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ORIGINAL RESEARCH PAPER

Mathematical Modeling of Drying Behavior of Carrot Slices in a Cabinet Dryer

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Abstract

Mathematical modeling allows better design, control, and prediction of the drying process for various food products. The aim of the present work was to study the drying behavior of carrot slices and select a suitable mathematical model for the prediction of drying behavior. In addition, the rehydration characteristics of dried carrots were also studied. Whole carrots (2 to 3.5 mm thickness and 3 to 4 cm diameter) were hot water blanched (98℃ for 5 min), prior to drying at 50℃, 55℃, 60℃, 65℃, 70℃ in cabinet dryer. The unblanched carrots were also dried at 50℃ to work as a control. The drying time (10 h) and equilibrium moisture content (EMC), (12.99 ± 1.2% dry basis; db) were higher in control when compared with blanched counterpart (t = 7 h and EMC 9.64 ± 0.5% db) at the same drying condition (at 50℃). The drying time ranged from 4-7 h for blanched samples depending upon the drying temperatures but the EMC of blanched carrots was not affected (p = 0.26) with an increase in drying temperatures. The Page model was best fitted at most of the drying temperatures. Effective mass diffusion was not affected by blanching conditions in the control and blanched samples dried at 50℃. However, when the drying temperature was increased from 50℃ to 70℃, the effective diffusion coefficients was also increased from 1.64 x 10^{-10} to 4.15 x 10^{-10} m^2/s, respectively. The measure of temperature sensitivity (E_a) ranged from 17.8 to 70.7 kJ/mol. Rehydration ratio (RR) of control samples (3.46 ± 0.11) was significantly (p = 0.013) lower than that of blanched samples (4.6 ± 0.2) when compared at the same drying temperature (50℃) and the maximum RR was 5.2 ± 0.87 at 60℃. It can be concluded that the carrots dried at 60°C possessed the highest rehydration quality in comparison to other drying temperatures.

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Introduction

Carrot is a popular root vegetable and possesses array of nutrients like carotenoids (60-134 mg/kg), ascorbic acid (54-132 mg/kg), carbohydrates (6-10.6%) and fibers (1.2-2.4%) (Matejkova & Petrikova, 2010; Raees-ul & Prasad, 2015; Wszelaczyńska et al., 2019; Burns, 2023). Carrot production in Nepal is relatively growing and has been estimated to be 37724.9 MT in 2015/16 (MoAD, 2017), thereby contributing as an important source nutrient of Nepali diet. Carrots can be eaten raw and can also be used in a variety of cooked dishes or even as raw material in food processing industries in the form of juice, concentrate, chips, cubes, shreds, or powder (Sharma et al, 2012; Raees-ul & Prasad, 2015; Burns, 2023). Food processors prioritize finding suitable processing techniques to extend the shelf-life of raw carrots due to their high moisture content, aiming to ensure consistent availability, meet market demand, and enhance flexibility (Mastromatteo et al., 2012).

Refrigeration and controlled atmosphere storage are typically recommended to retain maximum quality attributes for long-term storage but are expensive due to high energy costs for continuous system operation. Likewise, farmers and local food processors lack the basic infrastructure and technical skills to manage such an integrated cold chain (Hasan et al, 2019; Makule et al, 2022). So, hot air drying can be a suitable alternative for preserving carrots by removing both free and bound moisture from food. The hot air drier operates by allowing heat energy from heated air to diffuse into the food and then evaporate off the surface, reducing the moisture content of the samples to a predetermined level. These mechanisms result in the reduction of water activity, which in turn retards deterioration from microbial, enzymatic, and adverse chemical reactions in food (Kucuk et al., 2014; Chinweuba et al., 2016).

