PA_3 (3mm/70°C), b^*, β-carotene and ascorbic acid which are principal attributes of sample PA_2 described the positive axis of PC2.

Different degrees of correlation between the CIELAB colour parameters and the bioactive compounds of dried pumpkin slices were determined. For example, b^* had strong positive correlation with β-carotene ($r = 0.981$, $p < 0.001$) whereas L^* exhibited strong positive correlations with total phenol, flavonoids and antioxidant activity ($r = 0.933$ to 0.978, $p < 0.001$). Additionally, ΔE values correlated negatively with β-carotene, total phenol, flavonoids and antioxidant activity ($r = -0.780$ to -0.992, $p < 0.05$). Therefore, the colour parameters could be good indicators for the prediction of the contents of bioactive compounds retained in convective air-dried pumpkin slices. The antioxidant activity had a positive relationship with β-carotene ($r = 0.752$), total phenols ($r = 0.903$), flavonoid ($r = 0.917$) and ascorbic acid ($r = 0.241$). Similarly, Priori et al. [60] observed a higher positive correlation between antioxidant activity and total phenols ($r = 0.801$) and a lower correlation between β-carotene and antioxidant activity ($r = 0.217$) in different accessions of *Cucurbita moschata*. Also, a linear relationship between total phenols and antioxidant activity in blueberries ($r = 0.981$) was reported [65].

4. Conclusion

The present study investigated the influence of different slice thicknesses and convective air drying temperatures on the drying and colour change kinetics, and bioactive compounds of dried pumpkin slices. The drying behaviour of the pumpkin slices was adequately described by the Midilli et al. model. CIELAB colour values for L^* and b^* decreased while a^* and ΔE increased throughout the drying process. The rate of change of a^*, b^* and ΔE increase with increasing drying air temperature and reducing slice thickness while the rate of decrease in L^* values of pumpkin slices increases with decreasing drying air temperature and increasing slice thickness. The changes in L^* and b^* values followed the first-order reaction kinetics model while the variations in a^* and ΔE followed the zero-order reaction kinetics ($R^2 > 0.97$). The drying parameters greatly affected the retention of bioactive compounds and antioxidant activity of dried pumpkin slices. Mostly, thinner slices (3 mm) dried faster and had higher retention of bioactive compounds and antioxidant activity than the thicker (5 mm) slices. The pumpkin slices dried at 60 °C had the highest retention of β-carotene, ascorbic acid and antioxidant activity whereas total phenolics and flavonoid contents were higher in the 70 °C dried pumpkin products. The results of the study suggest that 3 mm slice thickness and 60 °C drying air temperature could be used to produce high-quality dried pumpkin products. Besides, the drying and colour change kinetics parameters could be useful for the prediction of the drying behaviour and quality changes in pumpkin slices during convective air drying.

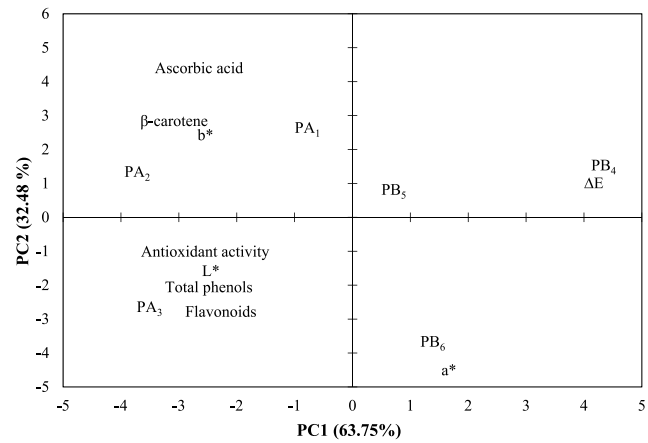

Fig. 8. A PCA biplot of dried pumpkin samples and their quality properties. Where L^*, a^*, b^* and ΔE represent lightness, redness, yellowness and total colour difference respectively. Samples PA_1, PA_2 and PA_3 are pumpkin slices of 3 mm thickness dried at 50, 60 and 70 °C while PA_4, PA_5 and PA_6 represent the 5 mm slice thickness dried at respective air temperatures.

CRediT authorship contribution statement

Solomon Kofi Chikpah: Conceptualization, Methodology, Investigation, Formal analysis, Writing-original draft. **Joseph Kudadam Korese:** Conceptualization, Resources, Supervision, Writing-review & editing, Funding acquisition. **Oliver Hensel:** Resources, Supervision, Writing-review & editing, Funding acquisition. **Barbara Sturm:** Supervision, Validation, Writing-review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This study is part of an ongoing project, UPGRADE Plus (323-06.01-03-2816PROC01), which is financially supported by the Federal Ministry of Food and Agriculture (BMEL), Germany based on the decision of the Parliament of the Federal Republic of Germany through the Federal Office for Agriculture and Food (BLE). The authors are grateful for financial support from the funding body. The University for Development Studies, Ghana is also hereby acknowledged for providing research facilities used during this study.

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