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Drying kinetics, energy efficiency, and moisture diffusion characteristics of African walnut (*Tetracarpidium conophorum*) during cabinet and oven drying

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This study investigated the drying kinetics, energy consumption, and mathematical modelling of African (Nigerian) walnut (*Tetracarpidium conophorum*) using cabinet and oven drying systems at temperatures of 50, 65, and 80 °C, with and without shells. Drying experiments were carried out to determine the removal of moisture, effective diffusivity of moisture, and specific energy consumption. The curves of moisture ratio were analyzed by means of six thin-layer drying equations, and the performance of the equations was tested by means of the coefficient of determination (R^2), root mean square error (RMSE), and sum of squared errors (SSE). Analysis of the results indicates that the drying time decreased significantly with an increase in the drying temperature, with the shortest drying time being obtained using the oven drying method at 80 °C. The value of the effective diffusivity coefficient increased with an increase in the temperature from $6.23 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ to $4.72 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, which indicates that the rate of diffusion of the moisture inside the material increases with an increase in the thermal gradient. The activation energy required for moisture diffusion ranged from 4.79 kJ/mol to 24.61 kJ/mol depending on the method of drying and condition of the sample material. The Midilli & Kucuk model was found to be the best fit among the models used to describe the experimentally obtained results for the different drying conditions. The energy analysis indicated an improvement in the energy efficiency of the drying process with an increase in the drying temperature, owing to the reduced drying time and SEC, with the highest energy efficiency for oven drying at 80 °C, where the SEC was found to be 0.11 kWh/kg of water removed. In a nutshell, the results show that oven drying at 80 °C is the best compromise between drying rate and energy efficiency. This study is significant because it can help optimize the drying process and enhance the industrial utilization of the underutilized oil-rich nut.

KEYWORDS

African walnut, Cabinet drying, drying kinetics, energy efficiency, moisture diffusivity, oven drying, *Tetracarpidium conophorum*

1 Introduction

The Nigerian walnut (*Tetracarpidium conophorum*), commonly referred to as the African walnut, is an underutilized but nutritionally important crop grown and consumed in several regions of West and Central Africa (Nkwonta et al., 2023). The nut is very rich in nutrients with high contents of polyunsaturated fatty acids (PUFAs), essential amino acids, minerals, and valuable bioactive antioxidant compounds that have high nutritional, medicinal, and socioeconomic potential (Ni et al., 2021). Yet despite its potential benefits, the nut remains unexploited in its use and commercialization, mainly due to the postharvest challenges associated with its high initial moisture content, typically reported in the range of 35%–50% (wet basis) that makes the nut very susceptible to microbial and physiological decay (Gama et al., 2018; Man et al., 2024a). For nuts and oilseeds, safe moisture content for storage is generally below 8%–10% (wet basis) to minimize spoilage and extend shelf life (Obeng-Akrofi et al., 2023); therefore, proper drying is essential to improve the stability and safety of African walnut during storage.

One of the most commonly used preservation methods for oil-rich nuts and oilseeds is drying. It is a method that decreases the moisture content to levels that prevent microbial development and enzymatic action. Of the commonly used drying processes, cabinet drying (Yasmin et al., 2022), or hot air or conventional oven drying (López and Hincapié-Llanos, 2024), is widely practiced due to its ease of operation and simplicity. Nevertheless, it is a process that is highly dependent on process variables which include drying temperature, air velocity, relative humidity, product geometry, sample thickness, as well as the presence or absence of a shell. In the case of African walnut nuts, for instance, it is important to consider that the nuts have a shell that acts as a material that hinders the flow of moisture. It is therefore important to have a good understanding of its effects on energy efficiency (Chen et al., 2020b).

For drying behavior description and prediction, various thin-layer drying models have been proposed and used extensively in drying studies related to agricultural crops. Empirical and semi-theoretical models such as Newton, Page, Henderson-Pabis, Logarithmic, Two-term, and Midilli & Kucuk models have been effectively used to describe the process of moisture loss and mass transfer in drying (Almeida et al., 2024; Aregbesola et al., 2015; Basso et al., 2025; Fufa et al., 2025; Man et al., 2024a). In drying studies related to other walnut varieties like *Juglans regia*, drying temperatures, initial moisture contents, and structural property effects on drying rates and diffusivity have been observed and documented in earlier studies. For example, Man et al. (2024a) studied the mass transfer in hot-air drying of walnuts related to both external and internal mass transfer, while Almeida et al. (2024), Chen et al. (2020a), Nwakuba et al. (2025), and Srivastava and Sit (2025) studied drying kinetic and diffusivity effects in nuts and oilseeds related to drying conditions and structural variations.

