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Characterization of Carrot *(Daucus Carota)* Slices During Oven Drying

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Abstract
This research investigated the drying properties of yellow carrots (Daucus Carota) using an oven dryer, with the potential to significantly improve the design of oven dryers. The study utilized the DS Memmert Universal oven UF55 dryer, drying 1.5, 3.0, and 4.5-mm thick carrot slices at 60, 70, and 80℃ temperatures. The variation in moisture content with time was recorded during dehydration to monitor the drying progress. The drying, drying rate, and Krischer curve plots were constructed using the recorded variation in moisture content over time. The study estimated the effective moisture diffusivities and dehydration activation energies of the carrots, as well as their thermodynamic properties, such as changes in Enthalpy (ΔH), Entropy (ΔS), and Gibbs free energy (ΔG). Observations indicated that carrot slices achieved a moisture ratio (dry basis) below 0.1 after approximately 25 and 70 minutes of drying. The statistical analysis of the moisture ratio data revealed that all models fitted to the thin-layer drying model had a coefficient of determination (R^2) value better than 0.99. The effective moisture diffusivity of the 1.5, 3.0, and 4.5-mm thick carrot slices, dehydrated at 60, 70 and 80℃, varied between 8.30E-09 to 6.78E-10 m^2s^{-1}. The study observed that the activation energy of dehydration varied between 3.2753E+04 and 2.3449E+04 J/mol for different slice sizes based on the moisture-content history data. The thermodynamic properties, such as changes in ΔH, ΔS, and ΔG, were subsequently estimated to range between 20,514.37 and 29,984.58 $J.mol^{-1}$, -123.77 and -109.38 $J.mol^{-1}.K^{-1}$, and 66,407.83 and 64,204.92 $J.mol^{-1}$, respectively. The data obtained from the study will prove beneficial in the specification, design, modelling, and operation of oven dryers.

Keywords: *Carrots, Oven Drying, Drying Curves, Thin Layer Dying Models, Thermodynamic Characteristics.*

1.0 INTRODUCTION

C*arrots* are root vegetables that are grown all over the world and are rich in nutrients. Although potatoes and broccoli are more nutritious (USFDA, 2008), carrots are still a great source of vitamins A and K, potassium and fiber. They also contain many valuable antioxidant nutrients, such as vitamin C and beta-carotene, which can help prevent certain cancers, reduce cholesterol and the signs of premature ageing, and improve vision. Additionally, carrots can positively affect human skin health, immune system, digestion, cardiovascular health, oral health, and body detoxification.

Nutritionists recommend moderate carrot consumption due to their high sugar content, especially in overripe carrots (da Silva Dias, 2014; Joshi & Nande, 2024). Other than this, it is obvious that consuming carrots is beneficial. In many regions, carrots are dried, powdered and used for bread, cakes, soups, stews, curries, and pies. They can also be eaten raw or as a snack. (Gupta, 2000) . They are sometimes eaten raw or eaten as a snack. The Chinese (Chapman, 2009), the Africans (Amagloh *et al,* 2012), and the Europeans (Rubatzky *et al.*, 1999), make carrot soup, carrot porridge and carrot puree respectively (Ding & Liu, 2024). A post-harvest preservation method is therefore needed to ensure that carrots are available throughout the year. Drying is a common method used to preserve carrots. Grishin *et al.* (1973) studied the kinetics of dehydrating vegetables and changes in the main chemical constituents (ascorbic acid, carotenes, essential oils, total sugars) due to the drying process. It was suggested to dry diced carrots (5-8 mm cubes) at 160°C and use them with onions as essential snack ingredients.

In 2002, Reyes *et al.* analyzed the drying process for carrot dice batches of 3 kg, measuring 9 x 9 x 3 mm, in a mechanically agitated fluidized bed drier. The drier operated at temperatures ranging from 70 to 160°C, air velocities of 1.1 to 2.2 m/s and stirring rates of 30 to 70 rpm. They found that drying at around 130°C with a drying time of less than 12 minutes resulted in minimal loss of carotenes. In 2003, Machewad *et al.* studied the drying properties of carrots and their suitability for producing various value-added products. The study found that carrots were chemically suitable for drying, and carrot shreds were feasible for further processing. However, leaching losses were observed in reducing and total sugars during pre-treatments, negatively affecting the beta-carotene content. The reconstitution ratio of dried carrot shreds was higher in pre-treated samples than in untreated. The shredded and dried carrots dehydrated in the open air had a lower reconstitution ratio; this suggested that dried carrot shreds were suitable for use as a base material for the preparation of carrot halwa. Upadhyay *et al.* (2008) studied carrot pomace's characterization and dehydration kinetics in open sun and in a tray dryer at 60, 65, 70, 75 and 80°C. Their observation indicated that by increasing the temperature from 60 to 75°C, β-carotene retention increased from 9.86 to 11.57 mg/100g, while ascorbic acid retention decreased from 22.95 to 13.53 mg/100g. Optimal drying was observed at 65°C based on β-carotene and ascorbic acid retention. Upadhyay *et al.* (2008) claimed that the Page thin layer drying model better-predicted drying data than the Lewis model based on the correlation coefficient (R^2).

This study uses an oven dryer to examine the dehydration kinetics and thermodynamic characteristics of carrot slices. Understanding these kinetics will help design continuous processing equipment and reduce the production time of dehydrated products.

2.0 METHODS, METHODOLOGY AND MATERIALS

2.1 Materials, Measurements and Sample Preparation

Conical and cylindrical root vegetables, known as carrots (*Daucus Carota*), were obtained from the local market in Lagos, Nigeria. The moisture content of the carrot slices was measured using an OHAUS Moisture Analyzer (MB45, OHAUS, Parsippany, NI, USA) with a precision of 0.01g and 0.01% for weight and moisture content, respectively. Additionally, the average dimensions (L for length, W for width, and T for thickness in mm) of the carrots were measured using a digital Vernier caliper (+0.02 mm) (Mitutoyo, Waterbury, CT, US). To prepare the carrots for this study, they were thoroughly washed, peeled, and sliced into 1.5, 3.0, and 4.5mm slices using a Mandolin slicer (SKU 1155700V2, OXO, Chambersburg, PA, USA).

