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# Thin layer drying and effect of temperature on the drying characteristics of bushbuck (*Gongronema latifolium*) leaves

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A R T I C L E I N F O

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A B S T R A C T

Determination of the drying properties of agricultural products holds several benefits, such as nutrient preservation, processing and storage. The effect of air temperature on the drying properties and kinetics of bushbuck leaves at 30, 40, 50, 60 and 70 °C temperature was investigated. The drying time declined as the temperature rose, indicating a falling rate drying phenomenon. Drying models such as Henderson and Pabis, Newton, Modified Page, Page, Midilli and others, Logarithmic, and Two-term were applied and fitted to the experimental data's moisture ratio. The non-linear regression fitting method results showed that the Midilli and other models gave the best-fit description for the drying process. The values obtained for the coefficient of determination ($R^2$) were observed to have varied from 0.9948 to 0.9995 for the various drying models evaluated. In contrast, the sum of square error (SSE) and root mean square (RMSE) estimate was observed to vary from 0.0056 to 0.0007 and 0.0310 to 0.0163, respectively. On the estimate for the effective moisture diffusivity ($D_{eff}$), it was observed that it depends on temperature and extends from $1.33 \times 10^{-9}$ to $4.83 \times 10^{-9}$ $m^2/s$. The value of the activation energy was 26.05 kJ/mol. From this study, it can be deduced that the Arrhenius model could predict the temperature effect on the drying process of bushbuck leaves.

## 1. Introduction

Medicinal plants' use could be traced back to the history of human civilisation, as early humans treated their illnesses by using plants and their products as antibiotics [1]. Some medicinal plants' values depend on the nutrients and bioactive compounds they provide to the human body, including phytochemicals, minerals, vitamins, and fibres [2].

Bushbuck (*Gongronema latifolium)* leaf vegetable is a tropical rainforest plant grown in West Africa and is associated with the *Asclepiadaceae* family, genus *Gongronema* and species of *latifolium* [3]. It is commonly known as "utazi" by the Igbos, "utasi" by the Ibibios, while the Yorubas in the southern part of Nigeria call it "Arokeke". The plant is known as "kurutunsurogya" by the akan-asantes in Ghana. The Serer people call it "gasub" in Senegal while in Sierra Leone, it is known as "ndondo-polole [3]. It is a climber with broad, heart-shaped green leaves and is characterised by a slightly sweet and bitter taste when eaten fresh. It can serve as a vegetable in soups such as ugba sauce, porridge yam, and nsala (white soup). It is also used as a garnish for dishes like ncha, nkwobi, abacha, and isiewu (goat head). It helps to reduce postpartum contraction, stimulate appetite and enhance the normal flow of the menstrual cycle. Freshly harvested bushbuck leaves have a high moisture content (82.95 % wet basis). Due to the high moisture content in the leaves, their shelf life is shorter because they are subjected to rapid deterioration, hence the need to preserve them.

Drying is the oldest and most widely practised unit operation for enhancing the shelf life of agricultural produce by removing moisture from the product, lowering postharvest losses and improving food security [4,5]. It preserves the food for a long time and adds value to it. It also improves the bio-accessibility and bioavailability of health-promoting compounds in food for off-seasonal use without considerable deterioration in nutrient levels and cuts transportation and storage costs. Improved product quality, reduced drying time, and higher energy efficiency are the major factors for effective drying, and most of the drying methods available were designed based on these factors [6–8].

Simulation modelling of the drying process is used to help engineers develop new ideas or designs, improve existing drying systems, and predict the system's performance, such as the airflow over the product

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**Fig. 1.** (a) Fresh bushbuck leaves (b) Dried sample.

or even for the control of the process [9,10].

Effective moisture diffusivity and activation energy are essential properties that control drying operations. Diffusion rates of molecules in solutions are widely considered critical to many chemical, biological, and industrial processes [2]. Understanding the diffusion rate will help select the appropriate drying variables to guarantee product quality and economical energy utilisation during drying. As a result of this, the following researchers studied the moisture diffusivity and activation energy of agricultural produce such as okra [8], red pepper [10], scent and lemon basil leaf [11], African oil bean seed [2], pepper [7], elephant apple [12], *Nauclea latifolia* leaves [13], bitter leaf [14], Pomegranate seeds [17], mango slices [18] among many others. Much information on effective moisture diffusivity and activation energy for different agricultural products exists in the literature; however, there needs to be more on bushbuck leaves. The empirical data required to model heat and mass transfer during drying is generated by determining effective moisture diffusivity and activation energy.

Therefore, this research work targets to investigate the kinetics and characteristics of drying bushbuck leaves using a vacuum oven dryer at different temperatures, select an appropriate drying model for the drying kinetics of the leaves by applying semi-empirical drying models in literature and calculate the effective moisture diffusivity and activation energy of bushbuck leaf.

