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Mathematical modelling of drying parameters of *Moringa oleifera* leaves in a cabinet dryer

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Abstract: This study focused on drying moringa leaves using a cabinet dryer. The impact of the 40, 50, and 60 °C drying air temperatures on the moisture content of the leaves at a constant air velocity with variation in weight (40, 80, and 120 g) was considered. Ten drying models were fitted to the drying data to describe the drying parameters of moringa leaves. The best model was chosen based on the highest coefficient of determination (R^2), and the lowest sum of square error (SSE) and root mean square error (RMSE) values. The Henderson and Pabis model best described the drying characteristics of the moringa leaves having the highest R^2 (0.9888) and lowest SSE (0.0401) and RMSE (0.0604). The effective moisture diffusivity increased with the temperatures ranging from 8.72×10^{-9} to 1.40×10^{-8} $m^2 \cdot s^{-1}$. The activation energy ranged from 90.4636, 40.4884, and 22.7466 $KJ \cdot mol^{-1}$ for 40, 80, and 120 g, respectively.

Keywords: agriculture; coefficient of determination; drying temperature; moisture diffusivity; thin layer drying

Moringa (*Moringa oleifera*) is the single species in the flowering plant family Moringaceae and is native to both Africa and Asia. It is planted for the benefits of its blooms, pods, and leaves. Moringa is known as the miracle tree because its leaves provide an abundant indigenous source of digestible proteins, vitamins, minerals, and carbohydrates that are required by people of all ages (Rong et al. 2022).

To enable storage of agricultural produce for a longer duration, the moisture content must be reduced to a certain well-defined "safe level". A reduction in the moisture content will prevent the growth of undesired chemical changes in the form of moulds, enzymes, and bacteria and the effect of micro-organisms, which result in the spoilage of fruits and vegetables. Agricultural produce drying entails the simultaneous transport of heat and mass to and from the food material (Okunola et al. 2021). Improved drying practices came about through the introduction and invention of the solar dryer, which produces better quality products over a short relative period compared to the direct subjection of agricultural produce to sunlight. It was observed by Adekanye et al. (2016) that a natural convection solar dryer in clear and sunny weather produces mould-free chips when dried between two to three days with up to a 12–13% moisture content, which holds a greater advantage over drying using direct

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sunlight. However, even with the greater advantage of a solar dryer over the sunlight drying method, they are both subjected to the same disadvantage of weather dependency, and, therefore, not reliable during the rainy seasons or wet weather. Due to the limitations encountered when using a solar dryer, an advanced improved method which is not dependent on the weather and seasons was invented.

Various drying methods have been developed, with the convective hot air-drying system being one of the most widely used (Chua et al. 2019). Several studies have been conducted on modelling the drying kinetics of various biomaterials and leaves using various types of dryers; for instance, pear fruits (Lahsasni et al. 2004), parsley leaves (Doymz et al. 2006), blanched carrot cubes (Zielienska and Markowski 2012), peppers (*Capsicum annum*) (Nkwocha et al. 2010), moringa oleifera leaves (Premi et al. 2010), the sweet cherry (Doymas and Ismail 2011), cassava chips (Ajayi et al. 2012), peppermint leaves (Ashtiani et al. 2017), Moldavian dragonhead leaves (Rudy et al. 2020), yams (Ojediran et al. 2020), okra (Okunola et al. 2021), *M. oleifera* (Ramarao et al. 2021), maize cobs (Kumar and Saha 2021), and the water yam (*Dioscorea alata*) (Okunola et al. 2023)

The goal of this research was to perform a thin layer drying experiment on *M. oleifera* leaves utilising a mechanical cabinet drier at 40, 50, and 60 °C at a constant air velocity of 1 m·s^{-1} in order to establish an effective drying model for *M. oleifera* leaves, to assess the effect of temperature levels on the drying properties of *M. oleifera* leaves, and to integrate the results of the experiment to ten mathematical models using acceptable statistical approaches. Due to the complexity of drying kinetics, mathematical models must be used to predict a food product's drying behaviour in order to identify the ideal drying operating conditions (Minaei et al. 2012). According to Olabode et al. (2015), moringa leaves contain vital nutrients that are essential to a person's health, and, moreover, the components of the leaves were affected differently by the drying temperatures.