2.2 The Experimental Process

The dehydration process was conducted using a DS Memmert Universal UF55 oven dryer (Memmert GmbH + Co.KG, 2022). Figure 1 provides a schematic diagram of the oven dryer. Fifty grams of uniformly sliced carrots were placed in each of the eleven Petri dishes. The dishes were then placed in the oven, pre-set to a specific temperature. After specific time intervals, one of the Petri dishes was removed from the oven, and the moisture content on a wet basis of the carrot slices was measured using a moisture analyzer. The experiments were conducted in triplicates to ensure the reproductivity of the results. The average values of moisture content were taken for final calculations. The oven dryer has a built-in fan to ensure that the temperature of the oven is uniform.

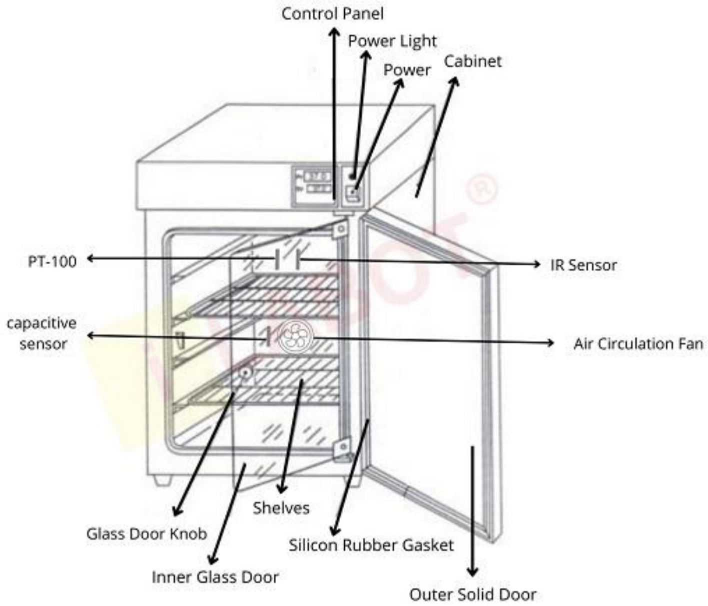

Figure 1: Schematic diagram of Oven dryer (Memmert GmbH + Co.KG, 2022)

2.3 Processing Experimental Moisture Content History Data

The moisture content history data gathered which was on a wet basis was first converted to the moisture content history data on a dry basis at any drying time and then to a moisture ratio using Equation 1. (Pala *et al.,* 1996) and Doymaz, 2004),

$$MR = MC_t/MC_i \quad (1)$$

where

MC_t is the moisture content of carrot after drying for time t and

MC_i is is the initial moisture content of fresh carrot all in the unit of g of water removed/g of solids.

2.3.1 Thin-Layer Drying Models

Many thin-layer drying models exists (Cihan and Ece 2001). However, the various drying models used in the food industry and listed in Table 1, were fitted to the moisture ratio (MR) to find the most used model for thin layer drying (Muhlbauer & Muller, 2020, El-Mesery *et al.,* 2024; Wang *et al.,* 2024). MATLAB Version R2023b employing the Trust Region and Levenberg-Marquardt Method for Nonlinear Least Square Problems (Gavin, 2013) were used to determine the parametric coefficients of each model through regression analysis. The models with a Coefficient of Determination (R^2) close to 1, Sum of Square Error (SSE) and Root Mean Square Error (RMSE) close to 0 were considered the most suitable (Akpinar, 2010; Tunde-Akintunde & Afon, 2010; El-Mesery & Mwithiga, 2014; John *et al*., 2014; Ogunnaike, 2010). After selecting the appropriate thin-layer drying model, drying curves are plotted based on the obtained data.

2.3.2 Effective Moisture Diffusivity Determination

Fick second law relates Moisture ratio with drying time according to Equation 2 (Crank, 1975).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}e^{-\left(\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right)} \quad 2$$

Equation 3 simplifies Fick's law for thin slices (Lopez *et al.,* 2000). Jena and Das (2007) and Taheri-Garavand *et al.* (2011) discussed extensively the reason for the simplification.

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \quad 3$$

Linearize Equation 3 to get Equation 4

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

Where,

MR is the moisture ratio,

D_{eff} (m^2s^{-1}) is the effective moisture diffusivity,

L (m) is the sample thickness and

t is the drying time (s).

A linear regression analysis between $\ln(MR)$ and time, t , gives a slope k_d as in Equation 5

$$k_d = \frac{\pi^2 D_{eff}}{4L^2} \quad 5$$

from which D_{eff} can be obtained according to the equation 6

$$D_{eff} = 4L^2\, k_d/\pi^2 \quad 6$$

2.3.3 Activation energy

Effective Moisture Diffusivity is significantly affected by temperature T, so an Arrhenius-type relationship is used to express the effect of temperature on effective diffusivity (Equation 7).

$$D_{eff} = D_0 e^{-\frac{E_a}{RT}} \quad 7$$

A linear regression analysis between $\ln(MR)$ and time, t , gives a slope k_r as in Equation 8

$$ln(D_{eff}) = ln(D_o) - \left(\frac{E_a}{RT}\right) \quad 8$$

Where,

D_{eff} (m^2s^{-1}) is the effective moisture diffusivity,

D_0 (m^2s^{-1}) is the pre-moisture diffusivity,

T (K) is absolute temperature and

R = 8.3145 J/mol·K.

2.4.4 Thermodynamic Properties

The thermodynamic properties of mass transfer process in the carrot slices were determined by Equations. 9, 10 and 11. The values obtained for the Activation energy (E_a) were used to evaluate values for Differential Enthalpy (ΔH), Differential Entropy ((ΔS)) and Gibbs free energy ((ΔG)) by mathematical expressions (Sanchez *et al.,* 1992):

The thermodynamic properties of the drying process were determined using Equations 9 to 11 (Jideani and Mpotokwana, 2009; Costa *et al.*, 2016; Nwakuba *et al.,* 2018)

$$\Delta H = E_a - RT_a \quad 9$$

$$\Delta S = R\left(\ln D_o - \ln\frac{K_B}{h_p} - \ln T_a\right) \quad 10$$

$$\Delta G = \Delta H - \Delta(T_a S) \quad 11$$

This study was carried out at constant temperature, therefore Equation 11 can be adjusted to give Equation 12

$$\Delta G = \Delta H - T_a \Delta S \quad 12$$

Where:

ΔH = enthalpy variation ($Jmol^{-1}$);
ΔS = entropy variation ($Jmol^{-1}K^{-1}$);
ΔG = Gibbs free energy variation ($Jmol^{-1}$);
D_0 = the pre-exponential factor of the Arrhenius equation (m^2/s).
R = Universal gas constant 8.3145 J/mol·K.
K_B = Boltzmann constant (1.38×10^{-34} Js^{-1});
h_p = Planck constant (6.626×10^{-34} Js^{-1});
T_a = absolute temperature (°K).