## 2. Materials and methods

Fresh samples of bushbuck leaves were purchased from a local supplier in the "*Ogige*" market in Nsukka, Nigeria. Experiments were conducted in the laboratory, Crop Science Department, Faculty of Agriculture, University of Nigeria Nsukka, Enugu State. The leaves were carefully separated from the stalk, washed and stored in the refrigerator at 4 °C for 24 h to equilibrate the moisture content (Fig. 1). The samples were removed from the refrigerator and allowed to attain room temperature, and a thickness of 0.1 mm was measured using a micrometre screw gauge. The samples were divided into portions of approximately 100 g each, and experiments were run in three replicates. One portion of the sample was dried in a convective oven at 105 °C for 24 h [8,12] to estimate the initial moisture content. Equation 1 was used to calculate the value of the initial moisture content of bushbuck leaves, which equals 82.95 % (wet basis) [15]:

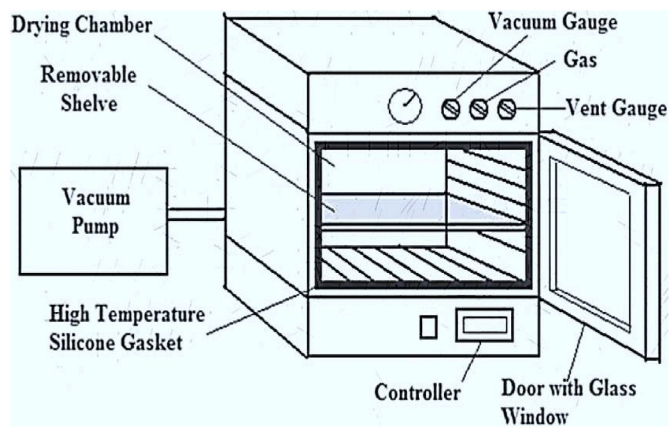


**Fig. 2.** Schematic diagram of the vacuum oven equipment.

$$M_o = \frac{w_o - w_d}{w_0} \, x\, 100 \quad (1)$$

$W_o$ and $W_d$ are the initial and product mass after drying, respectively.

The collection of plant material and the performance of experimental research on bushbuck leaves in this study complied with the guidelines stipulated by the National Agricultural Technology and Innovation Policy (NATIP) [16].

### 2.1. Drying equipment and procedure

Drying experiments on bushbuck leaves were performed in a laboratory vacuum oven dryer (Fig. 2) (Huanghua Faithful Instrument Co. China, DZ-3BE) with technical specifications: 50Hz, 220V, 2000W, vacuum degree of <133Pa and temperature range +10–250 °C. The DZ-3BE vacuum oven features an exhaust port that vents moisture away from the materials for drying and functions at relatively low temperatures. The oven was switched to run for 30 min without a sample before each experiment to attain a steady-state drying atmosphere. The experiments were conducted at five different temperatures, 30, 40, 50, 60, and 70 °C, for the samples. The clearance between two consecutive trays was kept at 50 mm in the drying chamber. One hundred grams of the fresh leaves were distributed evenly on the perforated stainless oven tray

**Table 1**
The thin layer drying models considered for the drying kinetics of bushbuck leaves.

| Models | Equations | References |
|---|---|---|
| Newton | $MR = \exp(-kt)$ | [18] |
| Henderson and Pabis | $MR = a\exp(-kt)$ | [19,13] |
| Page | $MR = \exp(-kt^n)$ | [20,12] |
| Modified Page | $MR = \exp(-kt)^n$ | [10] |
| Logarithmic | $MR = a\exp(-kt) + c$ | [21–23] |
| Two-term | $MR = a\exp(-k_0 t) + b\exp(-k_1 t)$ | [9] |
| Midilli and others | $MR = a\exp(-kt^n) + bt$ | [24,7] |

in a thin layer. During drying, moisture loss was measured by bringing out the sample and cooling it in an airtight glass jar. Then, the samples were weighed using a digital weighing balance with 0.1-g precision (MT-5000D, Metlar balance, USA) at predetermined intervals (30 min) till the final weights were constant for three concordant readings. All samples were taken in triplicates for all five temperature ranges. Drying calculations were performed according to the equations.

### 2.2. Mathematical modelling

Moisture removal was activated by the movement of individual molecules from the inward to the surface of the thin layer during the falling rate period [11,17]. Consequently, this resulted in the movement of the water molecules to the surrounding environment, where the material was dried via evaporation. This phenomenon is expressed by Fick's second law of diffusion as follows:

Moisture ratio (*MR*) was estimated using Equation (2)

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

Where $M_t$ is the moisture content at time t, *MR* is the moisture ratio, $M_o$ is the initial moisture content, and $M_e$ is the equilibrium moisture content (kg water per kg dry matter).

$$Drying\ rate = \frac{M_{t+dt} - M_t}{d_t} \quad (3)$$

Where $M_{t+dt}$ *and* $M_t$ are the moisture content at $t + dt$ and moisture content at t (kg dry matter), respectively, t is drying time (minutes).