MATERIAL AND METHODS

Description of the cabinet dryer

This study was conducted with the cabinet dryer presented in Figure 1.. It consists of an electric motor, a blower, an air inlet, a top vent, heating elements and units, a data logger, and sensors to observe the temperature and humidity. The drying chamber was made up of two perforated trays that were designed to allow heat to flow throughout the drying process.

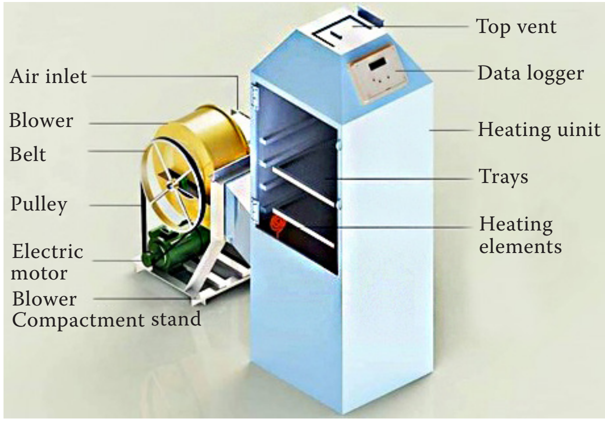

Figure 1. Diagram of the cabinet dryer

Machine operation. The leaves were evenly distributed across three drying trays within the cabinet dryer. The trays were perforated to allow heat convection on the moringa leaves, air is drawn through the inlet duct to the heating compartment, heated by the heating element and then distributed in the drying chamber. Sensors monitor and record the temperature and humidity development in the drying chamber, and a data logger is present to keep track of and record the drying activities and the results obtained from the ongoing process in the chamber.

Experimental methods and procedures. A 3 × 3 factorial randomised design was adopted in conducting this experiment. To carry out this experiment, various sets of drying temperatures (40, 50, and 60 °C), weights (40, 80, and 120 g), and constant air velocity of 1 m·s^{-1} were used. As temperatures above 70 °C can cause the leaves to lose some of their nutritional value, they were avoided (Olabode et al. 2015). The dryer was given 30 min to stabilise the drying conditions before each test run. The moisture content was assessed by drying a moringa specimen in a fixed air oven (Labtron, United Kingdom) at 105 °C for 24 h and calculating the moisture content using the American Society of Agricultural Engineers (ASAE) standard procedure (No. S448.2) (2003). The sample's initial moisture level was documented, and the sample was weighed before being placed in the dryer. The weight change was tracked during the experiment by weighing the sample on an electronic balance (EMS 3000-2 Kern, Germany) on a regular basis. The sample was weighed every 20 min until three consecutive results gave the same weights.

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The moringa leaf samples used in this research were sourced from the Teaching and Research Farm, Landmark University, Omu-Aran, Kwara State, Nigeria. The leaves were packed in jute bags and placed in a desiccator before the drying began.

Drying analysis and evaluation

Moisture content removed. The amount of moisture removed was calculated by subtracting the mass of moringa leaves before drying from the mass of the dried leaves after drying, as shown in Equation (1):

$$M_R = M_W - M_D \tag{1}$$

where: M_R – mass of the moisture removed (kg); M_W – mass of the parboiled moringa leaves before drying (kg); M_D – mass of the dried moringa leaves (kg).

Moisture ratio (MR): It was calculated using the non-exponential part of the applied thin-layer equations, which is expressed as Equation (2):

$$M_R = \frac{M - M_e}{M \ \ - M_e} \tag{2}$$

where: M – moisture content [(% dry basis d.b.)]; M_e – equilibrium moisture content (% dry basis); M_0 – initial moisture content (% dry basis).

Drying rate (DR): It was measured by the amount of water evaporated from the moringa per known drying time as shown in Equation (3):

$$DR = \frac{M_W - M_d}{t} \tag{3}$$

where: DR – drying rate (% d.b); t – drying time (h).