However, despite such improvements, very little scientific data are available on drying properties, modeling kinetics, and energy efficiency of African walnut (*T. conophorum*), particularly on drying characteristics of both shelled and unshelled Nigerian walnuts using drying cabinet and oven drying methods. Owing to differences in structure of shelled and unshelled walnuts that may greatly affect diffusion rates of moisture along with energy use, it is important to

develop species models for drying to facilitate optimal post-harvest handling of such underutilized plants. Accordingly, the goal of this work is to examine the drying rate, moisture diffusivity, as well as energy usage of African walnut when drying using both cabinet and oven drying methods, as well as when drying both shelled and unshelled African walnut. Six thin-layer drying models were considered to determine which of these models could be used as a drying model, with these models evaluated using statistical measures such as R^2 , RMSE, and SSE. This work combines kinetic modeling with energy usage to produce information that can be used to determine efficient drying methods that could improve postharvest handling of African walnut.

2 Materials and methods

2.1 Sample collection and preparation

Raw Nigerian walnuts (*T. conophorum*) were obtained from a local seed farm in Ile-Ife, Osun State, Nigeria. The nuts were sorted by hand to eliminate defective and infested samples, washed with clean water, and then boiled for 10 min to soften the shells. Boiling was included to reflect traditional pre-processing practices and to partially loosen the shell structure, which has been shown to influence internal moisture diffusion and shell permeability during drying (Wu et al., 2024). Boiled walnuts were then divided into two groups: unshelled samples and shelled samples (which were obtained by manual deshelling).

2.2 Determination of initial moisture content

The initial moisture content of shelled and unshelled walnut samples was determined by employing an oven-drying method following an AOAC standard procedure (AOAC International, 2023). 5 g of sample (triplicate) was measured and placed into pre-dried and pre-weighed aluminum pans with moisture capacity. The samples were dried in a hot air oven at $105 \pm 2^\circ\text{C}$ for 24 h or until constant weight is achieved.

After drying, samples were placed into a desiccator with silica gel and cooled to room temperature (approximately 30 min). The samples were re-weighed, and drying and weighing were repeated at 1 h intervals until mass variation was less than 0.01g, indicating constant weight.

Moisture content (wet basis) was calculated using Equation 1:

$$MC_{wb} (\%) = \frac{M_i - M_d}{M_i} \times 100 \quad (1)$$

where M_i is the initial mass of the sample (g), and M_d is the dry mass of the sample after oven drying (g).

The moisture content (MC) on a dry basis at any time t was calculated using Equation 2:

$$MC_{db} = \frac{M_i - M_d}{M_d} \quad (2)$$

The value of the initial moisture content of the walnut samples calculated using this method, had an average value of 24.5% (wet basis). This value was used as the initial moisture for the drying kinetics analysis. The final moisture content of the dried samples ranged from 0.7% to 1.3% (dry basis).

2.3 Drying experiments

Drying experiments were conducted using two drying systems: a cabinet dryer (Model SMO28-2, SHELLAB, USA) and a laboratory oven (Model UN55, Memmert GmbH + Co. KG, Germany). Each system was loaded with a total of 2 kg of walnut samples (1 kg shelled and 1 kg unshelled), and all trials were performed in triplicate to ensure repeatability. The walnuts were spread in a single layer on perforated trays to enhance air circulation and uniform drying.

The cabinet dryer operated at controlled air temperatures of 50, 65, and 80 °C, while the oven dryer was set to the same temperature levels under forced hot-air convection. Although air velocity was indirectly measured, the dryer was operated under constant-fan conditions, and the nominal air speed (1.5 m/s) was taken from manufacturer calibration curves, ensuring consistent and reproducible airflow.