The thin layer drying models presented in Table 1 were employed for this research work to analyse, describe and represent experimental kinetic data. From the equations, *k* represents the drying constant (per hour), c, n, and a are model parameters, and t is the drying time (in minutes).

The regression analyses were carried out with the help of a computer software package known as MATLAB R2023a (Mathworks, USA). The correlation coefficient ($R^2$), the root mean square error (RMSE), and the sum of square error (SSE) as estimated from equations (4)–(6), respectively, were the parameters employed for the selection of the best model [4,12,8,15][4,8,12,15]. For good fits, higher values of $R^2$ and lower values of RMSE and SSE were considered [6,19,21].

$$R^2 = \frac{\left(\sum MR_{exp} \times MR_{pre}\right)^2}{\sum MR_{exp}{}^2 \times \sum MR_{pre}{}^2} \quad (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{\frac{1}{2}} \quad (5)$$

$$SSE = \sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2 \quad (6)$$

Where $MR_{pre,i}$ and $MR_{exp,i}$ are the *ith* predicted and experimental moisture ratio, respectively, N is the number of observations.

### 2.3. Determination of effective moisture diffusivity and activation energy

Fick's second law was employed to describe the drying processes of food material during falling rate [17,23,25] as expressed in Equation (7) to determine effective diffusivity coefficients at different drying temperatures.

$$\frac{\delta M}{\delta t} = D_{eff}\frac{\delta^2 M}{\delta x^2} \quad (7)$$

Where $\frac{\delta M}{\delta t}$ = moisture content (dry basis) per unit time (sec), $x$ is coordinated in the direction of the mass transfer path (m), and $D_{eff}$ is the diffusivity ($m^2$/sec).

Considering the leaves as slab, the solution of Equation (7) can be given as Equation (8),

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

For long drying periods, according to Doymaz [19], Equation (8) can further be simplified to Equation (9).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \quad (9)$$

Where;

$D_{eff}$ = the effective diffusivity ($m^2$/s), $L$ = half thickness of the leaf (0.0001m), and t = the drying time (s).

The linear form of Equation (9) is expressed in Equation (10), according to Oladayo et al. [13].