Hot air drying of solid foods like carrots in a cabinet dryer is a useful low-cost batch drying technique at a small to moderate scale. In contrast to traditional sun drying techniques, mechanical drying is rapid and provides uniform, hygienic products with minimum losses (Aregbesola et al., 2015). Several researchers have reported the impact of operational parameters like temperature and air velocities on drying time and quality attributes including β-carotene and color changes during drying of carrots (Doymaz, 2004; Zielinska & Markowski, 2012; Eim et al., 2013; Velescu et al., 2013; Guiné et al., 2016; Doymaz, 2017). However, differences in variety (Markowski et al., 2006) and pretreatment conditions, namely blanching (Negi, 2001; Chen et al., 2017; Wang et al., 2021) can also influence the quality characteristics including beta carotene, color, and water absorption properties of carrots. The enzymes commonly found to have deteriorative effects in carrots are peroxidases (PODs) and catalase (Shivhare et al., 2009). Besides, it is worth mentioning that conventional drying temperatures (below 80℃) may not inactivate microbial activity completely. Instead, some thermophilic microorganisms may find a conducive temperature for growth, and also pathogenic microorganisms like *Salmonella* spp. may survive during drying (Chitrakar et al., 2019). So, blanching is a critical step before drying to ensure enzyme inactivation, facilitate moisture removal, shorten drying time, and reduce microbial load. The most effective hot water blanching conditions have been recommended to be ~95℃ for 5 min in the literature (Adhikari, 1995; Shivhare et al., 2009).

Drying kinetics of food is a complex process that involves both heat and mass transfer, mainly moisture transfer. Several attempts have been made by researchers to simulate the drying process by solving mathematical equations related to heat and mass transfer in a simplified way to characterize the system in a commercial drying process. Such a simplified set of mathematical equations is therefore solved to develop mathematical models and predict the performance in the real world. Therefore, these models can be a tool for decision makers for several applications like selecting suitable dryers, predicting moisture content, drying time, and optimizing processing conditions. In other words, without mathematical considerations, operators may have to rely on unsystematic and inefficient practices, which may incur extravagant costs, time, and tedious effort (Chinweuba et al., 2016; Onwude et al., 2016).

One approach to obtain a simplified mathematical model is to conduct drying experiments on a single layer of food products as opposed to deep bed drying. According to Chakraverty et al., (2003), a layer thickness of up to 20 cm can be considered as a thin layer. The temperature and the relative humidity of the drying air are considered in the same thermodynamic state at any time of drying. The main assumption while using thin-layer drying equations is that during the falling rate period, the decrease in moisture is proportional to the instantaneous difference between the moisture content of the product and the equilibrium moisture content of the drying medium. Thin layer drying equations can be categorized as theoretical (consider internal resistance to moisture transfer, diffusivity, conductivity, shape), semi-theoretical (derived from Fick's second law of diffusion) and empirical models (parameters have no physical meaning), the latter two categories consider external resistance to moisture transfer between product and the air (Chinweuba et al., 2016; Onwude et al., 2016; Mahapatra & Tripathy, 2018). Semi-theoretical models are popular and are suitable for modelling fruit and vegetable drying kinetics. These include Lewis, Page, Henderson & Pabis, Wang & Singh, Midilli and other models. Fick's law of diffusion is used by most of the authors to derive moisture diffusivity of the product.

Likewise, on most occasions, the dried product needs to be reconstituted by rehydration before consumption like in instant foods. Dehydrated products should possess fresh-like characteristics such as color, flavor, texture, volume, shape, and size after rehydration. Rehydration ratio is one of the quality indices that define the rehydration characteristics of dehydrated foods. It establishes the ability of food material to return to its original shape and it also shows the degree of cell destruction during drying as affected by its operating conditions. A higher rehydration ratio suggests a good quality dried product as the pores allow water to re-enter the cells easily (Marabi et al., 2003; Van der Sman, 2013).

As drying behavior and hence the rehydration properties of any food are influenced by the type of food matrix and pretreatment conditions, it is important to have a drying model suitable for local foods available in the country. The model thus developed will serve as a guide for industrialists in understanding the drying and rehydration behavior of carrots to avoid wasteful practices like trial-and-error methods or exhaustive search for optimum operating conditions. In this work, the impact of thermal blanching (98℃ for 5 min) followed by drying kinetics of conventionally grown carrots (*Nantis Forte*) available in Kathmandu, the capital of Nepal was studied at various temperatures (50℃, 55℃, 60℃, 65℃, and 70℃) using a cabinet dryer. The unblanched carrots were also dried at 50℃ to serve as a control. Therefore, the objectives of this study were to identify the effect of blanching on the drying and rehydration characteristics of carrots, to evaluate the impact of drying temperatures on drying time and rehydration behavior, and to fit the experimental data with selected mathematical models and estimate the fitted parameters including diffusion coefficient and activation energy, for drying of carrot.

Materials and Methods

Preparation of carrot samples

Fresh carrots (*Daucus carota* L.) were purchased from a local market in Kathmandu valley and kept in a refrigerator at 4℃ prior to use. The samples were washed with tap water to remove the adhering dirt and were sliced in thicknesses ranging from 2.04-3.57 mm and diameters of 3.03-4 cm using a sharp stainless-steel knife. The diameter of the carrot was measured manually using a Vernier caliper and the thickness was measured using a micrometer screw gauge.