3.0 RESULTS AND DISCUSSIONS

Thin carrot slices of 1.5, 3.0, and 4.5mm thickness, with an initial moisture content of 663% on a dry-basis, were dried until the moisture ratio was less than 0.1. The moisture ratio at each drying time was estimated using Equation 1. Five thin-layer drying models, presented in Table 1, were fitted to the moisture ratio data. The Regression Coefficients for fitting the moisture ratio history data to five thin-layer models are detailed in Table 2. Based on the results, all tested models accurately describe the drying kinetics of carrot slices with thicknesses of 1.5 mm, 3.0 mm, and 4.5 mm. The coefficient of determination (R^2) value was more significant than 0.98, and the RMSE and SSE were negligible. For simplicity, the Page Model is used to estimate predicted moisture ratios. Also presented in Table 3 are the Parametric Coefficients for the five models.

Table 1: Thin Layer Drying Models

S/N	Name	Model	Source
1	Page	$MR = \exp(-kt^n)$	(Page, 1949) (Akoy, 2014)
2	Silva *et al.* Model	$MR = \exp\,(-at - b\sqrt{t})$	(Pereira ,2014)
3	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(et\ al. - ht)$	(Karathanos ,1999)
4	Haghi & Ghanadzadeh	$MR = a\exp(-bt^c) + dt^2 + et + f$	(Haghi and Ghanadzadeh (2005).
5	Logarithmic	$MR = a\exp(-kt) + c$	(Togrul and Pehlivan, 2003)

Table 2: Regression Coefficients for fitting data to 5 thin-layer models for carrot slices

	Temperature →	60℃			70℃			80℃		
Size	Model	R^2	SSE	RMSE	R^2	SSE	RMSE	R^2	SSE	RMSE
1.5 mm	Logarithmic	1.00	0.00	0.01	1.00	0.00	0.00	1.00	0.00	0.00
	Haghi and Ghanadzadeh	1.00	0.00	0.04	1.00	0.00	0.00	1.00	0.00	0.00
	Silva *et al.*	1.00	0.00	0.00	1.00	0.00	0.01	1.00	0.00	0.00
	Peleg	1.00	0.00	0.02	1.00	0.01	0.02	1.00	0.00	0.02
	Modified Henderson and Pabis	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
3.0mm	Logarithmic	1.00	0.00	0.01	1.00	0.00	0.01	0.99	0.01	0.03
	Haghi and Ghanadzadeh	1.00	0.00	0.00	1.00	0.00	0.01	1.00	0.00	0.01
	Silva *et al.*	1.00	0.00	0.00	1.00	0.00	0.01	1.00	0.00	0.02
	Peleg	1.00	0.00	0.02	1.00	0.00	0.02	0.99	0.01	0.02
	Modified Henderson and Pabis	1.00	0.00	0.04	1.00	0.00	0.00	1.00	0.00	0.02
4.5mm	Logarithmic	1.00	0.00	0.02	0.99	0.01	0.03	1.00	0.00	0.01
	Haghi and Ghanadzadeh	1.00	0.00	0.02	1.00	0.00	0.01	1.00	0.00	0.01
	Silva *et al.*	1.00	0.00	0.02	1.00	0.00	0.02	1.00	0.00	0.01
	Peleg	0.99	0.01	0.03	0.99	0.01	0.04	0.99	0.01	0.03
	Modified Henderson and Pabis	1.00	0.00	0.02	1.00	0.00	0.02	1.00	0.00	0.01

Table 3: Parametric Coefficients for The Models Obtained By Fitting Data To The Thin Layer Models For The Carrot Slices

	60℃			**70℃**			**80℃**		
Logarithmic Model									
Constants	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm
A	9.82E-01	9.94E-01	1.02E+00	9.90E-01	9.74E-01	1.13E+00	9.92E-01	9.59E-01	1.02E+00
B	4.87E-02	3.96E-02	3.39E-02	8.68E-02	4.66E-02	1.43E-02	9.01E-02	7.03E-02	5.97E-02
C	8.80E-03	6.00E-04	-1.43E-02	9.70E-03	1.23E-02	-1.02E-01	4.40E-03	8.30E-03	-7.20E-03
Haghi & Ghanadzadeh Model									
Constants	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm
A	2.37E+00	8.95E-01	6.18E-01	7.31E-01	1.65E+00	-2.98E-02	1.05E+00	2.05E+00	8.33E-01
B	3.81E-02	4.92E-02	4.09E-02	9.43E-02	5.23E-02	5.37E-01	9.67E-02	9.51E-02	5.23E-02
c	8.45E-01	9.54E-01	1.03E+00	1.08E+00	8.03E-01	1.25E-01	9.52E-01	2.63E-01	1.07E+00
D	0.00E+00	0.00E+00	0.00E+00	1.00E-04	0.00E+00	0.00E+00	0.00E+00	2.00E-04	1.00E-04
E	1.51E-02	-2.00E-03	-7.20E-03	-9.10E-03	6.30E-03	-1.32E-02	1.30E-03	-2.22E-02	-6.00E-03
F	-1.37E+00	1.05E-01	3.83E-01	2.70E-01	-6.51E-01	1.03E+00	-4.73E-02	-1.05E+00	1.66E-01
Silva *et al.* Model									
Constants	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm
A	4.05E-02	3.77E-02	3.76E-02	7.96E-02	3.62E-02	2.40E-02	8.35E-02	5.29E-02	6.60E-02
B	3.66E-02	1.10E-02	-1.46E-02	1.81E-02	4.81E-02	-5.41E-02	2.13E-02	7.49E-02	-2.43E-02
Peleg Model									
Constants	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm
A	1.46E+01	1.92E+01	#######	8.70E+00	1.53E+01	6.07E+01	8.16E+00	1.04E+01	1.41E+01
B	8.49E-01	8.10E-01	7.70E-01	8.28E-01	8.48E-01	6.16E-01	8.31E-01	8.19E-01	7.49E-01
Modified Henderson and Pabis Model									
Constants	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm	1.5mm	3.0mm	4.5mm
	9.25E-01	9.43E-01	6.38E-01	2.89E-01	6.67E-02	-1.23E+01	-1.08E+00	9.51E-01	1.10E+00
B	8.11E-02	3.10E-02	3.29E-02	7.77E-01	4.08E-02	3.05E-02	7.83E-02	2.93E-01	4.75E-02
C	-5.90E-03	2.19E-02	3.45E-01	-6.59E-02	8.93E-01	1.32E+01	2.00E+00	-2.47E-01	-1.39E-01
g	1.76E+00	1.91E-02	3.89E-01	7.36E-02	1.75E+00	6.40E-03	4.09E-01	1.77E+00	8.78E-02
K	4.43E-02	4.09E-02	3.53E-02	1.82E-01	1.79E+00	3.22E-02	7.41E-02	6.57E-02	5.82E-02