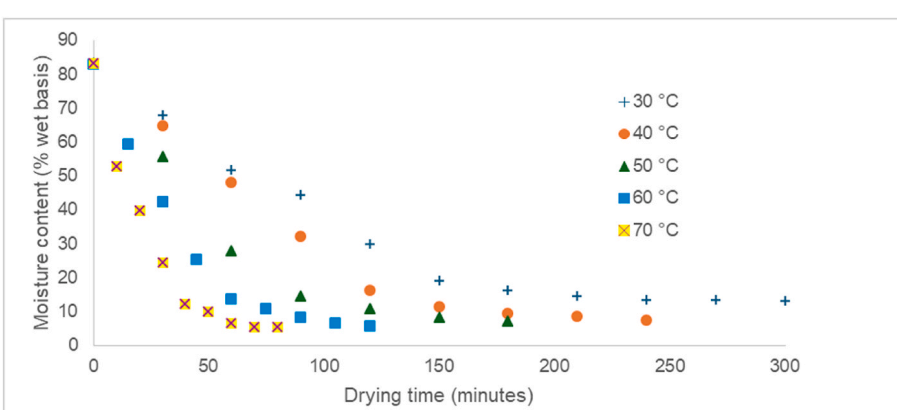


**Fig. 3.** Influence of drying temperature on the moisture content of bushbuck leaves.

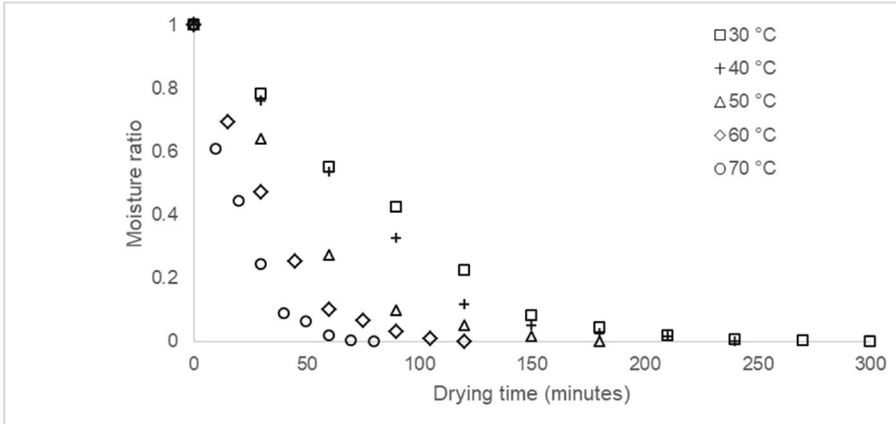


**Fig. 4.** Influence of drying temperature on the moisture ratio of bushbuck leaves.

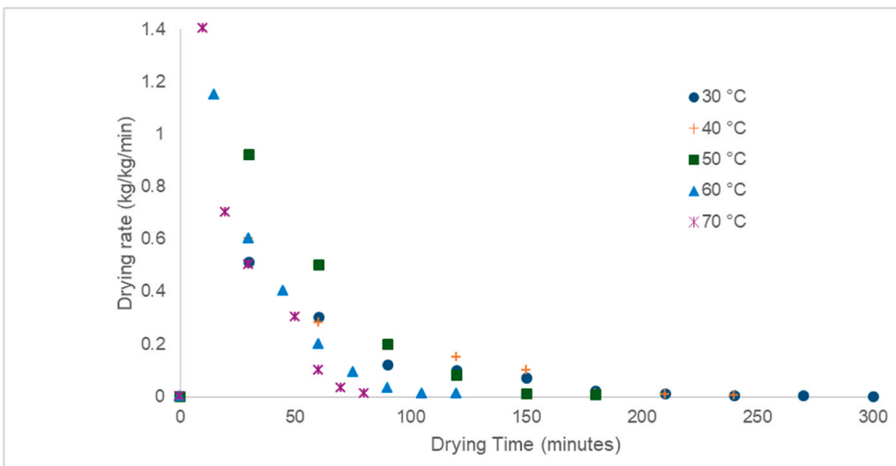


**Fig. 5.** Drying rate versus drying time of bushbuck leaves.

$$LnMR = Ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{10}$$

The $D_{eff}$ of the leaves were obtained by plotting *Ln MR* versus time

Arrhenius Equation generally describes that the $D_{eff}$ is dependent on temperature [18,25];

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{11}$$

Where $E_a$ is the activation energy (kJ/mol), $D_0$ is the diffusion coefficient of the Arrhenius equation ($m^2/s$), $T$ is the absolute temperature (K), and $R$ is the universal gas constant (8.314 kJ/mol K).

Taking the natural logarithm on both sides yields Equation (12);

$$\ln D_{eff} = \ln D_0 - \left(\frac{E_a}{R}\right) \times \frac{1}{T} \tag{12}$$

The parameter $E_a$ can be calculated from the plot of $\ln D_{eff}$ versus $\frac{1}{T}$, which yields a straight line with $-\frac{E_a}{R}$ as the slope.

## 3. Results and discussion

### 3.1. Effect of temperature on drying

Fig. 3 shows the drying behaviour of bushbuck leaves with an initial moisture content of 82.95 % to a final value of 5.03 %. The temperature had a remarkable effect on the drying characteristics of the leaves, as expected. The time required to bring the initial moisture of the leaves to the final value, as shown in Fig. 3, were 80, 120, 180, 240 and 300 min at 70, 60, 50, 40, and 30 °C, respectively.

The plot between the moisture ratio of bushbuck leaves and the drying time is represented in Fig. 4, showing that the moisture ratio decreases as the drying time increases. It was observed that the kinetics of food materials were influenced by drying temperature, as reported by other researchers [11,13,19,22]. Hence, there is a faster reduction in moisture content at higher drying temperatures because of an increase in drying rate. Also, the drying occurred in a falling rate period [20], indicating that a constant rate did not occur in the drying process of bushbuck leaves. Researchers have reported similar outcomes for the drying of red pepper [10], elephant apple [12], Millet seed [20], mango slices [18], green beans and okra [19], *Nauclea latifolia* leaves [13], apricot [9], and thyme leaves [26].

As seen in Fig. 5, the drying rate rapidly increases and then slowly decreases as drying progresses. Generally, it is observed that the drying rate reduces with time or with the reduction of moisture content. The drying rate was highest at 70 °C during the first 30 min of drying, and it also showed that drying occurred at a falling rate, and no constant rate was recorded. Similar results have been observed in the drying of different fruits and vegetables: Indian spinach [6], pepper [7], and cotton seeds [25]. Akpinar et al. [10] reported that drying during the falling rate period is governed by water diffusion in the solid. Thus, temperature had a crucial effect on the drying rate.