Mathematical modelling. Ten typical thin layer drying models were used to simulate the drying kinetics (Table 1). A non-linear regression analysis using the Statistical Package for Social Sciences (version SPSS 28.0) program was used to estimate the constants of each model. The models' reliability was tested using statistical criteria such as the coefficient of determination (R^2), sum of square error (SSE), and root mean square error (RMSE). When R^2 is high and RMSE and SSE are lower, a model is said to have a good fit between the experimental and predicted values (Golpour et al. 2022). The comparison criteria method was determined using Equations 4, 5 and 6:

$$R^2 = \frac{\sum (MR_{pred} - MR_{exp})^2}{\sum (MR_{AV} - MR_{exp})^2} \tag{4}$$

$$SSE = \left[\frac{1}{N} \sum (MR_{exp} - MR_{pred})^2 \right] \tag{5}$$

$$\text{RMSE} = \left[\frac{\sum (MR_{pred} - MR_{exp})^2}{N} \right] \frac{1}{2} \tag{6}$$

where: MR_{pred} – predicted moisture ratio; MR_{exp} – experimental moisture ratio; MR_{AVpred} – average predicted moisture ratio; N – number of data points.

RESULTS AND DISCUSSION

Drying conditions' effects on the moisture ratio and drying time. The drying curve depicting the drying process of the moringa leaf is as shown in Figures 2, 3 and 4. It was observed

Table 1. Drying models used to characterise the thin layer drying behaviour of the moringa leaves

Model	Equation	Reference
Newton	$MR = \exp(-kt)$	Doymaz and Ismail (2011)
Two-term	$MR = a \times \exp(-k_1t) + b \times \exp(-k_2t)$	Wang et al. (2007)
Henderson & Pabis	$MR = a \times \exp(-kt)$	Koua et al. (2009)
Wang & Singh	$MR = 1 + at + bt^2$	Bal et al. (2010)
Hii et al.	$MR = a \times \exp(-kt) + (1-a) \exp(-kat)$	Hii et al. (2009)
Verma et al.	$MR = a \times \exp(-kt) + (1-a) \exp(-gt)$	Doymaz (2005)
Diffusion Approach	$MR = a \times \exp(-kt) + (1-a) \exp(-kbt)$	Yaldiz et al. (2001)
Midilli and Kucuk	$MR = a \times \exp(-kt^n) + bt$	Doymaz (2008)
Page	$MR = \exp(-kt^n)$	Doymaz (2004)
Logarithmic	$MR = a_0 + a \times \exp(-kt)$	Doymaz and Ismail (2010)

MR – moisture ratio; k_{0-2} – drying constants; a, b, n – model parameters; t – time

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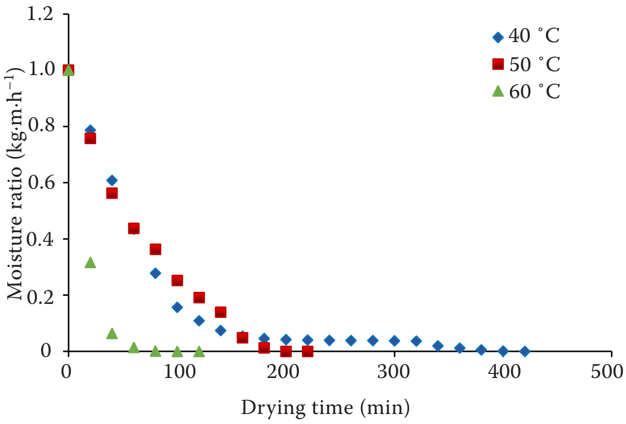

Figure 2. Moisture ratio *vs* drying time (40 g)

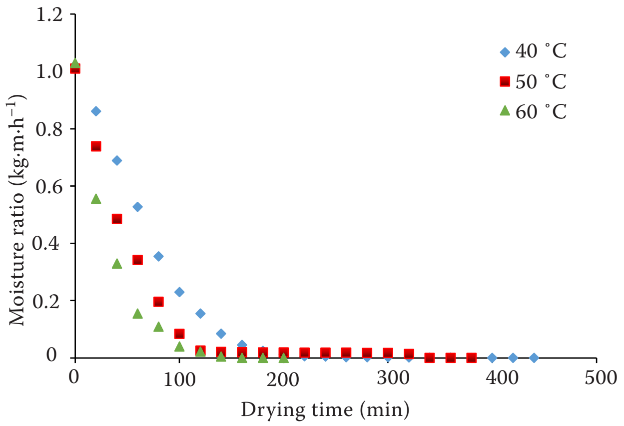

Figure 3. Moisture ratio *vs* drying time (80 g)

