MATHEMATICAL MODELLING OF DRYING KINETICS OF CORIANDER LEAVES (*CORIANDRUM SATIVUM* L.) USING A CONVECTIVE DRYER

Olabinjo, Oyebola Odunayo, Asamu, Augustine Ifeoluwaposimi and Filani, Iyanuoluwa Olasunkanmi
Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria
*E-mail: oyebolabinjo@gmail.com

Abstract
Drying is generally considered as the oldest and commonly used technique for preserving food materials. Moisture content removal from agricultural materials ensures that the products have improved shelf life, enhanced properties, better storage, easy transportation and handling. Drying characteristics of Coriander leaves using an oven dryer was studied at four different temperatures (40, 50, 60 and 70°C). The effect of the drying temperatures on moisture content of the leaves was investigated. Thirteen drying models were fitted to the drying data to establish the model that best describes the drying characteristics of Coriander leaves and gives better prediction. Hii et al. model proved to be the most reliable and suitable model for describing the oven drying characteristics of Coriander leaves under the drying temperature range. Effective moisture diffusivity of Coriander leaves ranged from 6.6577 × 10^{-12} m^2/s to 16.18652 × 10^{-12} m^2/s for the drying temperatures. Activation energy was found to be similar, ranging between 19.84629 -19.86699 kJ/mol. Thus, suggesting that the energy required to eliminate moisture within the leaves for each temperature condition is similar. Mathematical models have been employed to investigate the drying behaviour and kinetics of agricultural product, thus, controlling drying process.

Keywords: Coriander leaf, drying kinetics, modelling, moisture diffusivity, activation energy

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1. INTRODUCTION

Coriander (*Coriandrum Sativum L.*), is a vegetable found in Africa and belongs to the Asteraceae family of crops (Sakpere *et al.*, 2013). Vegetables and herbs including Coriander can either be consumed in their fresh state or dried to aid storage and preservation (Sarimeseli, 2011). Coriander leaf possesses tremendous medicinal value and is useful for treating headache, indigestion, fresh wounds and for curing sleeping sickness (Ajibesin, 2008; Dansi *et al.* 2012). The sticky and succulent stems and leaves of Coriander are utilized in central and western Africa for making stews and spicy vegetable soups.
Coriander nutrition is basically due to its green leaves and dried fruits/seeds. Like all other green leafy vegetables, its leaves are a rich source of vitamins, minerals and iron. Its leaves contain high amount of vitamin A (β-carotene) and vitamin C. The green herbs contain vitamin C upto 160 mg/100 g and vitamin A upto 12 mg/100 g (Girenko, 1982). It is very low in saturated fat and cholesterol and a very good source of thiamine, zinc and dietary fiber. Green coriander contains 84% water (Bhat *et al.*, 2014).
Drying is generally considered as the oldest and commonly used technique for preserving food materials. Moisture content removal from agricultural materials ensures that the products have improved shelf life, enhanced properties, better storage, easy transportation and handling.
Some of the factors that affect the drying behaviour of agricultural materials include moisture present in food material, composition, geometry and thickness of the food material (Sinha *et al*., 2010). Some conventional drying methods for drying vegetables include sun drying, and use of hot air (oven), while in recent times, solar, infrared or microwave drying have been employed (Seung *et al.*, 2016).
The complexity of drying process, which involves simultaneous mass and heat transfer, makes a definite process control essential. Mathematical models have been employed to investigate the drying behaviour and kinetics of

agricultural product, thus, controlling drying process.
A number of studies have reported the drying characteristics of vegetables and fruits, some of which includes those on collard leaves (Alibas, 2009), okra slices(Wankhade *et al.*, 2013), moringa leaves (Ali *et al.*,2014) and spider plant leaves (Omolola *et al.*, 2019).However, studies on the drying behaviour of Coriander leaves using oven have not been published in literatures.
The objectives of this research were to investigate the effects of temperature on the drying characteristics of Coriander leaves and to determine the best thin layer drying models that describes its drying behaviour.