Drying was continued until each sample attained a constant mass. Weights were recorded at 1-h intervals at the early stage of drying and at 30-min intervals as the moisture loss approached equilibrium. All measurements were obtained using a digital balance (± 0.01 g precision). The ambient laboratory temperature (28 ± 2 °C) and relative humidity ($65\% \pm 5\%$) were monitored using a digital thermo-hygrometer, for documentation purposes only. As the dryers are closed systems, the ambient conditions did not have any direct effects on the drying process other than the minimal exposure during the periodic removal of the samples for weighing.

2.4 Drying kinetics and moisture ratio determination

The moisture content (MC) on a dry basis at any time t was calculated using Equation 3:

$$MC_t = \frac{W_t - W_d}{W_d} \quad (3)$$

where W_t is the sample weight at time t (g), and W_d is the oven-dry weight (g).

The dimensionless moisture ratio (MR) was computed using Equation 4:

$$MR = \frac{MC_t - MC_e}{MC_0 - MC_e} \quad (4)$$

where MC_t is the moisture content at time t (g water/g dry matter), MC_0 is the initial moisture content, and MC_e is the equilibrium moisture content, taken to be negligible (Macedo et al., 2020). Equilibrium moisture content (Me) was assumed negligible relative to initial moisture content, as validated by preliminary tests showing final moisture levels of 0.7%–1.3% dry basis.

All moisture contents were expressed on a dry basis (g water/g dry matter). Experimental data were processed using Python 3.12 (SciPy library) for curve fitting and model evaluation.

2.5 Effective moisture diffusivity determination

The effective moisture diffusivity, D_{eff} , describes the internal moisture migration rate and was estimated from Fick's second law of diffusion, applicable to materials in which the falling-rate period governs moisture transfer (Popescu et al., 2023). The Nigerian

walnut approximates a near-spherical geometry; therefore, the spherical model of Fick's second law was applied.

Assuming uniform initial moisture distribution, negligible external resistance, and constant diffusivity, the analytical solution to Fick's second law for spherical geometry is given by Macedo et al. (2020) as shown in Equation 5:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 D_{eff} t}{r^2}\right) \quad (5)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), r is the radius of the walnut (m), t is the drying time (s).

2.6 Activation energy determination

The activation energy for moisture diffusion was determined based on the Arrhenius relationship for the dependence of the effective moisture diffusivity on the drying temperature. The Arrhenius-type equation for the relationship is expressed as Equation 6 below

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (6)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy for moisture diffusion ($J \cdot mol^{-1}$), R is the universal gas constant ($8.314 J \cdot mol^{-1} K^{-1}$), and T is the absolute drying temperature (K).

The activation energy is determined from the linear form of the Arrhenius Equation 7 below

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R} \left(\frac{1}{T}\right) \quad (7)$$

The activation energy was determined from the slope of the linear regression of $\ln(D_{eff})$ against $\left(\frac{1}{T}\right)$, with the slope of the linear regression curve related to $\frac{E_a}{R}$ from which the activation energy was calculated.

The activation energy for moisture diffusion, using this approach, has been determined for various agricultural materials based on the temperature dependence of moisture diffusivity during drying processes (Chen et al., 2020b; Öztekin et al., 2022; Pinheiro and Castro, 2023)

2.7 Specific energy consumption analysis

The specific energy consumption (SEC) was calculated as the ratio of the total energy delivered during the whole process of drying to the total mass of water removed using Equation 8.

$$SEC = \frac{E}{m_w} \quad (8)$$

where E is the total energy consumed (kWh), and m_w is the mass of water evaporated (kg).

Energy consumption was estimated based on the rated power of each dryer and the total drying duration. The cabinet dryer had a rated power of 4.6 kW, while the Memmert oven was rated at 2 kW.

2.8 Mathematical modelling

Six different thin-layer drying models, namely, Newton, Page, Henderson-Pabis, Logarithmic, Two-term, and Midilli-Kucuk, were

TABLE 1 Thin-layer drying models used to describe Nigerian walnut drying behavior.