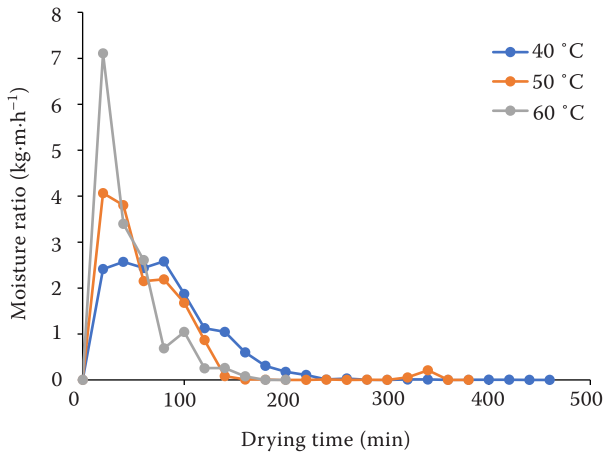

Figure 4. Drying rate *vs* time using 40 g

that as the temperature increased, the moisture ratio decreased in relation to the time at the same period. This observation is consistent with the findings of Mirzaee et al. (2009). The steady drop in the moisture ratio suggests that diffusion dictated the internal mass transport (Premi et al. 2010). Due to the increased rate of air heat supply to the leaves and the acceleration of the moisture migration, a higher drying air temperature decreased the moisture ratio faster (Demir and Tulek 2014).

The total time taken for the moringa leaves to reach the equilibrium moisture content from an initial moisture content of 300% d.b. at the varying drying conditions, ranged between 120 to 460 min. The temperature was found to have an inverse relationship with the drying. This observation agreed with that recorded by Mirzaee et al. (2009). Furthermore, it was observed that the moisture ratio decreased significantly with the drying time. The results demonstrate that the steady rate phase was missing, and the drying of moringa leaves occurred during the falling rate period. These findings are consistent with those of other studies (Premi et al. 2010; Ali et al. 2014; Ayoola and Goodluck 2015; Ramarao et al. 2021).

Effects of the drying conditions on the drying rate. Figure 4 shows the fluctuation in the drying rate with the drying time under various drying conditions. It was observed that the drying rate directly increases with the temperature and inversely decreases with the drying time.

Additionally, Table 2 shows that temperature and weight have a significant effect on the drying rate as they have P values less than 0.05 ($P < 0.05$). It was noted that the increasing moisture content caused an increase in the drying rate, and *vice versa*. Doymaz et al. (2006), Ayoola and Goodluck (2015), and Olabode et al. (2015) all reported similar findings.

Mathematical modelling. Ten thin layer drying models were used in fitting the drying data obtained during the drying experiment. The criteria for the suitability fit of a model was conducted based on the highest R^2 and lowest RMSE and SSE values. Table 3 shows the statistical results of the best fit models under various drying conditions. The best fits for drying the moringa leaves at the various drying conditions

Table 2. Variance analysis of the effect of several parameters on the drying rate

Source	R^2	*df*	RMSE	*F*-value	*P*-value
Temperature	1.15	1	1.15	36.80	0.0018
Weight	0.2985	1	0.2985	9.53	0.0272

R^2 – coefficient of determination; *df* – degree of freedom; RMSE – root mean square error

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Table 3. Best models for the moringa leaves with the statistical analysis at variable temperatures and weights

Temperature (°C)	Weight (g)	Model	R^2	RMSE	SSE
40	40	Newton	0.9690	0.0701	0.1405
		Henderson & Pabis	0.9613	0.0723	0.1082
	80	Newton	0.9338	0.1050	0.2426
		Henderson & Pabis	0.9219	0.1068	0.2509
	120	Newton	0.8659	0.1586	0.5533
		Henderson & Pabis	0.8495	0.1611	0.5710
50	40	Newton	0.9446	0.1082	0.1405
		Henderson & Pabis	0.9353	0.1125	0.1519
	80	Henderson & Pabis	0.9866	0.0348	0.0230
		Newton	0.9890	0.0348	0.0232
	120	Henderson & Pabis	0.9866	0.0348	0.0230
		Newton	0.9890	0.0348	0.0232
60	40	Henderson & Pabis	0.8822	0.2213	0.3428
		Page	0.8383	0.2188	0.3350
	80	Henderson & Pabis	0.9888	0.0604	0.0401
		Page	0.9798	0.0559	0.0344
	120	Page	0.9627	0.0703	0.0692
		Henderson & Pabis	0.9560	0.0832	0.0968