2. MATERIALS AND METHODS

2.1 Material

Fresh Coriander leaves were collected from Ilara-mokin, a village close to Akure, the capital of Ondo State and were thoroughly washed and sorted. An electric oven installed at the department of Agricultural and Environmental Engineering of the Federal University of Technology, Akure, Ondo State was utilized to dry the leaves according to the selected temperatures.

2.2 Drying method

The initial moisture content of the leaves was measured adopting AOAC (2000) method by placing the leaves in oven at 105°C for 24h. 50g of the cleaned Coriander leaves was used for each experimental run. The leaves were evenly distributed on the tray in the oven at 40, 50, 60 and 70 °C temperature.
Readings were taken periodically to monitor changes on the leaves at fixed intervals (30mins) during the drying process. These readings became constant when the leaves became fully dried.
Upon drying, data were analyzed to investigate the drying kinetics. The obtained dried leaves were subsequently cooled and preserved in the desiccator to prevent them from moisture absorption.

2.3 Mathematical Modelling

Moisture ratio (MR) and the drying rate (DR) were determined using equation 1 and 2 below. (Yaldiz *et al.*,2001).

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (1)$$

$$DR = \frac{M_{t+dt} - M_c}{dt} \qquad (2)$$

Where MR is the dimensionless moisture ratio, M_t is the moisture content at time t of the drying process (g/g dry solid), M_e is the equilibrium moisture content (g/g dry solid), and M_o is the initial moisture content (g/g dry solid). The equilibrium moisture content (Me) was assumed to be 0 g/g dry solid for microwave drying since it is relatively small compared to M_t and M_o (Roberts *et al.*, 2008). Therefore, equation 1 was simplified to

$$MR = \frac{M_t}{M_0} \qquad (3)$$

From equation 2 expressed above, M_{t+dt} is the moisture content at time t+dt, while M_t is the moisture content at specific time t. M_0 and M_e remains the initial moisture content and equilibrium moisture content respectively. Different mathematical models as expressed in Table 1 were applied in fitting the drying curves.
Microsoft Excel was used in performing the non-linear regression analysis. R^2, X^2, RMSE and SSE of each mathematical model which represents the coefficient of determination, chi square, root mean square error, and reduced sum square error respectively were also calculated. The best drying model was selected based on the lowest value of X^2, RMSE and SSE and highest value of R^2.

2.4 Effective moisture diffusivity and activation energy determination

Fick's second law of diffusion was utilized in determining the effective diffusivity. Equation 4 (Doymaz, 2005) was used in determining the effective moisture diffusivity of the samples as described.

Table 1: Mathematical models applied to the oven drying curves of Coriander leaves

S/N	Model	Equation	References
1	Newton	$MR = \exp^{-kt}$	Pangavhane, and Singh (1999)
2	Henderson and pabis	$MR = aexp^{-kt}$	Ceylan, (2007)
3	Page	$MR = exp\,(-kt^{n})$	Guiné *et al*., (2011)
4	Logarithmic	$MR = aexp^{-kt} + c$	Ganesapillai *et al*. (2011)
5	Two term model	$MR = aexp^{-kt} + cexp^{-gt}$	Doymaz (2009)
6	Verma et al	$MR = aexp^{-kt} + (1-a)\exp^{-gt}$	Verma *et al*., (1985)
7	Diffusion approach	$MR = aexp^{-kt} + (1-a)\exp^{-kgt}$	Yaldız *et al*.,(2001)
8	Midili kucuk	$MR = aexp^{-kt^{n}} + bt$	Midilli, Kucuk *et al*., (2002)
9	Wang and singh	$MR = 1 + at + bt^{2}$	Miranda *et al*. (2009)
10	Hii et al.	$MR = aexp^{-k_1 t^{n}} + c\exp^{-gt^{n}}$	Hii *et al*., (2008)
11	Modified Henderson Pabis	$MR = aexp^{-kt} + b\exp^{-gt} + cexp^{-ht}$	Karathanos (1999)
12	Modified Page I	$MR = \exp^{-kt^{n}}$	Overhults (1973)
13	Modified Page II	$MR = \exp^{-k\left(\frac{t}{l^{2}}\right)^{n}}$	Diamante (1993)

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

Upon plotting a graph of ln (MR) against time, the slope in equation 5 is used in computing the moisture diffusivity of the samples.