Model	Equation	Reference
Newton	$MR = \exp(-kt)$	Kusuma et al. (2023)
Page	$MR = \exp(-kt^n)$	Abano (2020)
Henderson and pabis model	$MR = a \exp(-(kt))$	Kusuma et al. (2023)
Logarithmic model	$MR = a \exp(-(kt) + c)$	Kusuma et al. (2023)
Two-term exponential	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	Rashid et al. (2022)
Midilli-Kucuk	$MR = a \exp(-kt^n) + bt$	Midilli and Kucuk (2023)

used in describing the drying behavior of Nigerian walnuts. The model equations and references are summarized in Table 1. All nonlinear regression analyses were conducted using Python 3.12 (SciPy optimize.curve_fit), and goodness-of-fit indicators (R^2 , RMSE, SSE) were computed using NumPy and custom Python scripts for reproducibility.

The models selected here represent the categories of thin-layer equations in common use: simple exponential (Newton), modified exponential (Page), empirical exponential with geometric parameter (Henderson and Pabis), logarithmic models for materials with shrinkage (Logarithmic), multiexponential moisture transport (Two-term), and semiempirical hybrid models that combine exponential and linear terms (Midilli–Kucuk). These models were selected to capture the wide range of possible moisture transport behavior expected in nuts with complex shell–kernel structures.

3 Results and discussion

3.1 Drying kinetics and thin-layer modelling

Drying properties of African walnut (*T. conophorum*) using cabinet drying and oven drying methods with temperatures of 50, 65, and 80 °C were studied using thin-layer drying models. Drying data was transformed into dimensionless moisture ratio (MR), which was then applied to six thin-layer drying models: Newton, Page, Henderson–Pabis, Logarithmic, Two-term, and Midilli & Kucuk. Nonlinear regression analysis was carried out using Python software version 3.12.

The results of the fitting of all six models at different drying temperatures, as well as for shelled and unshelled samples, are presented in Table 2. Table 3 summarizes the results of the best models at different drying conditions. Among all six models employed in this work, it was found that the Midilli & Kucuk model was always the best at all temperatures, with high values of R^2 of 0.998–0.999, as well as lowest values of RMSE and SSE. This revealed its high capacity to well describe the drying process of Nigerian walnuts. The Two-term and Page models gave fair results for certain conditions, mainly at intermediate and higher temperatures (50 °C–65 °C), whereas the Newton and Henderson–Pabis models gave poor results for all conditions, with R^2 values lower than 0.80. The comparable superior performance of the Midilli and Kucuk model has also been shown for other biological materials such as green tea and coriander leaves (Jayasuriya et al., 2023; Midilli and Kucuk, 2023; Öztekin et al., 2022).

In the Midilli & Kucuk model, the constants a , b , k , and n stand for.

- k - drying rate constant (in min^{-1}), which is a measure of the drying rate
- n - dimensionless exponent that represents the deviation from the exponential drying rate curve
- a , b - dimensionless constants that characterize the contribution of the exponential and linear drying rate curves, respectively.

The constants k and n , which are used in the Midilli & Kucuk model, increased with the drying temperature for both the cabinet and the oven dryers, indicating the increased diffusivity of moisture with the increased thermal energy input (Li et al., 2026). For instance, when whole walnuts were dried in the cabinet dryer, the value of k increased from 0.0817 min^{-1} at a temperature of 50 °C to 0.2236 min^{-1} at a temperature of 80 °C, as shown in Table 2.

Figures 1–12 show a comparison between experimental and theoretical MR values. The Midilli & Kucuk model was very close to experimental results throughout the process of drying. The simpler models moved away from experimental results towards the end of the process. The importance of semi-empirical models that contain both exponential and linear components is thus evident.

Between these two systems, oven drying provided shorter total drying times, because of its forced convection and uniform air temperature distribution. Cabinet drying provides more stable thermal conditions and better energy utilization, making this a more sustainable method, despite the longer drying times. This phenomenon has also been reported for similar kinds of convective dryers when drying starchy foods (Anajekwu et al., 2020; Singh et al., 2020).

3.2 Effect of temperature and drying method on drying behavior

The drying time was reduced with an increase in temperature for both cabinet and oven drying methods. The total drying times varied between 7 and 8 h for 50 °C to about 4 h for 80 °C, with shelled samples attaining equilibrium moisture content 10%–20% faster than whole samples.