**Table 2**
Statistical parameters, constants and coefficients for fitted models for drying of bushbuck leave at different temperatures.

| Model | Temperature (°C) | Model constants and coefficients | $R^2$ | RMSE | SSE |
|---|---|---|---|---|---|
| Newton | 30 | $k = 0.4836$ | 0.9803 | 0.0422 | 0.0178 |
| | 40 | $k = 0.6623$ | 0.9812 | 0.0461 | 0.0170 |
| | 50 | $k = 1.0100$ | 0.9876 | 0.0391 | 0.0092 |
| | 60 | $k = 1.5220$ | 0.9923 | 0.0292 | 0.0068 |
| | 70 | $k = 2.5160$ | 0.9938 | 0.0257 | 0.0052 |
| Page | 30 | $k = 0.4790$, n = 1.0120 | 0.9804 | 0.0444 | 0.0178 |
| | 40 | $k = 0.5902$, n = 1.2220 | 0.9903 | 0.0355 | 0.0089 |
| | 50 | $k = 0.9964$, n = 1.1060 | 0.9893 | 0.0398 | 0.0079 |
| | 60 | $k = 1.5660$, n = 1.1060 | 0.9945 | 0.0264 | 0.0049 |
| | 70 | $k = 2.5160$, n = 1.0000 | 0.9938 | 0.0275 | 0.0053 |
| Henderson and Pabis | 30 | $k = 0.4907$, a = 1.0140 | 0.9806 | 0.0441 | 0.0175 |
| | 40 | $k = 0.6886$, a = 1.0400 | 0.9837 | 0.0459 | 0.0147 |
| | 50 | $k = 1.0270$, a = 1.0180 | 0.9881 | 0.0420 | 0.0088 |
| | 60 | $k = 1.5510$, a = 1.0200 | 0.9928 | 0.0301 | 0.0063 |
| | 70 | $k = 2.5100$, a = 0.9975 | 0.9938 | 0.0274 | 0.0052 |
| Modified Page | 30 | $k = 0.4885$, n = 0.9901 | 0.9803 | 0.0499 | 0.0178 |
| | 40 | $k = 0.6038$, n = 1.0970 | 0.9812 | 0.0493 | 0.0171 |
| | 50 | $k = 0.8553$, n = 1.1810 | 0.9876 | 0.0429 | 0.0092 |
| | 60 | $k = 1.1480$, n = 1.3260 | 0.9923 | 0.0312 | 0.0068 |
| | 70 | $k = 1.5830$, n = 1.5890 | 0.9938 | 0.0274 | 0.0053 |
| Logarithmic | 30 | $k = 0.5761$, a = 0.9691, c = 0.0616 | 0.9839 | 0.0427 | 0.0146 |
| | 40 | $k = 0.6436$, a = 1.0630, c = −0.0288 | 0.9862 | 0.0408 | 0.0116 |
| | 50 | $k = 1.0840$, a = 1.0020, c = 0.0202 | 0.9910 | 0.0391 | 0.0075 |
| | 60 | $k = 1.5490$, a = 1.0200, c = −0.0005 | 0.9928 | 0.0325 | 0.0063 |
| | 70 | $k = 2.5710$, a = 0.9914, c = 0.0084 | 0.9978 | 0.0146 | 0.0020 |
| Two term | 30 | $k_0 = 0.5198$, a = 1.0280, b = 5.23e-02, $k_1 = -1.4830$ | 0.9893 | 0.0372 | 0.0097 |
| | 40 | $k_0 = 0.5516$, a = 4.7890, b = −3.7520, $k_1 = -0.5196$ | 0.9847 | 0.0527 | 0.0139 |
| | 50 | $k_0 = 0.8184$, a = 6.9450, b = −5.9310, $k_1 = 0.7892$ | 0.9937 | 0.0351 | 0.0054 |
| | 60 | $k_0 = 1.1190$, a = 19.0100, b = −18.0900, $k_1 = -1.1000$ | 0.9956 | 0.0178 | 0.0037 |
| | 70 | $k_0 = 1.5910$, a = 18.8500. b = −17.8800, $k_1 = 1.5570$ | 0.9961 | 0.0146 | 0.0026 |
| Midilli et al. | 30 | $k = 0.4745$, a = 0.9893, b = 0.0276, n = 1.3530 | 0.9938 | 0.0283 | 0.0056 |
| | 40 | $k = 0.6043$, a = 0.9906, b = 0.0208, n = 1.4760 | 0.9970 | 0.0232 | 0.0027 |
| | 50 | $k = 1.1600$, a = 1.0020, b = 0.0307, n = 1.4051 | 0.9995 | 0.0163 | 0.0007 |
| | 60 | $k = 1.8160$, a = 0.9956, b = 0.0295, n = 1.2670 | 0.9979 | 0.0194 | 0.0018 |
| | 70 | $k = 2.7340$, a = 0.9940, b = 0.0184, n = 1.0658 | 0.9943 | 0.0310 | 0.0048 |

### 3.2. Evaluation of the drying models

Table 2 summarises the statistical results, values of the drying coefficients and drying constants for the models selected. It can be observed that the drying constant ($k$) is dependent on temperature, increasing as the temperature rises. Three statistical parameters, $R^2$, RMSE and SSE, were employed to compare the goodness of fit of the thin layer drying models selected.