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}t\right) \qquad (5)$$

Slope = $\frac{\pi^2 D_{eff}}{4L^2}$

Where D_{eff} is the effective moisture diffusivity (m^2/s), MR is the moisture ratio and L is the half-thickness (m) of the samples.

Activation energy was calculated using the Arrhenius equation presented in equation 6 (Roberts *et al*., 2008).

$$D_{eff} = D_0 exp^{\frac{(-E_a)}{RT}} \qquad (6)$$

3. RESULTS AND DISCUSSION

3.1 Drying characteristics of Coriander leaves

The drying characteristics of Coriander leaves at different oven temperatures 40, 50, 60 and 70^{o}C showed in Figure 1. The moisture content of 90.06% (wb) was observed to be the initial moisture content of the leaves, however, the final moisture content of the dried samples reduced to 2.8% (wb), 7.23% (wb), 5.53% (wb), 0.05% (wb) for 40, 50, 60 and 70^{o}C respectively. Statistical analysis was carried out with respect to reduction in moisture ratio with drying time on the experimental data obtained from oven drying temperatures of 40,50,60 and 70^{o}C.Moisture content in the leaves decreased to a constant point in a time that was dependent on drying temperature, being lowest at 70^{o}C (360 min) and highest at 40^{o}C(780 min).Therefore, increasing drying temperature increases the amount of moisture removed from the samples.

3.2 Drying rate of Coriander leaves

As indicated by the curves in Figure 2, no constant drying rate period was observed for all the drying temperatures. However, the drying processes occurred in falling rate for all the temperatures. During this period, rate of evaporation of water to surrounding air exceeds the rate of water diffusing from the interior to the surface of the leaves. This infers that moisture diffusivity in the Coriander leaves were predominantly through diffusion mechanism. These results were similar to those obtained by Ali *et al.*, (2014) and Omolola *et al.*, (2019) observed a falling rate period in their studies on the drying of moringa leaves, spider plant leaves and coriander leaves respectively.

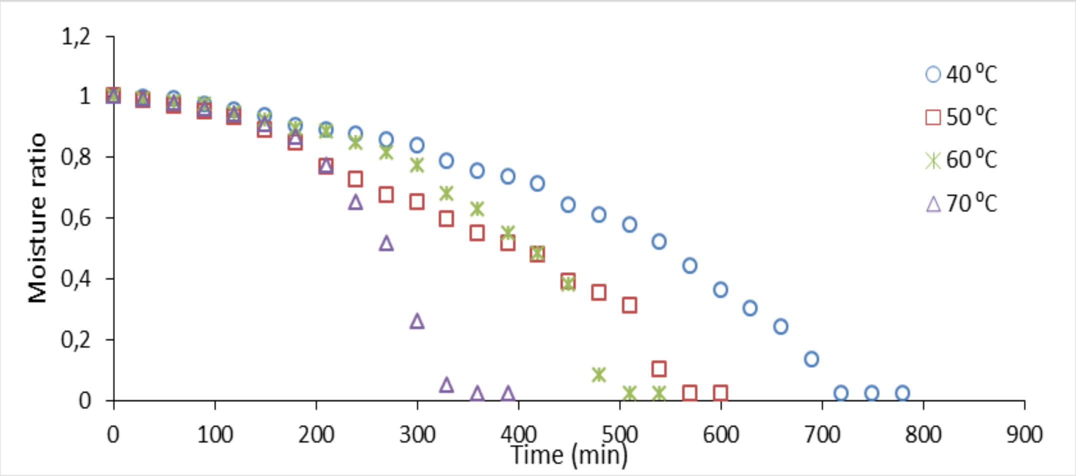

Figure 1:Oven drying curves of Coriander leaves at 40, 50, 60 and 70°C.