The moisture ratio continued to decrease steadily with time for all conditions (Figures 1 and 2), and this is because drying took place

TABLE 2 Comparative performance of thin-layer drying models for Nigerian walnut under different temperatures and drying conditions.

Sample	Temp (°C)	Model	R^2	RMSE	SSE	Key parameters
OD50W	50	Newton	0.478	0.0171	0.00235	$k = 0.0143$
		Page	0.983	0.00311	7.72×10^{-5}	$k = 0.0429; n = 0.3232$
		Henderson-pabis	0.750	0.01186	0.00113	$k = 0.00954; a = 0.977$
		Logarithmic	0.996	0.00157	1.96×10^{-5}	$k = 0.650; c = 0.0734; a = 0.926$
		Two-term	0.996	0.00156	1.94×10^{-5}	$a = 0.928; k_0 = 0.000378; b = 0.0711; k_1 = 0.679$
		Midilli-kucuk	0.998	0.00101	8.14×10^{-6}	$k = 0.0614; n = 0.740; a = 0.9999; b = 0.0222$
OD50S	50	Newton	0.678	0.0287	0.00660	$k = 0.0298$
		Page	0.954	0.0109	0.000948	$k = 0.0733; n = 0.4451$
		Henderson-pabis	0.808	0.0222	0.00394	$k = 0.0225; a = 0.9653$
		Logarithmic	0.990	0.00498	0.000198	$k = 0.5151; c = 0.1586; a = 0.8450$
		Two-term	0.993	0.00434	0.000150	$a = 0.2342; k_0 = 0.3507; b = 0.7683; k_1 = -0.0116$
		Midilli-kucuk	0.990	0.00504	0.000203	$k = 0.1200; n = 0.9376; a = 1.0016; b = 0.0542$
OD65W	65	Newton	0.663	0.0245	0.00421	$k = 0.0289$
		Page	0.994	0.00319	7.12×10^{-5}	$k = 0.0716; n = 0.3845$
		Henderson-pabis	0.823	0.0178	0.00221	$k = 0.0212; a = 0.9685$
		Logarithmic	0.997	0.00223	3.47×10^{-5}	$k = 0.622; c = 0.1284; a = 0.870$
		Two-term	0.999	0.00128	1.15×10^{-5}	$a = 0.9009; k_0 = 0.00579; b = 0.0989; k_1 = 0.8805$
		Midilli-kucuk	0.9997	0.000758	4.02×10^{-6}	$k = 0.0931; n = 0.6905; a = 1.0000; b = 0.0243$
OD65S	65	Newton	0.582	0.0274	0.00524	$k = 0.0295$
		Page	0.996	0.00259	4.71×10^{-5}	$k = 0.0785; n = 0.3341$
		Henderson-pabis	0.785	0.0196	0.00269	$k = 0.0209; a = 0.9644$
		Logarithmic	0.996	0.00283	5.62×10^{-5}	$k = 0.7312; c = 0.1267; a = 0.8720$
		Two-term	0.9998	0.000666	3.10×10^{-6}	$a = 0.9038; k_0 = 0.00651; b = 0.0961; k_1 = 1.125$
		Midilli-kucuk	0.9998	0.000647	2.93×10^{-6}	$k = 0.0923; n = 0.5720; a = 1.0000; b = 0.0162$
OD80W	80	Newton	0.601	0.0274	0.00525	$k = 0.0442$
		Page	0.997	0.00239	3.99×10^{-5}	$k = 0.1029; n = 0.2358$
		Henderson-Pabis	0.752	0.0216	0.00326	$k = 0.0321; a = 0.9648$
		Logarithmic	0.995	0.00302	6.39×10^{-5}	$k = 1.285; c = 0.1286; a = 0.8710$
		Two-term	0.997	0.00229	3.67×10^{-5}	$a = 0.8927; k_0 = 0.00690; b = 0.1072; k_1 = 1.803$
		Midilli-kucuk	0.938	0.0108	0.000812	$k = 0.0503; n = 2.49 \times 10^{-7}; a = 0.9831; b = -0.0194$
OD80S	80	Newton	0.656	0.0366	0.00938	$k = 0.0659$
		Page	0.997	0.00340	8.11×10^{-5}	$k = 0.1472; n = 0.2684$
		Henderson-pabis	0.781	0.0292	0.00597	$k = 0.0495; a = 0.9533$
		Logarithmic	0.994	0.00501	0.000176	$k = 1.188; c = 0.1860; a = 0.8132$
		Two-term	0.997	0.00359	9.04×10^{-5}	$a = 0.8544; k_0 = 0.0137; b = 0.1455; k_1 = 1.868$
		Midilli-kucuk	0.998	0.00296	6.14×10^{-5}	$k = 0.164; n = 0.4241; a = 0.99997; b = 0.0163$