$R^2$ values were more significant than 0.96 in all cases, indicating a good fit [10,18,19]. The $R^2$ values ranged from 0.9803 to 0.9995, while RMSE and SSE values ranged from 0.0527 to 0.0076 and 0.0178 to 0.0008, respectively. The results showed that the seven proposed drying models adequately predict thin layer drying kinetics and characteristics of bushbuck leaves. The Midilli et al. [24] model gave higher values of $R^2$ and lower RMSE and SSE values when compared to the other models tested. Hence, the Midilli and others model could be selected to appropriately represent the thin layer drying kinetics and characteristics of bushbuck leaves.

Fig. 6 shows the fitted Midilli models' predicted moisture ratio and experimental moisture ratio values with drying time. From the figures presented, the Midilli model gave a good representation of the experimental moisture ratio values for the drying kinetic of bushbuck leaves at different temperature levels. Comparable results were recorded by researchers such as Darvishi et al. [7] for pepper, Doymaz [19] for okra and Akoy [18] for mango slices.

### 3.3. Effective moisture diffusivity

The effective moisture diffusivity was calculated using Fick's second law of diffusion (Eq. (10)) by plotting ln(MR) versus drying time (in minutes), as shown in Fig. 7. The effective moisture diffusivity was evaluated using slopes. The curves are fitted to a straight line, showing that liquid diffusion is the driving force regulating the drying process. The values of the effective moisture diffusivity for the different ranges of drying air temperature are presented in Table 3. It can be observed that the values of the $D_{eff}$ were found to be $1.33 \times 10^{-9}$, $1.52 \times 10^{-9}$, $1.76 \times 10^{-9}$, $2.64 \times 10^{-9}$ and, $4.83 \times 10^{-9}$ $m^2/s$ at 30, 40, 50, 60 and 70 °C, respectively. Drying at 70 °C gave the highest moisture diffusivity. $D_{eff}$ of bushbuck leaves increase considerably with an increase in temperature [20]. The $D_{eff}$ values obtained from this study lie within the generally acceptable range for food materials and were found to agree with the study of Thuy et al. [27] for roselle seed at air drying temperatures of 55, 60, 65 and 70 °C with the calculated moisture diffusivity coefficient varied from $5.426 \times 10^{-10}$ to $1.074 \times 10^{-9}$ $m^2/s$. Hssaini et al. [28] studied the kinetics, energy efficiency and mathematical modelling of thin-layer solar drying of fig slices. They showed that the values of the effective moisture diffusivity were obtained between $1.9556 \times 10^{-9}$ and $4.0511 \times 10^{-8}$ $m^2/s$ in the range of drying temperature of 60–80 °C. A study on drying characteristics of yam slices in a convective hot air dryer at 50, 60 and 70 °C by Ojediran et al. [29] found the value of the effective moisture diffusivities to vary from $6.382 \times 10^{-9}$ to $1.641 \times 10^{-8}$ $m^2/s$.