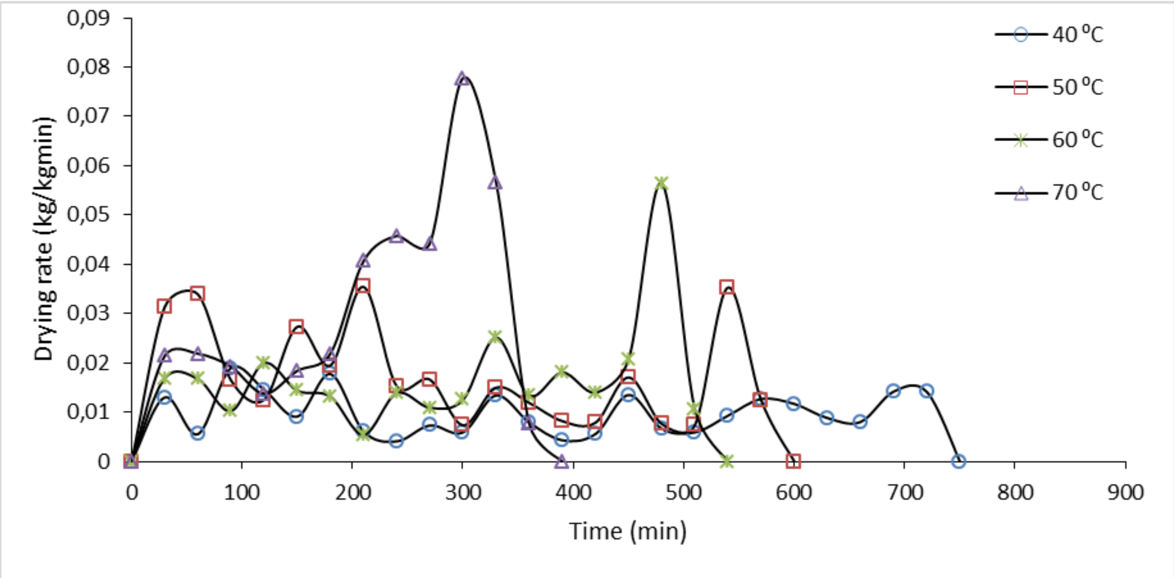

Figure 2: Drying rate vs time of Coriander leaves at 40, 50, 60 and 70°C

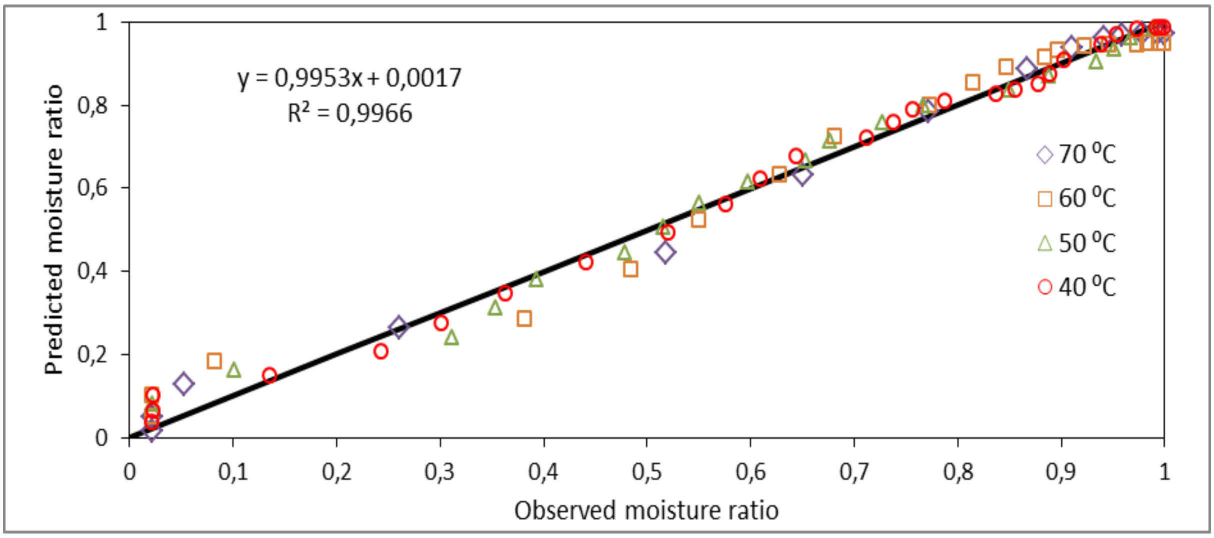

Figure 3: Predicted MR against experimental MR for the Hii *et al*. model at drying temperatures of 40, 50, 60 and 70°C