300g of fresh carrots
↓
Washing
↓
Slicing (2.04 -3.57 mm)
↓
Blanching (98℃ for 5min)
↓
Dipping in ice water (~ 4ºC)
↓
Removing surface moisture (blotted paper)
↓
Determination of initial moisture content (Hot air oven method)
↓
Thinly arranged in a tray
↓
Drying at 50℃-70℃ (Cabinet dryer)
↓
Dried carrot
↓
Rehydration ratio evaluation
↓
Packaging and storage

Figure 1
Flow diagram of preparation of samples and thin layer drying of carrot slices

Blanching

Prior to loading in a dryer, carrot slices were blanched by dipping the 300 g samples in a hot water bath at 98 ± 2℃ for 5 min. Briefly, the blanched carrot slices were immediately dipped in ice water until the samples were cooled to 4℃ and then surface water was removed using blotting paper. The subsequent experimental procedure has been illustrated in Figure 1.

Drying procedure

At first, for every batch, the initial moisture content of fresh samples was obtained by oven drying method at 105℃ for 3 h (AOAC, 2005). The samples were loaded in a non-perforated tray. Weight loss of samples was recorded by using a digital balance (model SF- 400, Generic, China), which has 1-10000 g measurement range with a reading accuracy of 1 g.

Prior to loading the blanched carrot slices, the hot air cabinet dryer was run for 30 min to reach the equilibrium condition at each of the specific drying temperature (50℃, 55℃, 60℃, 65℃, and 70℃). The unblanched carrot slices (500 g) were also dried at 50℃ to work as a control. Briefly, every batch of the samples blanched (300 g) and unblanched (500 g) were weighed before loading into the dryer and then at every one-hour interval until three consecutive constant weights were noted i.e. equilibrium moisture content was reached at each of the stated drying temperatures. The drying experiments were carried out in triplicates (three independent batches on different days) for each of the stated drying temperatures. Then, the dried samples were packed into polyethylene bags, which were then heat-sealed and stored in incubators at ambient temperature. The moisture ratio at each value was used for drawing the drying curves.

Drying kinetics

Moisture content (db) at each stage was used to estimate the drying rates (DR) at different temperatures. DR was calculated as given in equation 1:

$$[DR] = [M_t - M_{t+dt}]/[dt] \qquad (1)$$

where, M_t is the moisture content at the time (t) = [t], $[M_{t+dt}]$ is the moisture content at time [t+dt] and [dt] is the time interval between these two points during drying. Drying rate (DR) was thus obtained from slope of the plot of moisture versus time.

It was worth mentioning that the initial moisture content of the sample may vary slightly between the batches, and thus to minimize errors and make it readily comparable to other data on similar applications, the moisture content of the sample at different stages of drying was normalized by converting into dimensionless form known as moisture ratio (MR) as suggested by Darvishi et al. (2012) and can be expressed as given in equation 2:

$$[MR] = [M_t - M_e]/[M_o - M_e] \qquad (2)$$

where, M_t is the moisture content (kg moisture/kg dry solids) at any stage during drying, M_e is the moisture content (kg moisture/kg dry solids) at the equilibrium point, known as equilibrium moisture content and M_o is the initial moisture content (kg moisture/kg dry solids) i.e., when drying time (t) = 0. MR was thus defined as a fraction of the free moisture remaining in the sample at drying time (t) = t at specific drying temperature and relative humidity RH.

Model assumptions and limitations:

(1) Ambient temperature and relative humidity of environment fairly remains constant throughout drying time.

(2) Drying air velocity remains constant and temperature gradient within the product is negligible for thin layer drying.

(3) Errors due to variability in samples size and dimensions will be minimized by normalizing moisture content into dimensionless form (MR).

(4) Other pretreatment conditions have not been studied.

Six different types of thin-layer drying models were tested to select the best models that described the drying curve of the carrot slices.

The Lewis model was written as given in equation 3 (Lewis, 1921):

$$MR = \exp(-kt) \qquad (3)$$

Where k is the drying constant (s^{-1}).

The Page model was written as given in equation 4 (PAGE, 1949):

$$MR = exp(-kt^n) \quad (4)$$

Where k is the drying constant (s^{-1}) and n is the model constant (dimensionless).