(Continued)

TABLE 2 Continued

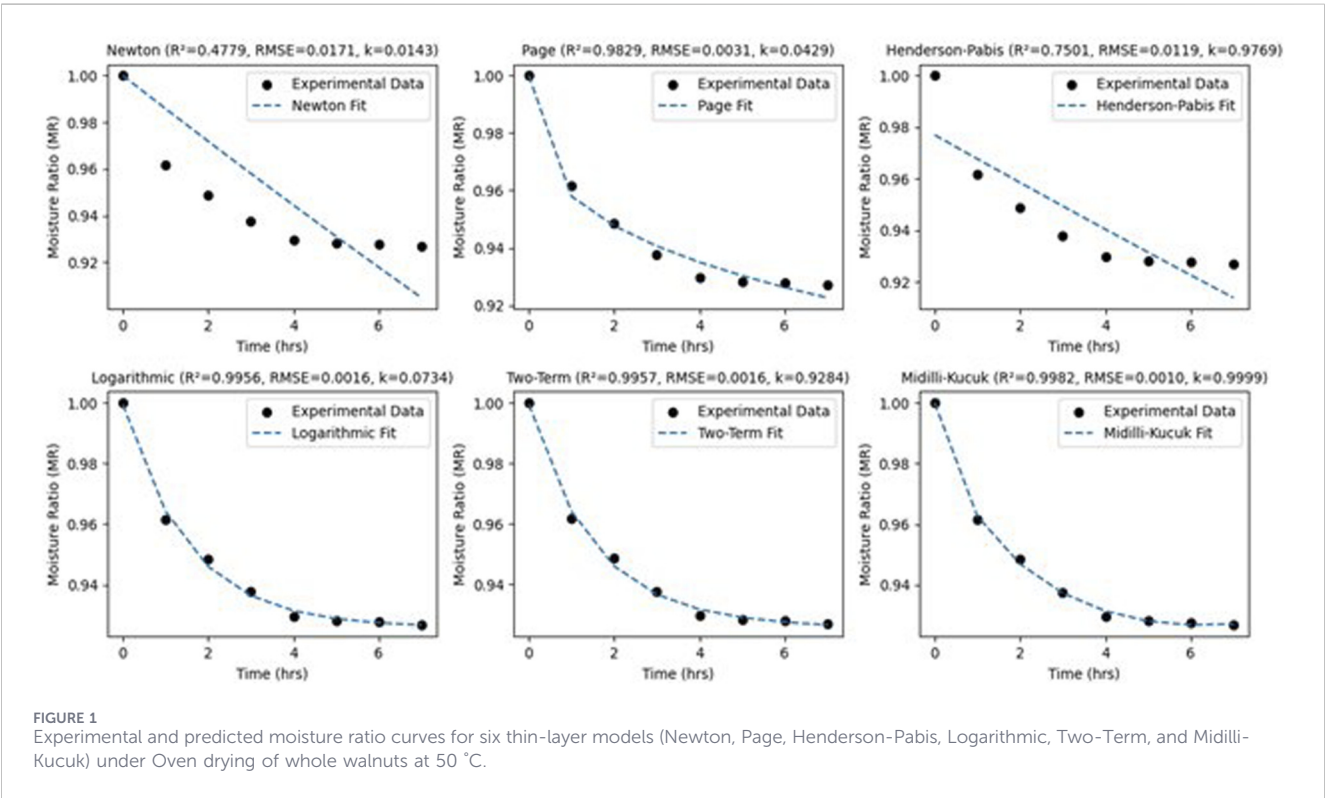
Sample	Temp (°C)	Model	R^2	RMSE	SSE	Key parameters
CA50W	50	Newton	0.706	0.0257	0.00727	$k = 0.0262$
		Page	0.997	0.00273	8.21×10^{-5}	$k = 0.0731$; $n = 0.4322$
		Henderson-pabis	0.873	0.0169	0.00315	$k = 0.0192$; $a = 0.960$
		Logarithmic	0.992	0.00417	0.000192	$k = 0.398$; $c = 0.160$; $a = 0.836$
		Two-term	0.997	0.00256	7.19×10^{-5}	$a = 0.901$; $k_0 = 0.00923$; $b = 0.0981$; $k_1 = 0.802$
		Midilli-kucuk	0.999	0.00149	2.44×10^{-5}	$k = 0.082$; $n = 0.633$; $a = 0.9999$; $b = 0.0127$
CA50S	50	Newton	0.252	0.0401	0.0177	$k = 0.0285$
		Page	0.996	0.00282	8.76×10^{-5}	$k = 0.1104$; $n = 0.2448$
		Henderson-pabis	0.694	0.0257	0.00726	$k = 0.0171$; $a = 0.935$
		Logarithmic	0.988	0.00501	0.000276	$k = 0.800$; $c = 0.157$; $a = 0.840$
		Two-term	0.999	0.00130	1.85×10^{-5}	$a = 0.874$; $k_0 = 0.00589$; $b = 0.1263$; $k_1 = 1.303$
		Midilli-kucuk	0.999	0.00108	1.28×10^{-5}	$k = 0.114$; $n = 0.399$; $a = 1.000$; $b = 0.00833$
CA65W	65	Newton	0.722	0.0328	0.00969	$k = 0.0384$
		Page	0.995	0.00448	0.000181	$k = 0.0981$; $n = 0.436$
		Henderson-pabis	0.864	0.0229	0.00473	$k = 0.0288$; $a = 0.953$
		Logarithmic	0.996	0.00404	0.000147	$k = 0.466$; $c = 0.201$; $a = 0.796$
		Two-term	0.998	0.00297	7.96×10^{-5}	$a = 0.142$; $k_0 = 0.727$; $b = 0.857$; $k_1 = 0.0101$