Table 2: Modelling the drying kinetics of Coriander leaves

Model	Temperature (°C)	Model constants		R^2	RMSE	SSE	X^2
Newton	40	k = 0.0846		0.8392	0.1635	0.1666	0.0278
	50	k = 0.1194		0.8869	0.1337	0.137	0.0188
	60	k = 0.1121		0.7707	0.1881	0.1933	0.0374
	70	k = 0.1194		0.7716	0.2192	0.2275	0.0517
			Average	**0.8171**	**0.17613**	**0.1811**	**0.03393**
Henderson and Perbis	40	k = 0.1077, a = 1.19		0.8111	0.1427	0.1483	0.022
	50	k = 0.1461, a = 1.1618		0.8658	0.1154	0.1213	0.0147
	60	k = 2.1305, a = 0.1395		0.7422	0.1683	0.1779	0.0316
	70	k = 0.1461, a = 1.1618		0.737	0.1962	0.2119	0.0449
			Average	**0.789025**	**0.15565**	**0.16485**	**0.0283**
Page	40	k = 0.0007, n = 3.1747		0.9792	0.051	0.053	0.0028
	50	k = 0.0107, n = 2.2915		0.9661	0.058	0.061	0.0037
	60	k = 0.1286, n = 0.9412		0.9704	0.0609	0.0644	0.0041
	70	k = 0.0107, n = 2.2915		0.9916	0.0361	0.039	0.0015
			Average	**0.976825**	**0.0515**	**0.05435**	**0.003025**
Logarithmic	40	k = 0.0005, a = 148.3274, c = -147.1752		0.927	0.0871	0.0924	0.0085
	50	k = 0.0015, a = 65.6502, c = -64.5419		0.9598	0.062	0.067	0.0045
	60	k = 0.1386, a = 1.0011, c = 0.0545		0.8594	0.1223	0.1333	0.0178
	70	k = 0.0015, a = 65.6502, c = -64.5419		0.8739	0.1332	0.1503	0.0226
			Average	**0.905025**	**0.10115**	**0.11075**	**0.01335**
Two term model	40	k = 0.2257, g = 0.3125, a = 5.2852, c = -4.3723		0.9179	0.0959	0.1039	0.0108
	50	k = 0.146, g = 0.1749, a = 1.1557, c = 0.006		0.8658	0.1154	0.1282	0.0164
	60	k = 0.1614, g = 0.0403, a = 0.8671, c = 0.1982		0.7458	0.1677	0.1887	0.0356
	70	k = 0.146, g = 0.1749, a = 1.1557, c = 0.006		0.8868	0.1331	0.1575	0.0248
			Average	**0.854075**	**0.128025**	**0.144575**	**0.0219**
Verma et al	40	k = -0.066, g = -0.0626, a = -22.6132		0.9925	0.028	0.0297	0.0009
	50	k = -0.0637, g = -0.0544, a = -10.3047		0.9889	0.0327	0.0353	0.0012
	60	k = 0.0237, g = 0.1344, a = 0.0974		0.9806	0.052	0.0567	0.0032
	70	k = -0.0637, g = -0.0544, a = -10.3047		0.9539	0.0818	0.0922	0.0085
			Average	**0.978975**	**0.048625**	**0.053475**	**0.00345**
Diffusion approach	40	k = 0.2518, g = 1.0153, a = 93.8644		0.9125	0.0979	0.1039	0.0108
	50	k = 0.3261, g = 1.0225, a = 58.1063		0.9403	0.077	0.0831	0.0069
	60	k = 0.1121, g = 1, a = 3.0345		0.8674	0.1224	0.1334	0.0178
	70	k = 0.3261, g = 1.0225, a = 58.1063		0.8761	0.1703	0.1921	0.0369
			Average	**0.899075**	**0.1169**	**0.128125**	**0.0181**