The Henderson and Pabis model was written as given in equation 5 (Westerman et al., 1973):

$$MR = aexp(-kt) \quad (5)$$

Where k is related to effective diffusivity and a is dimensionless model constant.

The Wand and Singh model was written as given in equation 6 (Wang & Singh, 1978):

$$MR = 1+at+bt^2 \quad (6)$$

Where a and b are dimensionless model constants.

The Midilli model was written as given in equation 7 (Midilli et al., 2002):

$$MR = aexp(-kt)+bt \quad (7)$$

Where a and b are the model constants, and k is the drying constant (s^{-1}).

The Logarithmic model was written as given in equation 8 (Togrul & Pehlivan, 2003):

$$MR = aexp(-kt)+c \quad (8)$$

Where a and c are dimensionless empirical constant.

In this study, diffusivity was assumed to be the only physical mechanism during the falling rate period to describe the transfer of moisture to the food surfaces and can be mathematically represented by using Fick's second law of diffusion for a slab as shown in equation 9:

$$\frac{\partial M}{\partial t} = D_{eff}\partial^2 M/\partial x^2 \quad (9)$$

The solution of Fick's equation can be applied for different solid geometry, e.g. slab, with some assumptions; uniform initial moisture distribution, negligible external resistance to heat and mass transfer, constant temperature, and constant effective diffusion coefficient. According to Crank, solving equation 9, with appropriate initial and boundary conditions by treating carrot slices as circular slab with constant diffusivity can be written as:

$$MR = \left[\frac{8}{\pi^2}\right]\left[\sum \frac{1}{(2n+1)^2} exp\left(-(2n+1)\pi^2 \frac{D_{eff}}{4L^2}\ t\right)\right] \quad (10)$$

where D_{eff} is the effective diffusivity (m^2/s), and L is the half thickness of slab (m). For long drying times and by only using the first term, n = 0, equation 10 can be expressed in logarithmic forms as shown in equation 11 (Darvishi et al., 2012).

$$Ln(MR) = Ln\left[\frac{8}{\pi^2}\right] -[\pi^2 \frac{D_{eff}}{4L^2}]\ t \quad (11)$$

Here a plot of Ln(MR) vs drying time generates a straight line, from which the D_{eff} can be estimated from the slope $[\pi^2 \frac{D_{eff}}{4L^2}]$ of the line.

Activation energy

The Arrhenius equation can be used to describe the temperature sensitivity of D_{eff} in terms of activation energy (E_a, kJ/mol) which can be obtained from the fitted curve as shown in equation 12 suggested by Zielinska & Markowski (2010).

$$D_{eff} = D_o\ exp\ (- E_a/RT) \quad (12)$$

Where, D_o is the constant known as the pre-exponential factor (m^2/s), R is the universal gas constant (8.3143 kJ/molK) and T is the absolute temperature (ºK).

Rehydration ratio

The ability of dried food products to re-absorb moisture when soaked in water can be explained in terms of rehydration ratio (RR). The procedure was followed as described by Prakash et al., (2004). Briefly, dried carrot samples (5 g) were immersed in distilled water (150 ml) put in a 500 ml capacity beaker and boiled for 5 min. Water was drained, and excess water from the rehydrated carrots was removed using a paper towel. Rehydration ratio (RR) was then obtained by dividing the rehydrated weight by the initial weight using equation 13 as under:

$$RR = \frac{\text{Weight of rehydrated sample}}{\text{Weight of dried sample}} \quad (13)$$

Data analysis

Data were analyzed using MATLAB (R2022b), Mathworks Inc, USA) software package. The goodness of fit of the models were based on maximum value of coefficient of determination (R^2) and minimum sum of squared errors (SSE). The parameters of models were estimated using a curve fitter by custom fitting of the equations as available in the software. Test of significant difference between the treated and untreated samples was conducted at 5% significance level (p = 0.05).