		Midilli-kucuk	0.999	0.00160	2.30×10^{-5}	$k = 0.117$; $n = 0.709$; $a = 0.9998$; $b = 0.0247$
CA65S	65	Newton	0.486	0.0454	0.0186	$k = 0.0417$
		Page	0.993	0.00548	0.000270	$k = 0.1303$; $n = 0.310$
		Henderson-pabis	0.756	0.0313	0.00881	$k = 0.0280$; $a = 0.934$
		Logarithmic	0.996	0.00394	0.000139	$k = 0.716$; $c = 0.201$; $a = 0.797$
		Two-term	0.9999	0.000501	2.26×10^{-6}	$a = 0.836$; $k_0 = 0.00764$; $b = 0.1641$; $k_1 = 1.011$
		Midilli-kucuk	0.999	0.00179	2.88×10^{-5}	$k = 0.146$; $n = 0.574$; $a = 1.0002$; $b = 0.0222$
CA80W	80	Newton	0.0800	0.0578	0.0301	$k = 0.0768$
		Page	0.986	0.00704	0.000446	$k = 0.1733$; $n = 0.202$
		Henderson-pabis	0.595	0.0384	0.0132	$k = 0.0436$; $a = 0.915$
		Logarithmic	0.997	0.00329	9.74×10^{-5}	$k = 1.993$; $c = 0.193$; $a = 0.806$
		Two-term	0.998	0.00248	5.51×10^{-5}	$a = 0.819$; $k_0 = 0.00518$; $b = 0.180$; $k_1 = 2.282$
		Midilli-kucuk	0.999	0.00179	2.89×10^{-5}	$k = 0.224$; $n = 0.473$; $a = 1.0001$; $b = 0.0390$
CA80S	80	Newton	-0.074	0.0684	0.0421	$k = 0.0874$
		Page	0.997	0.00343	0.000106	$k = 0.2056$; $n = 0.150$
		Henderson-pabis	0.541	0.0447	0.01799	$k = 0.0467$; $a = 0.898$
		Logarithmic	0.991	0.00638	0.000366	$k = 2.660$; $c = 0.211$; $a = 0.788$
		Two-term	0.998	0.00320	9.20×10^{-5}	$a = 0.812$; $k_0 = 0.0105$; $b = 0.1883$; $k_1 = 3.661$
		Midilli-kucuk	0.9998	0.00100	9.06×10^{-6}	$k = 0.226$; $n = 0.266$; $a = 0.99999$; $b = 0.0151$