Midili kucuk	40	k = 0.001, b = -0.0194, a = 1.0157, n = 2.7989		0.9891	0.0337	0.0365	0.0013
	50	k = 0.0025, b = -0.0356, a = 0.9947, n = 2.5856		0.9854	0.0373	0.0415	0.0017
	60	k = 0.1266, b = 0.0016, a = 1.0457, n = 1.0047		0.9644	0.0628	0.0707	0.005
	70	k = 0.0025, b = -0.0356, a = 0.9947, n = 2.5856		0.9832	0.0497	0.0588	0.0035
			Average	**0.980525**	**0.045875**	**0.051875**	**0.002875**
Wang and smith	40	a = -0.0044, b = -0.0059		0.9931	0.0269	0.028	0.0008
	50	a = -0.0339, b = -0.0066		0.9885	0.0332	0.035	0.0012
	60	a = -0.0776, b = 0.0015		0.9796	0.0509	0.0538	0.0029
	70	a = -0.0339, b = -0.0066		0.892	0.1603	0.1732	0.03
			Average	**0.9633**	**0.067825**	**0.0725**	**0.008725**
Hii et al.	40	k = 0, g = 0.0047, a = 0.854, c = 0.1325, n = 4.712		0.994	0.0256	0.0284	0.0008
	50	k = -0.051, g = -0.3239, a = 1.3483, c = -0.3308, n = 0.7123		0.9889	0.0325	0.0373	0.0014
	60	k = 0.0575, g = 0.0046, a = 0.6804, c = 0.3086, n = 1.723		0.9764	0.0509	0.0593	0.0035
	70	k = -0.051, g = -0.3239, a = 1.3483, c = -0.3308, n = 0.7123		0.9925	0.0334	0.0416	0.0017
			Average	**0.98795**	**0.0356**	**0.04165**	**0.00185**
Modified Henderson Pabis	40	k = 34.0107, a = -0.0742, g = -35.0704, b = -0.0753, h = 2.0404, c = -0.0527		0.9909	0.0307	0.0348	0.0012
	50	k = -28.3484, a = -0.0565, g = -28.3484, b = -0.0565, h = 57.7085, c = -0.0547		0.9891	0.0323	0.0382	0.0015
	60	k = 0.05, a = 0.0015, g = 0.05, b = 0.0015, h = 0.05, c = 0.1		0.8783	0.1138	0.1376	0.0189
	70	k = -28.3484, a = -0.0565, g = -28.3484, b = -0.0565, h = 57.7085, c = -0.0547		0.9537	0.0807	0.1067	0.0114
			Average	**0.953**	**0.064375**	**0.079325**	**0.00825**
Modified Page I	40	k = 0.1034, n = 3.1206		0.9787	0.0509	0.0529	0.0028
	50	k = 0.1378, n = 2.2881		0.966	0.058	0.061	0.0037
	60	k = 0.1409, n = 1		0.9701	0.0609	0.0643	0.0041
	70	k = 0.1378, n = 2.2881		0.9933	0.0346	0.0373	0.0014
			Average	**0.977025**	**0.0511**	**0.053875**	**0.003**
Modified Page II	40	k = 0.9425, a = 0.0396, n = 3.7165, L = 4.1519		0.9838	0.0418	0.0453	0.002
	50	k = 0.9595, a = 0.0667, n = 2.5528, L = 2.5661		0.9686	0.0554	0.0616	0.0038
	60	k = 1, a = 0.8, n = 0.9, L = 0.7		0.9749	0.0524	0.0589	0.0035
	70	k = 0.9595, a = 0.0667, n = 2.5528, L = 2.5661		0.9944	0.028	0.0332	0.0011
			Average	**0.980425**	**0.0444**	**0.04975**	**0.0026**

3.2 Modelling of drying curves

The result from the statistical parameter estimations of the thirteen models, showed R^2, RMSE, SSE and X^2 values were ranged from 0.7370 to 0.9944, 0.0256 to 0.219191, 0.02798 to 0.227465 and 0.000783 to 0.05174 respectively, within the experimental range of study (Table 2). The value of R^2 with higher value above 0.90 is above sixty percent with at least six models (Page, Verma *et al.*, Midilli and Kucuk, Hii *et al*., Modified page I and Modified page II) in each temperature gave a good fit experimental data with R^2 greater than 0.91 in all cases.