However, the values of $D_{eff}$ obtained from our study were higher than

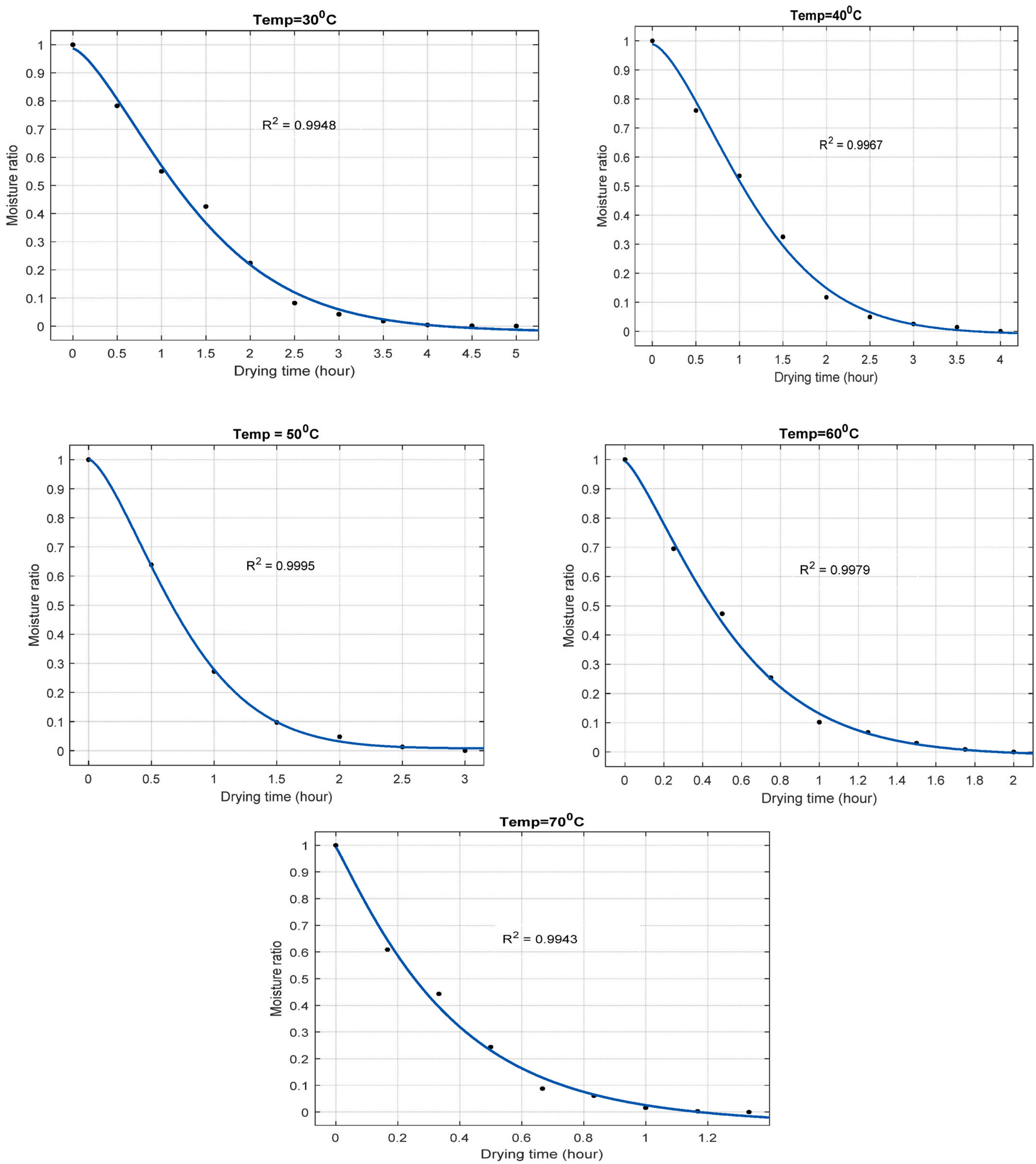


**Fig. 6.** The fitted Midilli and other models for drying bushbuck leaves at different temperature ranges.

those published by Hii et al. [30] in studying the new thin layer model and product quality of cocoa, the effective diffusivities for the three air temperatures (60, 70 and 80 °C) ranged from $7.46 \times 10^{-11}$ to $1.87 \times 10^{-10}$ $m^2/s$. Vijay et al. [31] also reported the effective diffusivity value of cotton seeds under open sun drying as $1.991 \times 10^{-11}$ $m^2/s$.

### 3.4. Activation energy

The values of Ln(Deff) versus 1T were presented in Fig. 8 to obtain the effect of temperature on the effective moisture diffusivity. The plot was a straight line over the temperature ranges investigated, indicating Arrhenius dependency. The activation energy was calculated from the slope of the straight line, which was found to be 26.05 kJ/mol. This

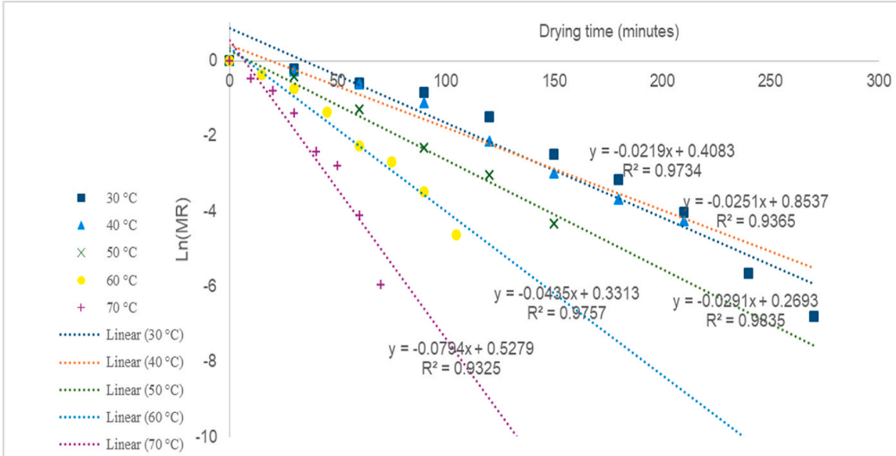


**Fig. 7.** Plot of *Ln(MR)* versus drying time of bushbuck leaves.

**Table 3**
Effective moisture diffusivities and statistical analyses of a linear model of bushbuck leaves.

| Temperature (°C) | Linear Equation | Slope ($k$) | $D_{eff}$ ( $m^2/s$) | $R^2$ |
|---|---|---|---|---|
| 30 | $y = -0.0219x + 0.4083$ | −0.0219 | $1.33 \times 10^{-9}$ | 0.9734 |
| 40 | $y = -0.0251x + 0.8537$ | −0.0251 | $1.52 \times 10^{-9}$ | 0.9365 |
| 50 | $y = -0.0291x + 0.2693$ | −0.0291 | $1.76 \times 10^{-9}$ | 0.9835 |
| 60 | $y = -0.0435x + 0.3313$ | −0.0435 | $2.64 \times 10^{-9}$ | 0.9757 |
| 70 | $y = -0.0794x + 0.5279$ | −0.0794 | $4.83 \times 10^{-9}$ | 0.9325 |

value of $E_a$ obtained from this study was found to lie within the generally acceptable range of 12.70–110.00 kJ/mol [10,19,27,30], where higher $E_a$ indicate higher sensibility to air temperature.