R^2 – coefficient of determination; RMSE– root mean square error; SSE – sum of square error

were obtained and better predicted by Newton, Henderson and Pabis and Page, but Henderson and Pabis had a higher R^2 of 0.988 and lower and ranging from 0.035 to 0.221 and from 0.0230 to 0.3428, respectively, and was, therefore, chosen to represent the drying characteristics of the moringa leaf.

The predicted moisture ratio and the measured moisture ratio. Figures 5, 6 and 7 depict the correlation between the expected and experimental moisture ratios with respect to the drying time, weights and temperature using the best fit models with the highest R^2 value. This indicated that the moisture ratio values of the model banded well along the experimented moisture ratio, and clearly indicates the suitability of the models in describing the drying characteristics of the moringa leaves.

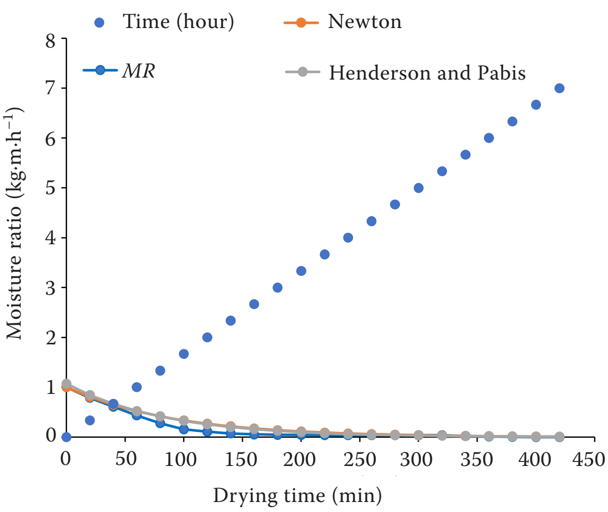

Figure 5. Moisture ratio (*MR*) *vs* time for 40 g and 40 °C using the two best models

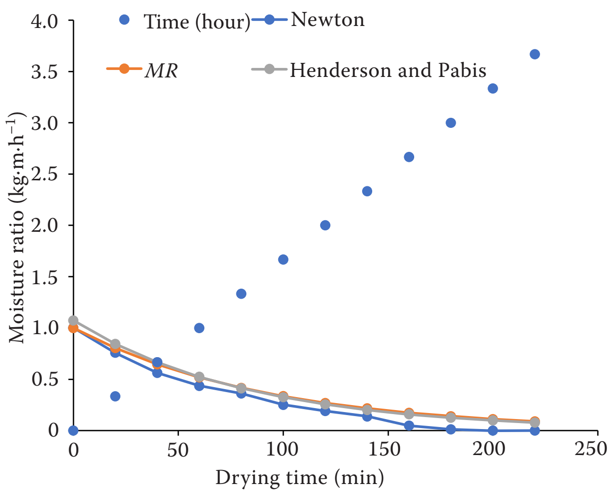

Figure 6. Moisture ratio (*MR*) *vs* time for 40 g and 50 °C using the two best models

Effective diffusivity of the moringa leaf at different weights and temperatures. The effective diffusivity of the moringa leaf was determined from the slope (k) by comparing the natural log of the mois-

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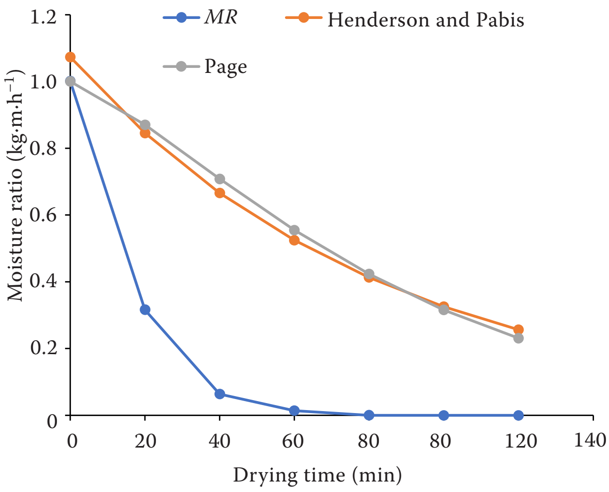