Table 1 represents the list of mathematical models that were used in fitting the curves obtained from the plot of moisture ratios against oven drying time. The outcome from the analysis is required to determine the consistency, suitability and reliability the of models. The most suitable model was selected based on the lowest value of X^2, RMSE and SSE and highest value of R^2. According to the results, the Hii *et al*. model satisfied the condition for selecting the best model. The average of its coefficient of determination R^2 (0.98795) ranked highest while its SSE, Chi square and RMSE with 0.04165, 0.00185, 0.0356 value respectively ranked lowest. Hence, Hii *et al*. model best describes the drying characteristics of Coriander leaves and gives better prediction than other models at oven drying of 40°C since it has the highest R^2 value (0.994).

The result of experimental moisture ratio data was plotted against the predicted moisture ratio of the best model to validate the goodness of fit of the model as shown in Figure 3.

The linear relationship was given by equation7.

$$Y = 0.9963x + 0.0017 \quad (7)$$

The coefficient of determination values exceeded 0.99, inferring that the fit was good and predict correctly the drying process of Coriander leaves.

3.3 Effective Moisture Diffusivity and Activation Energy

In order to investigation of the effective moisture diffusivity (D_{eff}) for coriander under oven drying conditions. In this research, the effective moisture diffusivity values of the coriander for different temperatures of were calculated using the slope derived from the linear regression ln(MR) versus drying time (Eq.6). The plots gave straight lines with high determination coefficients ranging between 0.9535 and 0.9994.

Since all the samples of the Corinader leaves showed a falling rate period in their drying characteristics, Fick's second law of diffusion was utilized in determining the effective diffusivity. Table 3 shows the estimated diffusivity constant, D_0, and activation energy, E_a for the different temperatures. The D_{eff} values obtained, presented in Table 3, ranged from 6.658 x 10^{-12} to 16.19 x 10^{-12} m^2 $s^{-1.}$ The values obtained for D_{eff} are in consonance with those reported by Ankita and Prasad (2013), for spinach, D_{eff} found to vary in the range 1.380 × 10^{-11} to 4.720 ×10^{-10} m^2/s and 2.204 × 10^{-11} to 4.303 × 10^{-10} m^2/s for the untreated and blanched leaf samples, respectively of spinach leaves as reported by Prasad and Ankita (2017).

The activation energy (Ea) of drying process of coriander calculated from the slope of the linearized Arrhenius relationship ranged 19.846KJ/mol to 19.867KJ/mol. The activation energy decrease with increase in drying temperature.

The activation energy is higher than the value obtained in the microwave drying of okra (5.54 W/g) (Dadali *et al.*, 2007).

Table 3: Estimated diffusivity constant and activation energy for 40, 50, 60 and 70°C

Temperature (°C)	D_{eff} (10^{-12}) m^2/s	D_o	E_a (kJ/mol)
70	6.6577	6.607011	19.84629
60	8.207619	8.147063	19.85234
50	9.362241	9.295227	19.85773
40	16.18652	16.07404	19.86699

4. CONCULSIONS

In this study, the oven drying characteristics of Coriander leaves were investigated. It was observed that increasing the drying temperature increased the amount of moisture removed from the leaves. More so, the drying processes occurred in falling rate for all the temperatures (40,50, 60, 70^{o}C), inferring that moisture diffusivity in the Coriander leaves were predominantly through diffusion mechanism. Hii et al. model best describes the drying characteristics of Coriander leaves and gives better prediction than other models at oven drying of 40^{o}C since it had the highest value of R^2(0.994) and lowest value of SSE and RMSE. The effective moisture diffusivity (D_{eff}) values ranged from 16.18652 × 10^{-12} m^2/s to 6.6577 × 10^{-12} m^2/s. Activation energy was found to be almost similar for the different temperatures ranging between 19.84629 -19.86699 kJ/mol. This suggests that the energy required to eliminate moisture within the leaves under the varying oven drying temperatures are similar. This study contributes to literature and knowledge by presenting insights on the drying of Coriander leaves.

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