3.1 The Drying Curve

Figures 2 to 4 present the drying curves of carrot slices, featuring experimental data points and the logarithmic model lines. The Logarithmic Thin layer model is chosen from all the models for its simplicity. All the models follow exponential decay, and no significant difference exists between them. The practical implications of these findings are evident in the drying times. Carrot slices with a thickness of 1.5 - 4.5 mm took around 50-70 minutes to dry to a moisture ratio of approximately 0.1 when dried at a temperature of 60℃, as depicted in Fig. 2. Similarly, carrot slices with the same thickness took about 30-60 minutes to dry to a moisture ratio of 0.1 when dried at 70℃, as shown in Fig. 3. Finally, when dried at 80℃, carrot slices with a thickness of 1.5 - 4.5 mm took around 25- 40 minutes to dry to a moisture ratio of approximately 0.1, as indicated in Fig. 4.

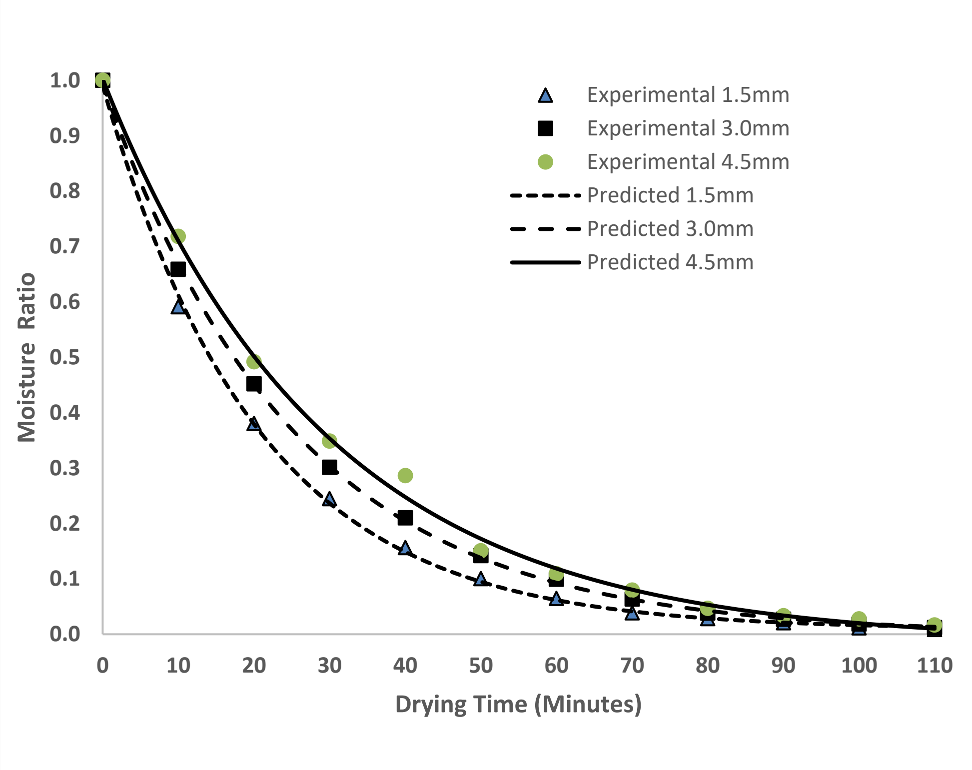

Figure 2 Comparison of experimental data and predicted moisture ratio using Logarithmic model for at 60℃