Figure 7. Moisture ratio (*MR*) *vs* time for 40 g and 60 °C using the two best models

ture ratio (ln *MR*) with the drying time (*t*) for all the investigated drying parameters (Table 4). The moringa leaf effective diffusivity ranged between 8.72×10^{-9} m^2·s^{-1} to 1.40×10^{-8} m^2·s^{-1}. Table 4 shows that the lowest value of the effective moisture diffusivity was obtained from the minimum weight used and that increase in the sample weight increases the value of the effective moisture diffusivity at a constant drying temperature.

Table 5 shows the variation in the temperature and weight with respect to the effective moisture diffusivity. The lowest effective moisture diffusivity value was 8.72×10^{-9} m^2·s^{-1} which was obtained at a temperature of 40 °C and a weight of 40 g. The moisture diffusivity with regards to the variation in the weight was affected by the drying temperature because the drying temperature affected the internal mass transfer during drying (Nwajinka et al. 2014; Akowuah et al. 2021).

Activation energy of the moringa leaf at different weights and temperature. The activation energy is the required quantity of energy necessary to initiate a reaction, i.e., moisture diffusion in food products. The activation energy (KJ·mol^{-1}) of the moringa leaf was calculated by plotting the natural logarithm of the estimated effective diffusivity (ln D_{eff}) against the reciprocal of the absolute temperature (1·K^{-1}). The activation energy decreased with an increase in the weight of the samples, this effect has also been seen in various research studies (Demiray and Tulek 2014; Wang et al. 2018)

Table 6 shows the calculated activation energy 90.46362, 40.48838, and 22.74661 (KJ·mol^{-1}) at different weights of 40, 80 and 120 g, respectively. The obtained activation energy is in the general range of food materials as stated to be 12.7 to 110 KJ·mol^{-1} by Zogzas et al. (1996). These results are in coherence with the findings of Ojediran and Raji (2011).

Table 4. Variation in the effective diffusivity with the weight

Weight (g)	D_{eff} (m^2·s^{-1})	R^2
40	8.72417*E*–09	0.8646
80	1.52402*E*–08	0.9723
120	1.78402*E*–08	0.9607

D_{eff} – the effective diffusivity; R^2 – coefficient of determination

Table 6. Activation energy of the moringa leaf at different weights

S/N	Weight (g)	Activation energy (KJ·mol^{-1})
1	40	90.4636
2	80	40.4884
3	120	22.7466

S/N – serial number

Table 5. Effective diffusivity using the temperature and weight

Temperature (°C)	Weight (g)	D_{eff} (m^2·s^{-1})	R^2
	40	8.72417*E*–09	0.8646
40	80	1.52402*E*–08	0.9723
	120	1.78402*E*–08	0.9607
	40	2.40669*E*–08	0.6445
50	80	1.40761*E*–08	0.7101
	120	1.74288*E*–08	0.8879
	40	7.36932*E*–08	0.9483
60	80	3.92212*E*–08	0.8601
	120	3.04635*E*–08	0.9724

R^2 – coefficient of determination; D_{eff} – effective diffusivity

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CONCLUSION

The moringa leaf drying characteristics were investigated in a cabinet dryer at temperatures of 40, 50, and 60 °C. The drying rate increased with an increase in the temperature and a reduction in the drying time was observed. In absence of a constant rate period, drying took place in the falling rate period. The effective moisture diffusivity of the moringa leaf ranged from 8.72×10^{-9} $m^2 \cdot s^{-1}$ to 1.40×10^{-8} $m^2 \cdot s^{-1}$ when dried at 40 to 50 °C. The activation energy was deduced by relating the effective moisture diffusivity with the drying temperature and was calculated as 90.4636, 40.4884 and 22.7466 ($KJ \cdot mol^{-1}$) for 40, 80 and 120 g, respectively. The drying behaviour of moringa leaf was explained using ten (10) models. The experimental data were fitted into these models. Among these models, Henderson & Pabis gave the best results and showed a good relationship with the experimental data.

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