Results and Discussion

Impact of blanching

The drying curve (at 50℃) of blanched and unblanched carrot slices is depicted in Figure 2a. It was found that blanching significantly affected the drying kinetics of carrots resulting in the reduction of drying time from 10 h to 7 h. Similar results were also reported in blanched pineapple slices (Agarry et al., 2013). The drying curve showed that at first the rate of removal of water was very high in blanched samples and then gradually decreased until it reached the asymptote at equilibrium moisture value. Pretreatment (98°C for 5 min) might have relaxed the cellular structure of the blanched carrot slices that facilitate faster (3 h) removal of the water during drying when compared with unbalanced samples. Likewise, the equilibrium moisture content of blanched samples was lower (9.64% db) than the unblanched samples (12.99% db) at the same drying condition. This could be due to higher binding ability of water in unblanched samples possessing rigid cell structures. In addition, some soluble solids, that possibly bind water, are also lost during blanching, and might have resulted in a lower level of residual moisture in the final dried product. Variations in the final moisture content of the dried leafy vegetables due to pretreatment conditions (blanching time-temperature combinations) have also been reported by Njoroge et al. (2015).

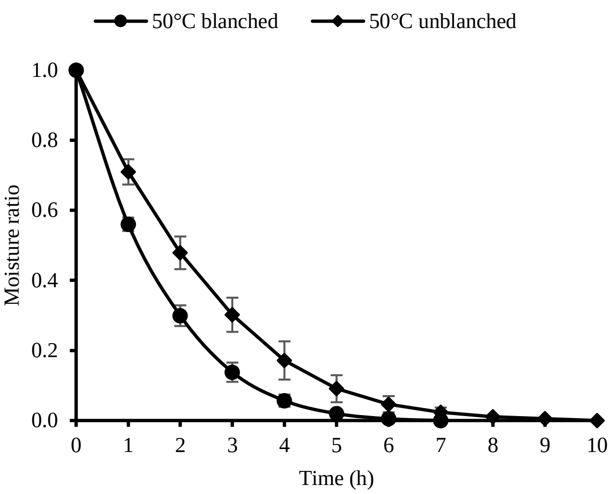

Figure 2a
Drying curve (moisture vs time) of carrot at 50°C

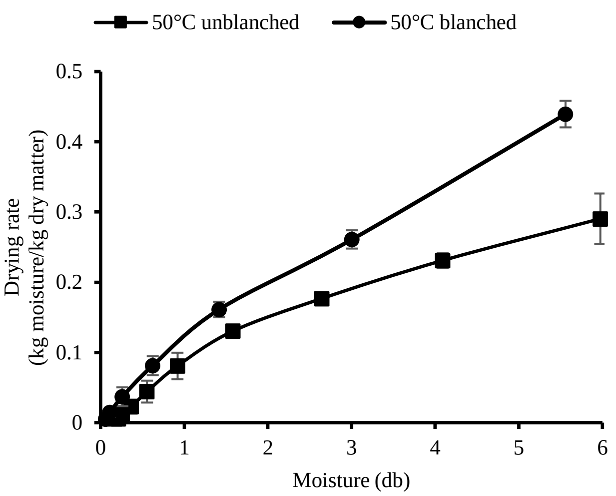

Figure 2b
Drying rate vs Moisture content (db) at 50°C

A plot of drying rate (kg moisture/kg dry matter) versus moisture content (db) (Figure 2b) did not show a constant rate period in both the blanched and unblanched samples possibly due to transient time where the measurements were taken at longer time intervals (1 h). The dominant falling rate period during drying thus indicated that internal mass transfer in these samples was predominantly due to diffusion. The moisture diffusivity of carrots during air drying has also been reported in the literature (Zielinska & Markowski, 2010).