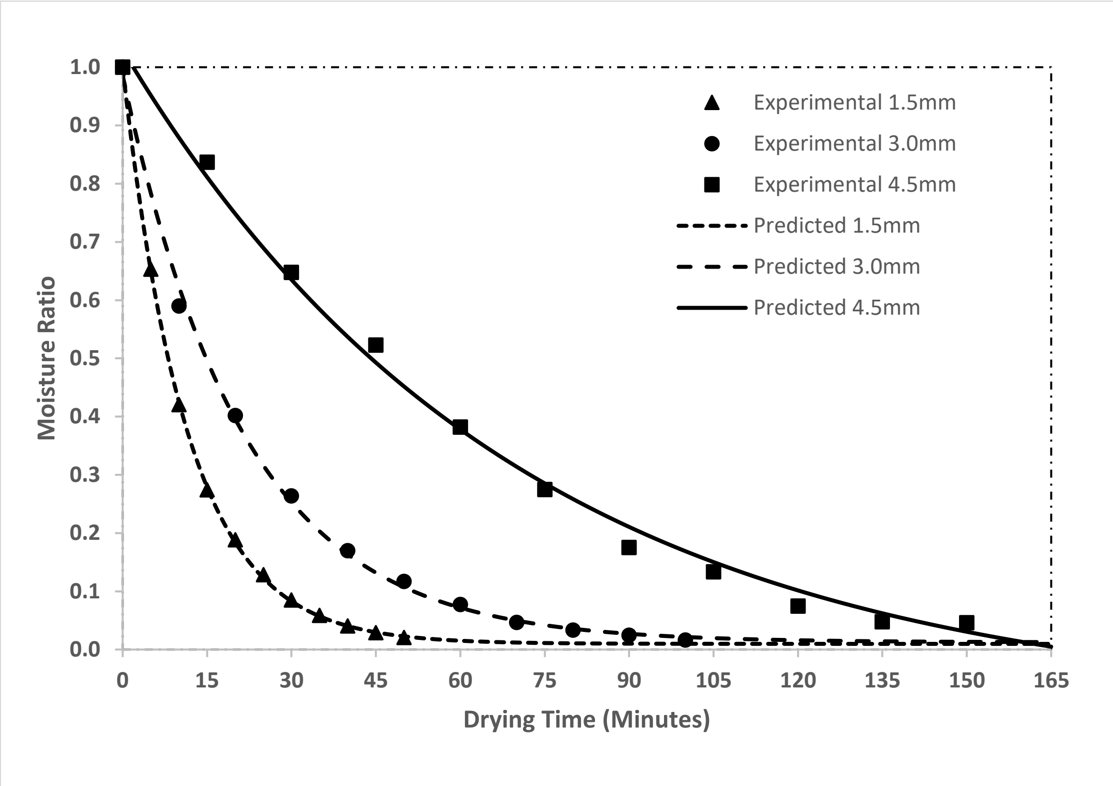

Figure 3: Comparison of experimental data and predicted moisture ratio using Logarithmic model for at 70℃

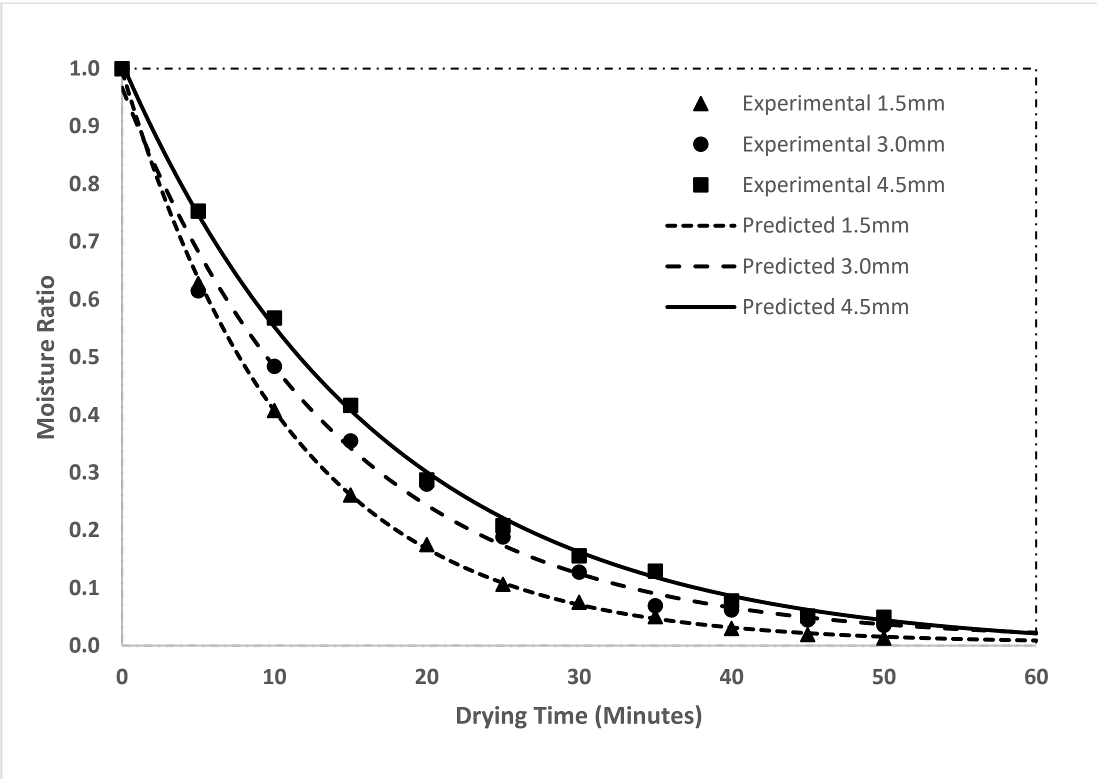

Figure 4: Comparison of experimental data and predicted moisture ratio using Logarithmic model for at 80℃

3.2 The Drying Rate Curve

Figures 5-7 illustrate drying rate curves for 1.5mm, 3.0mm, and 4.5mm carrot slices dehydrated at 60, 70, and 80°C. The selected thin-layer drying model was used to obtain theoretical line plots of drying rates due to limited data points (Kemp *et al*., 2001). Drying rates increase to a maximum value and then decrease. Sensible heat is transferred to the carrot slices and the contained moisture during the increasing drying rate. The falling-drying-rate period has two stages: unsaturated drying and saturated drying. The maximum drying rate happens in a short period, called the constant rate period. This characteristic is typical of drying thin-layer slices of agricultural products. (Akinola *et al.,* 2018; Akinola & Ezeorah, 2020; Zielinska and Markowski, 2010; Seremet *et al.,* 2016).