This value is similar to or slightly higher than the values calculated from the study of Nag and Dash [12] and Turan and Firatligil [26], with published $E_a$ values of 21.95 kJ/mol for elephant apple drying in the temperature range of 50–80 °C and 21.40 kJ/mol for thyme leaves drying at 50–80 °C temperature range, respectively. However, it is lower than the $E_a$ values reported by Kadam et al. [32], Mbegbu et al. [11], Oladayo et al. [13], Akoy [18], Ojediran and Raji [20], and Rajkumar et al. [33]; for basil (33.21 kJ/mol), lemon basil leaf (32.35 kJ/mol), *Nauclea latifolia* leaves (40.55 kJ/mol), mango slices (37.99 kJ/mol), millet (36.19 kJ/mol) and tamarind fruit (35.16 kJ/mol), respectively. Afolabi and Agarry [8] also reported $E_a$ values in the range of 10.39–14.97 kJ/mol for okra drying. This implies that, during the drying process, molecules would attain their transition state quickly, and the overall reaction occurred faster.

## 4. Conclusion

Seven thin-layer drying models described bushbuck leaves' vacuum oven drying kinetics. The drying process took 300 min to reduce the moisture content of the leaves from 82.95 % to 5.03 % wet basis. Drying curves were obtained from the experimental kinetic data to describe the drying process of the leaves, which was primarily influenced by temperature. It occurred in the falling rate period without a constant rate; hence, diffusion was the main driving force. The Midilli and others models showed better fits for the description of experimental data. This model gave the lowest value of RMSE = 0.0163 and SSE = 0.0007 and the highest value of $R^2 = 0.9995$ compared to other models investigated. The effective moisture diffusivity for the different temperatures was calculated within the $4.83 \times 10^{-9}$ to $1.33 \times 10^{-9}$ $m^2/s$ range. The

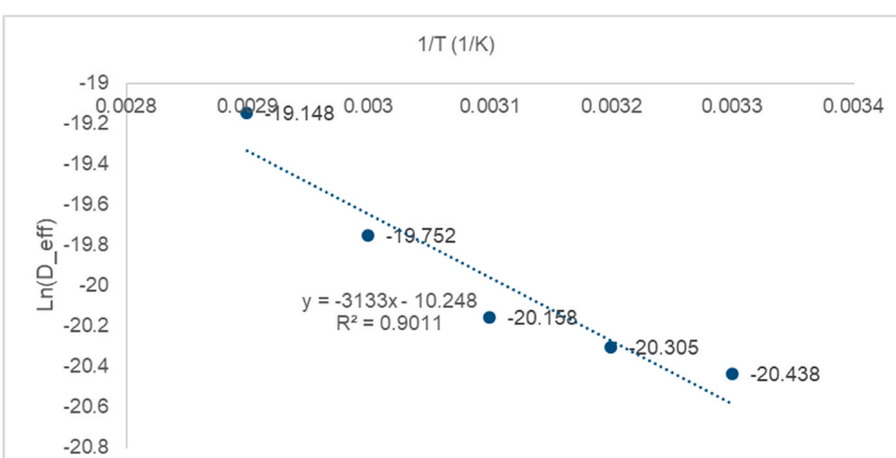


**Fig. 8.** Arrhenius relationship between temperature and adequate moisture diffusivity.

Arrhenius equation confirmed the dependence of the effective diffusion coefficient on the drying temperature, in which the activation energy found for the drying phenomenon was 26.05 kJ/mol. The knowledge this research contributes will enhance the design and optimisation of processing operations that require internal moisture transport for bushbuck leaves, such as drying and storage.

## CRediT authorship contribution statement

**N.N. Mbegbu:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.O. Ojediran:** Writing – review & editing, Validation, Supervision, Investigation, Formal analysis. **C.O. Nwajinka:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E.C. Chukwuma:** Writing – review & editing, Visualization, Validation, Supervision, Software, Project administration, Investigation, Formal analysis, Data curation. **Mathias Aniobi:** Methodology, Formal analysis.

## Declaration of competing interest

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

## Data availability

The dataset used and analysed during this current study is available upon request. The request should be directed to the lead author: mbegbunkechi@gmail.com.


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