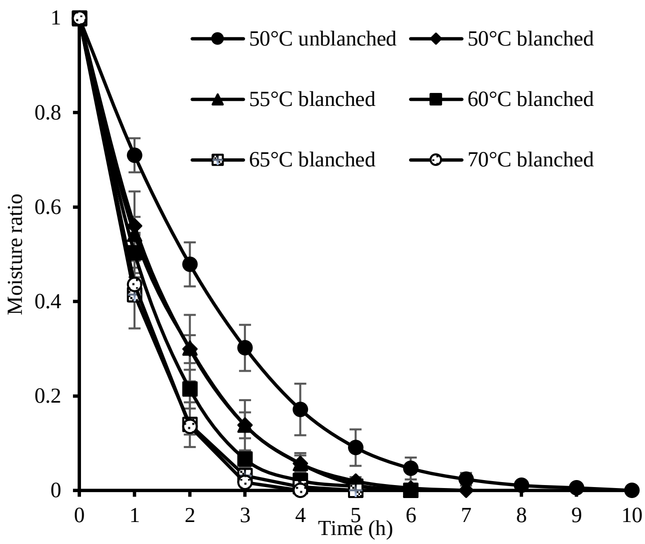

Figure 3a
Changes in moisture ratio of carrot slices throughout the drying time

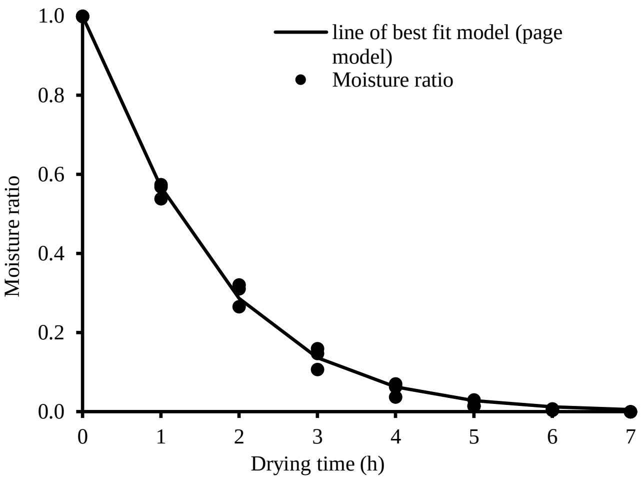

Figure 3b
Experimental and predicted moisture ratio variation with drying time of blanch carrot during cabinet drying at 50°C

Drying curves and mathematical modelling

Blanched carrot samples were dried at 50°C, 55°C, 60°C, 65°C, and 70ºC to understand the impact of heat on carrot slices (Figure 3a). The results showed that temperature rise reduced the drying time and its value ranged from 4-7 h depending upon the drying temperatures. The results are in agreement with the findings reported by Doymaz (2004) for carrot slices (≥ 4mm thickness) blanched at 80°C. Likewise, the equilibrium moisture content of dried blanched carrot was not significantly different (p = 0.26) with the increase in drying temperatures.

The experimental results of the change in moisture ratio during drying were fitted with various drying models and the parameters were estimated as shown in Table 1. It was found that the value of R^2 ranged between 0.97 and 0.99 in all the selected models. The Page models (with two parameters; k, n) were best fitted at most of the drying temperatures and their values of SSE ranged between 0.004 and 0.024. It can be seen that the Logarithmic model (SSE = 0.032) can be best represented at 55°C drying temperature. However, it is suggested to use Page model (SSE = 0.037) even at this temperature to avoid complexity and overfitting when using the Logarithmic model (with three parameters; k, a, c). Figure 3b shows the line of best fit obtained by plotting the predicted moisture ratio using the estimated parameters of the Page model and then compared with the experimental data points at each of the drying temperatures. Page model has also been suggested while studying air drying characteristics of carrots by Zielinska & Markowski, (2010) while Doymaz (2017) recommended the Midilli model, and Mahapatra, & Tripathy, (2018) suggested Wang and Singh model for similar products.

The estimated parameter (n) in the Page model is very close to 1 (1.1-1.3), and thus the value of another fitted parameter, k, is comparable to the drying rate constant (k) in the Lewis model. This parameter k is sensitive to changes in temperature and hence its value increased by ~1.5 times at 70°C when compared to 50°C. Likewise, the parameter k is significantly different ($p<0.05$) for blanched samples when compared with unblanched (control) ones at the same drying temperature (50°C). As explained earlier, this can be attributed to the reduced drying time of blanched samples.