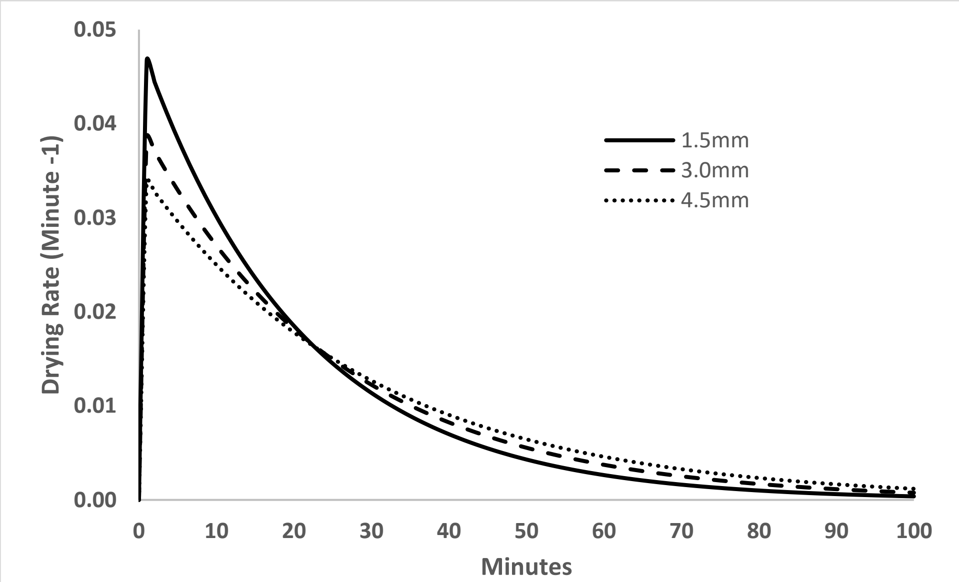

Figure 5: Drying Rate curve for 1.5 – 4.5 mm thick carrot slices at 60℃

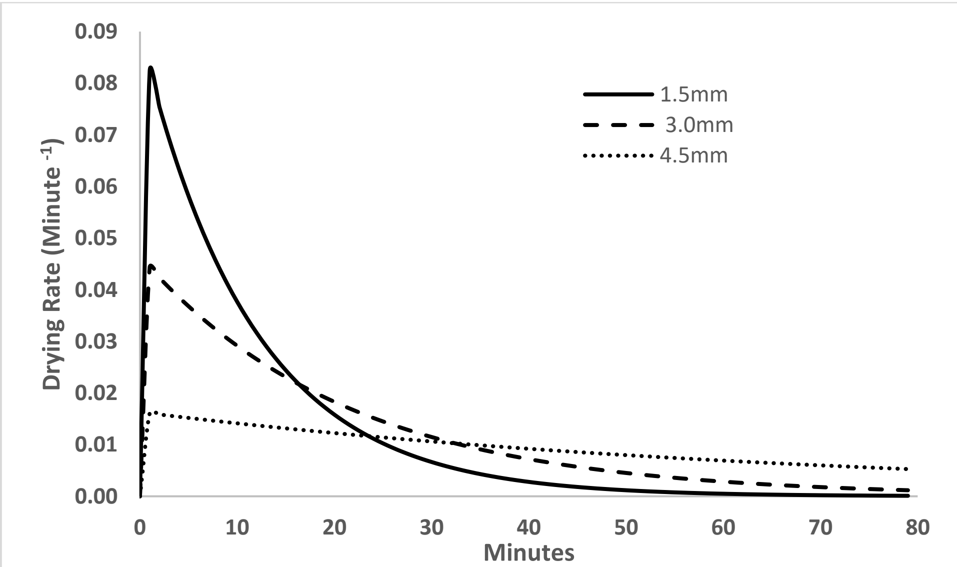

Figure 6: Drying Rate curve for 1.5 – 4.5mm thick carrot slices at 70℃

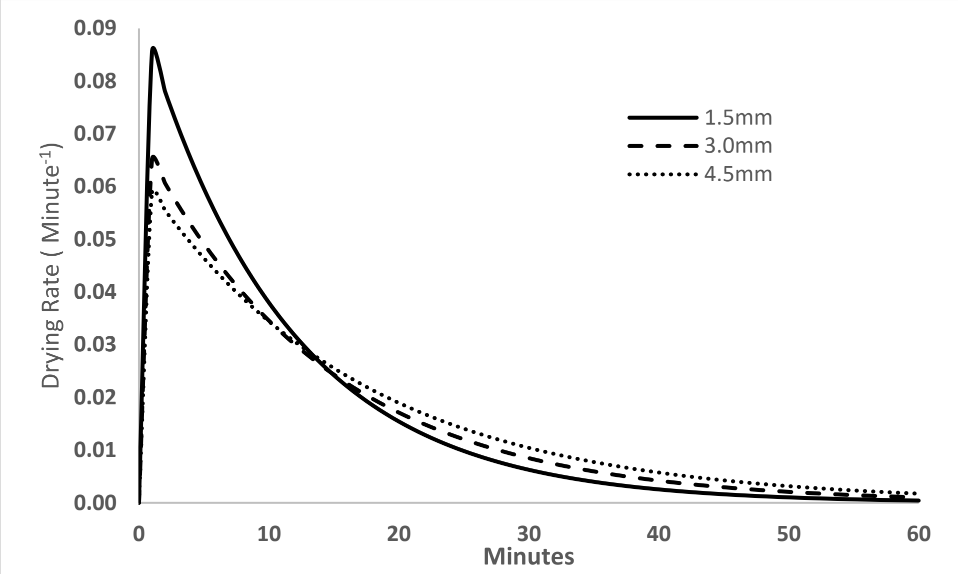

Figure 7: Drying Rate curve for 1.5 – 4.5mm thick carrot slices at 80℃

3.3 The Krischer Curve

Figures 8, 9, and 10 show the drying process of carrot slices at different thicknesses and temperatures. The plots, known as Krischer curves, include both the drying curve and the drying rate curve. The drying process has four stages: initial heating, constant rate, and two falling rate stages. The plots reveal that the drying rate increases from its initial value reaches a peak during the constant rate stage and then declines during the falling rate stages. The 1.5 mm thick carrot slices exhibit the most significant increase in drying rate because they offer the least resistance to moisture.

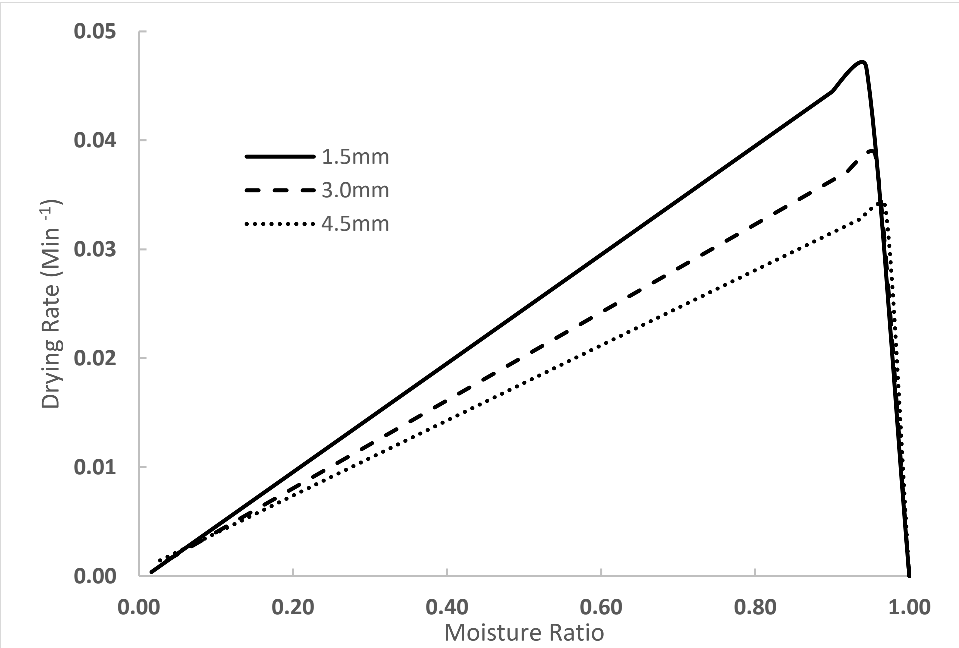

Figure 8: Krischer curve for 1.5 – 4.5 mm thick carrot slices at 60℃

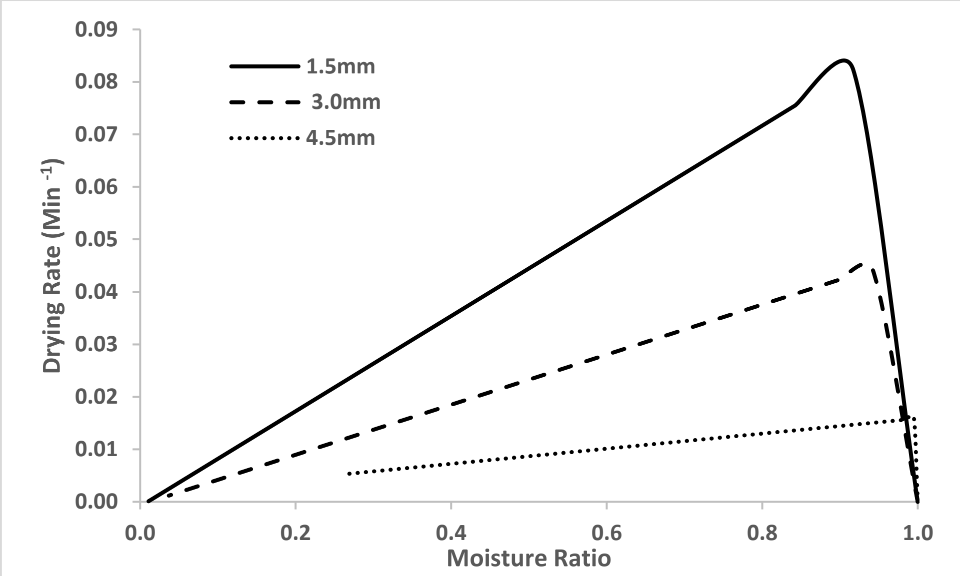

Figure 9: Krischer curve for 1.5 – 4.5mm thick carrot slices at 70℃

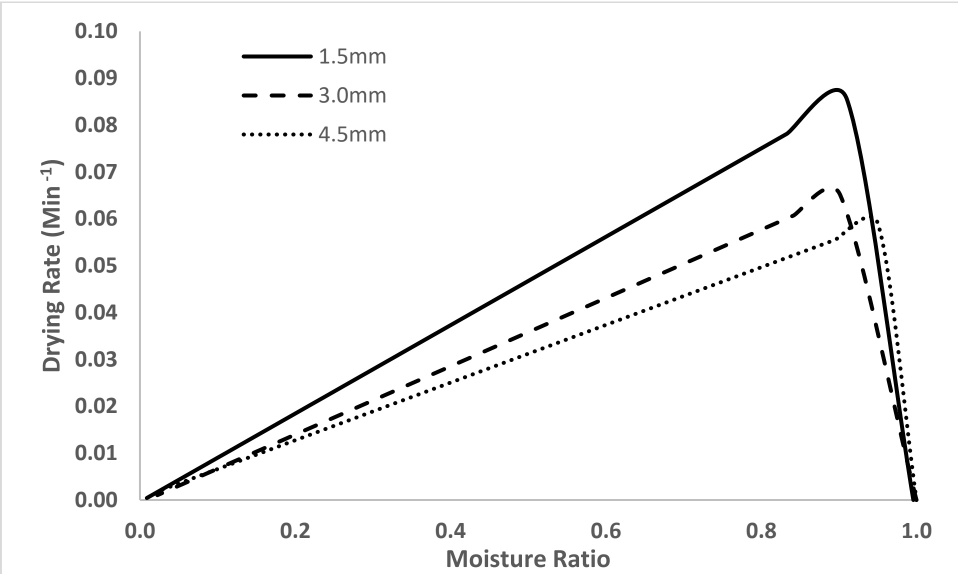

Figure 10: Krischer curve for 1.5 – 4.5mm thick carrot slices at 80℃

3.4 Effective Moisture Diffusivity and Activation Energy

To obtain the Effective Moisture Diffusivity D_{eff} of thin slices, a linear regression analysis is performed on $Ln(MR)$ and drying time. The regression analysis is based on Equation 4 using the gathered moisture ratio history data. The slope K_d of the linear relationship defined in Equation 5 is used to calculate the D_{eff} value using Equation 6. Table 4 presents the D_{eff} values for different sizes and temperatures.

Table 4: Effective Moisture Diffusivity of carrot slices D_{eff}(m^2. s^{-1})

Temperature ℃	1.5 mm	3.0 mm	4.5 mm
60	6.7833E-10	2.4333E-09	5.0500E-09
70	1.2033E-09	2.5333E-09	2.7167E-09
80	1.3200E-09	4.1667E-09	8.3000E-09

The Arrhenius-type relationship is used to estimate the Activation Energy of dehydration; this relationship links the Effective Moisture Diffusivity to the absolute temperature (as shown in Equation 7). To estimate the Activation Energy of dehydration, we need to calculate the slope of Equation 7 using the values of effective moisture diffusivity obtained at different temperatures.

The resultant slope of the Arrhenius regression analysis gave the activation energy E_a (kJ/mol) computed as 3.2753E+04, 2.6060E+04 and 2.3449E+04 J/mol for 1.5 mm, 3.0 mm and 4.5 mm yam thickness respectively, see Table 5. This implies that removing 1 kg of water from carrot slices of thickness 1.5, 3 and 4.5 mm needs approximately 3.2753E+04, 2.6060E+04 and 2.3449E+04 J of energy. The values of the activation energy obtained in this report are in the range for various food materials (Zogzas *et al.,* 1996). Furthermore, the results show that low thickness results to lower activation energy while higher thickness results to higher activation energy, which corresponds to the literature reported by Sanful *et al.,* 2015.