Table 1
Statistical result of different drying models at various temperature

Model	*Treatments*											
	50°C unblanched		*50°C blanched*		*55°C blanched*		*60°C blanched*		*65°C blanched*		*70°C blanched*	
	Constant	*SSE/ R^2*	*Constant*	*SSE/ R^2*	*Constant*	*SSE/ R^2*	*Constant*	*SSE/ R^2*	*Constant*	*SSE/ R^2*	*Constant*	*SSE/ R^2*
Lewis ***MR = exp(-kt)***	k=0.415	0.051/ 0.98	k=0.0629	0.013/ 0.99	k=0.638	0.041/ 0.98	k=0.766	0.018/ 0.99	k=0.945	0.021/ 0.99	k=0.932	0.017/ 0.99
Page ***MR = exp(-kt^n)***	k=0.322	0.024/ 0.99	k=0.565	0.006/ 0.99	k=0.588	0.037/ 0.98	k=0.688	0.160/ 0.99	k=0.876	0.016/ 0.99	k=0.825	0.004/ 0.99
	n=1.229		n=1.148		n=1.114		n=5.000		n=1.201		n=1.325	
Henderson and Pabis ***MR = aexp(-kt)***	a=1.032	0.047/ 0.98	a=1.011	0.013/ 0.99	a=1.006	0.025/ 0.98	a=1.012	0.018/ 0.99	a=1.006	0.021/ 0.99	a=1.010	0.017/ 0.99
	k=0.426		k=0.635		k=0.641		k=0.773		k=0.950		k=0.939	
Wang and singh ***MR = 1+at+bt^2***	a=-0.271	0.072/ 0.98	a=-0.394	0.068/ 0.97	a=-0.422	0.069/ 0.97	a=-0.469	0.068/ 0.97	a=-0.565	0.075/ 0.97	a=-0.621	0.012/ 0.99
	b=0.018		b=0.037		b=0.043		b=0.052		b=0.075		b=0.094	
Midilli ***MR = aexp(-kt)+bt***	a=1.021	0.035/ 0.98	a=1.050	0.015/ 0.99	a=1.000	0.035/ 0.98	a=0.1008	0.014/ 0.99	a=1.004	0.019/ 0.99	a=1.000	0.571/ 0.99
	k=0.398		k=0.612		k=0.599		k=0.741		k=0.915		k=8.999	
	b=-0.004		b=-0.005		b=-0.007		b=-0.005		b=-0.005		b=0.025	
Logarithmic ***MR = aexp(-kt) + c***	a=1.065	0.033/ 0.99	a=1.036	0.007/ 0.99	a=1.042	0.034/ 0.98	a=1.037	0.013/ 0.99	a=1.029	0.018/ 0.99	a=1.068	0.007/ 0.99
	k=0.376		k=0.581		k=0.571		k=0.711		k=0.883		k=0.799	
	c=-0.046		c=-0.031		c=-0.043		c=-0.030		c=-0.025		c=-0.063	

Estimation of effective moisture diffusivity and activation energy

As stated earlier, when only a falling rate period was observed, it was understood that the drying was predominantly happening due to diffusion phenomena and thus the moisture transfer was described by applying Fick's second law of diffusion. By using the curve fitting tools and from equation 11, the effective moisture diffusivity (D_{eff}) was estimated in the range of 1.64×10^{-10} to 4.15×10^{-10} m^2/s depending on the drying temperature (Table 2). The higher value of D_{eff} at the higher temperature indicated higher water vapor pressure inside the pores of carrot slices resulting in pressure-induced opening of the pores and hence faster moisture diffusion (Mahapatra & Tripathy, 2018).

The results also showed that D_{eff} in unblanched (control) samples and blanched samples were not significantly different (p>0.05) at the same drying temperature (50°C). The results obtain align with the values (2.58×10^{-10} to 17.2×10^{-10} m^2/s) reported by Doymaz (2017) and Zielinska & Markowski (2010) for hot air drying of carrots but lower than the values (2.59×10^{-8} to 6.36×10^{-8} m^2/s) estimated by Mahapatra & Tripathy (2018) for solar drying of carrots. Variations in results can be due to shape, initial moisture content of the material, drying methods, and drying equipment.

The measure of temperature sensitivity of D_{eff} can be estimated from the Arrhenius equation (12) that contains a parameter known as an activation energy (E_a). Higher the E_a value, the lesser will be the resistance to change in temperature for D_{eff}. This parameter is also an index that indicates the bonding potential of moisture in moist material (Mahapatra & Tripathy, 2018). Results showed that the activation energy for changes in D_{eff} of carrots was in the range of 17.8 to 70.7 kJ/mol. This value falls in the general range of 12.7 to 110 kJ/mol for food materials (Aghbashlo, 2008). For instance, E_a in the range of 38.2-45.6 kJ/mol has been reported for solar-dried carrots (Mahapatra & Tripathy, 2018), 23.63-33.24 kJ/mol has been reported for hot-air drying of carrot slices (Wu et al., 2014) and 35.5-43.4 kJ/mol for variously pretreated carrots slices dried in a convective dryer (Doymaz, 2017).