Table 5: Activation Energy of Dehydration E_a of carrot slices and the Pre-exponential factor of the Arrhenius equation D_0

Carrot slice size →	**1.5mm**	**3.0mm**	**4.5mm**
Activation Energy of Dehydration E_a (kJ/mol)	3.2753E+04	2.6060E+04	2.3449E+04
Pre-exponential factor of the Arrhenius equation D_0 (m^2/s).	1.0032E-04	2.7589E-05	1.8133E-05

3.5 Thermodynamic parameters

The changes in Enthalpy (ΔH), Entropy (ΔS) and Gibbs free energy (ΔG) were calculated to study the thermodynamic behavior of the 1.5, 3.0- and 4.5-mm dehydrated carrot slices size at temperatures of 60, 70 and 80℃ respectively (Equations 9, 10 and 11). Table 6 shows Enthalpy (ΔH) changes concerning operating temperature for a given Carrot size. There was no significant change in Enthalpy for any given slice size following an increase in process temperatures. However, given a temperature, the change in Enthalpy decreases as the Carrot slice thickness increases. This suggests a higher energy requirement to dehydrate larger sliced carrot slices. The results were positive (ΔH > 0), indicating an endothermic process requiring a supply of heat energy for dehydration.

Table 6: Differential Enthalpy ΔH ($J. mol^{-1}$) for dehydration of Carrot slices

Temperature ℃	**1.5 mm**	**3.0 mm**	**4.5 mm**
60℃	29,984.58	23,291.41	20,680.66
70℃	29,901.44	23,208.26	20,597.51
80℃	29,818.29	23,125.12	20,514.37

Table 7 displays the variations in Entropy (ΔS) for different Carrot slice sizes under different drying temperatures. ΔS does not change significantly with the temperature for any given slice thickness. However, the Entropy (ΔS) for a given slice size decreases as the drying temperature increases.

Table 7: Differential Entropy (ΔS) ($J. mol^{-1}. K^{-1}$) for dehydration of Carrot slices

Temperature	**1.5 mm**	**3.0 mm**	**4.5 mm**
60℃	-109.38	-119.88	-123.29
70℃	-109.62	-120.12	-123.54
80℃	-109.85	-120.36	-123.77

Table 8 presents the result obtained for changes in Gibbs free energy (ΔG) for different Carrot sizes at the various operating temperatures. For a given temperature, ΔG decreases with slice size. For a given slice size, ΔG increases with temperature. The values obtained were all positive (ΔG > 0), implying that energy is required to modify the internal structure of Carrot slices. ΔG increases upon an increase in operating temperature from 60 - 80℃.

Table 8 Change in Gibbs Free energy (ΔG) (J. mol^{-1}) for dehydration of Carrot slices

Temperature ℃	1.5 mm	3.0 mm	4.5 mm
60℃	66,407.83	63,211.70	61,737.83
70℃	67,501.03	64,409.92	62,970.19
80℃	68,596.60	65,610.51	64,204.92

4.0 CONCLUSIONS

The study examined the drying characteristics of yellow carrot slices using a DS Memmert Universal Oven UF55 dryer. The dryer operated at three different temperatures, namely 60 ℃, 70 ℃, and 80 ℃, to dry sliced carrots of varying thicknesses, i.e., 1.5 mm, 3.0 mm, and 4.5 mm. After analyzing the data, the following conclusions were drawn.

1. The time required to dry the carrot slices decreased with increased temperature. This finding has practical implications for the dehydration process, suggesting that higher temperatures can significantly reduce drying time. Similarly, the time required to dry the carrot slices increased with increased slice size, a finding that underscores the importance of slice size control in the dehydration process. These findings align with the work of Akinola and Ezeorah (2020), Akinola *et al.* (2019), and Akinola *et al.* (2020) on the Refractance Window dehydration of Yam, green plantain, and Taro respectively.
2. The time required to dry 1.5 to 4.5-mm thick carrot slices to a moisture ratio of below 0.1 in an oven dryer at 60 to 80℃ temperatures was approximately 25 and 70 minutes These findings align with the work of Akinola and Ezeorah (2020), Akinola *et al.* (2019), and Akinola *et al.* (2020) who dehydrated yam, plantain, Taro samples of similar slice size and temperatures and obtained similar drying times
3. The variation in moisture ratio during dying was analyzed using regression analysis, and all tested thin-layer drying models showed a regression coefficient better than 0.98. The RMSE and SSE values, which were almost zero, provide a strong indication of the accuracy of our analysis. This should instill confidence in the robustness of our findings. The Logarithmic Thin-Layer drying Model was chosen because of its simplicity.
4. The effective moisture diffusivity, D_{eff}, varied from 8.30E-09 to 6.78E-10 m^{2}s^{-1}, showing that at a given temperature, D_{eff}, increased with increasing sample size.
5. The activation energy estimated for 1.5mm, 3mm and 4.5mm were 3.2753E+04, 2.6060E+04 and 2.3449E+04 J/mol respectively.
6. Changes in Enthalpy (ΔH), Entropy (ΔS) and Gibbs free energy (ΔG) were calculated to study thermodynamic behavior. ΔH varied between 120,514.37 and 29,984.58 J.mol^{-1}, ΔS varied between 123.77 and -109.38 J.mol^{-1}.K^{-1}, and ΔG varied 66,407.83 and 64,204.92 J/mol, respectively.
7. A positive ΔG value indicates the additional energy must be input for dehydration to occur.

NOMENCLATURE

Symbol	Definition

D_0	Pre-exponential factor of the Arrhenius
D_{eff}	Moisture Diffusivity (m^2s^{-1})
E_a	Activation Energy ($J.mol^{-1}$)
ΔG	Changes in Gibbs free energy ($J.mol^{-1}$)
ΔH	Changes in enthalpy ($J.mol^{-1}$)
h_p	Planck constant (6.626×10^{-34} Js^{-1});
K_B	Boltzmann constant (1.38×10^{-34} Js^{-1});
K_B	Boltzmann constant (1.38×10^{-34} Js^{-1});
R^2	Coefficient of Regression (Dimensionless)
L	Sample thickness (m)
MR	Moisture Ratio (Dimensionless)
R	Universal gas constant 8.3145 J/mol·K.
RMSE	Root Mean Square Error (Dimensionless)
SSE	Sum of Square Error (Dimensionless)
ΔS	Changes in entropy ($J.mol^{-1}$)
T_a	absolute temperature (°K)

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