Table 2
Estimated effective moisture diffusivity and activation energy of carrot slices at different drying temperatures

Temperature (°C)	*D_{eff} (m^2/s)*	*E_a (KJ/mol)*
50 (unblanched)	1.617×10^{-10}	44.25
50 (blanched)	1.641×10^{-10}	44.25
55 (blanched)	2.319×10^{-10}	44.25
60 (blanched)	2.289×10^{-10}	44.25
65 (blanched)	4.017×10^{-10}	44.25
70 (blanched)	4.151×10^{-10}	44.25

Comparison of rehydration ratios

Rehydration ratio (RR) measures the extent of structural damage that results from changes in characteristic properties such as porosity and water binding ability of food materials due to drying. As shown in Figure 4, RR of unblanched (control) samples (3.46 ± 0.11) was significantly (p = 0.013) lower than that of blanched samples (4.6 ± 0.2) when dried at 50°C. The lower RR in control samples could be explained by the higher initial moisture content (equilibrium moisture content) of the dried sample, which leads to faster saturation during water uptake. The result regarding the RR of blanched carrots is comparable to carrots dried on a solar cabinet dryer (RR 4.7) but lower than that dried on a fluidized bed dryer (RR 5.62) at 50°C and higher than that dried in a mechanical dryer at 60°C as reported in the literature (Prakash et al., 2004; Al-Amin et al., 2015).

Figure 4 also showed that the RR of blanched samples increased with an increase in air temperature up to 60°C and then started to decline with further increase in drying temperatures at 65°C 50°C and 70°C. The maximum RR was 5.2 ± 0.87 at 60°C. As the drying temperature increases, it initially enhances the ability of macromolecules within dried carrots to absorb water and swell. This leads to an increase in the RR of blanched samples up to 60°C, indicating improved water absorption and swelling properties. However, beyond 60°C, the RR begins to decline, which could be attributed to higher structural damage within the carrots. This structural damage may impair the water-binding ability of cellular components, leading to a decrease in RR at higher drying temperatures of 65°C and 70°C. Therefore, while higher drying temperatures initially support water absorption and swelling, excessive heat may cause structural damage, ultimately reducing the effectiveness of the carrots' hydration properties. Similarly, higher drying temperature might have caused shrinkage as well as alteration of viscoelastic properties due to structural damage. Influence of viscoelastic behavior due to cross-linked network of cellular materials on hydration properties has also been reported by Van der Sman et al., (2013). Likewise, reduction in absorption of water in blanched and dried carrots at higher drying temperature (70°C) has also been reported by Doymaz (2017).

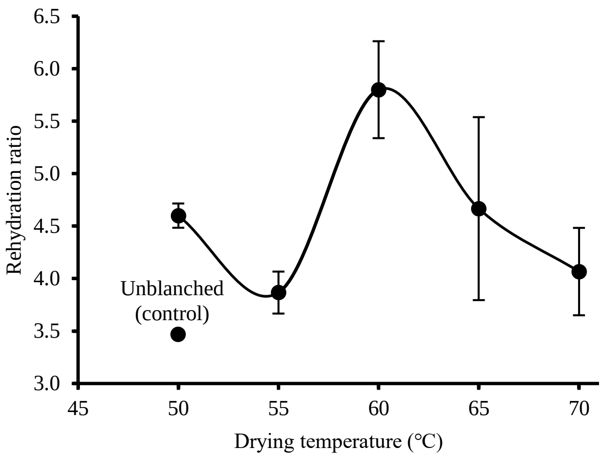

Figure 4
Effect of drying temperatures on rehydration ratio of blanched carrots

Conclusions

Falling rate period was only observed under the experimental conditions where the mass transfer process could be explained by the diffusion mechanisms. Blanching significantly reduced drying time from 10 h to 7 h when dried at 50°C. Drying times in blanched samples were also considerably reduced with increased temperature level. The drying behavior of carrots dried in the cabinet dryer was found to fit the Page model. Effective diffusion was not affected between control (unblanched) and blanched samples at 50°C. However, an increase in drying temperature from 50°C to 70°C increased the effective diffusion coefficients from 1.64×10^{-10} to 4.15×10^{-10} m^2/s, respectively. The measure of temperature sensitivity (E_a) ranged from of 17.8 to 70.7 kJ/mol. RR of unblanched (control) samples (3.46 ± 0.11) was significantly ($p = 0.013$) lower than that of blanched samples (4.6 ± 0.2) when compared at the same drying temperature (50℃) and the maximum RR was 5.2 ± 0.87 at 60℃. It can be concluded that the carrots dried at 60°C possessed the highest rehydration quality in comparison to other drying temperatures.

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Compliance with Ethical Standards

Conflict of Interest

The authors declare no conflict of interest.

Ethical approval

This work did not involve any animal study.

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