mostly in the falling-rate period, as is usual for products that have high moisture content, as drying in such products is controlled by internal diffusion mechanisms (Jayasuriya et al., 2023; Zhang et al.,

2023). As the drying temperature increased, the vapor pressure difference between the material and the drying air also increased, hence facilitating the diffusion of moisture.

TABLE 3 Best-fitting thin-layer drying models for Nigerian walnut under all drying conditions.

Sample	Temp (°C)	Best model	R ²	RMSE	SSE	Key parameters
OD50W	50	Midilli-kucuk	0.9982	0.00101	8.14×10^{-6}	$k = 0.06135$; $n = 0.74041$; $a = 0.99991$; $b = 0.02223$
OD50S	50	Two-term	0.9927	0.00434	1.50×10^{-4}	$k_0 = 0.23421$; $b = 0.35066$; $k_1 = 0.76832$
OD65W	65	Midilli-kucuk	0.9997	0.00076	4.02×10^{-6}	$k = 0.09306$; $n = 0.69049$; $a = 1.00000$; $b = 0.02433$
OD65S	65	Two-term	0.9998	0.00067	3.10×10^{-6}	$a = 0.90383$; $k_0 = 0.00651$; $b = 0.09609$; $k_1 = 1.12541$
OD80W	80	Two-term	0.9972	0.00229	3.67×10^{-5}	$a = 0.89272$; $k_0 = 0.00690$; $b = 0.10722$; $k_1 = 1.80309$
OD80S	80	Midilli-kucuk	0.9978	0.00296	6.14×10^{-5}	$k = 0.16358$; $n = 0.42410$; $a = 0.99997$; $b = 0.01634$
CA50W	50	Midilli-kucuk	0.9990	0.00149	2.44×10^{-5}	$k = 0.08172$; $n = 0.63291$; $a = 0.99986$; $b = 0.01271$
CA50S	50	Midilli-kucuk	0.9995	0.00108	1.28×10^{-5}	$k = 0.11442$; $n = 0.39931$; $a = 1.00004$; $b = 0.00833$
CA65W	65	Midilli-kucuk	0.9993	0.00160	2.30×10^{-5}	$k = 0.11705$; $n = 0.70904$; $a = 0.99980$; $b = 0.02472$
CA65S	65	Two-term	0.9999	0.00050	2.26×10^{-6}	$a = 0.83581$; $k_0 = 0.00764$; $b = 0.16410$; $k_1 = 1.01125$
CA80W	80	Midilli-kucuk	0.9991	0.00179	2.89×10^{-5}	$k = 0.22358$; $n = 0.47336$; $a = 1.00008$; $b = 0.03904$
CA80S	80	Midilli-kucuk	0.9998	0.00100	9.06×10^{-6}	$k = 0.22612$; $n = 0.26612$; $a = 0.99999$; $b = 0.01513$



For instance, in oven drying, it took around 4 h to completely dry at 80 °C compared to 7 h when drying at 50 °C (Table 2), while similar observations were recorded for cabinet drying. While it took less time to dry using oven drying due to increased air speed and forced convection, it was more even in cabinet drying due to better temperature stability and air circulation. Whole walnuts took longer to dry compared to shelled walnuts since drying was hindered by the shells. This was similar to observations recorded by Man et al. (2024a) and Fufa et al. (2025).

3.3 Model validation and selection

Validation of the model showed that the best model for the description of the kinetics of the drying of the Nigerian walnuts was the Midilli & Kucuk model. The predicted MR values from the model were almost overlapping with the experimental data, as shown in Tables 3 and Figures 1–12.

Although the Page and Two-term equations performed satisfactorily at medium temperatures, the Newton and

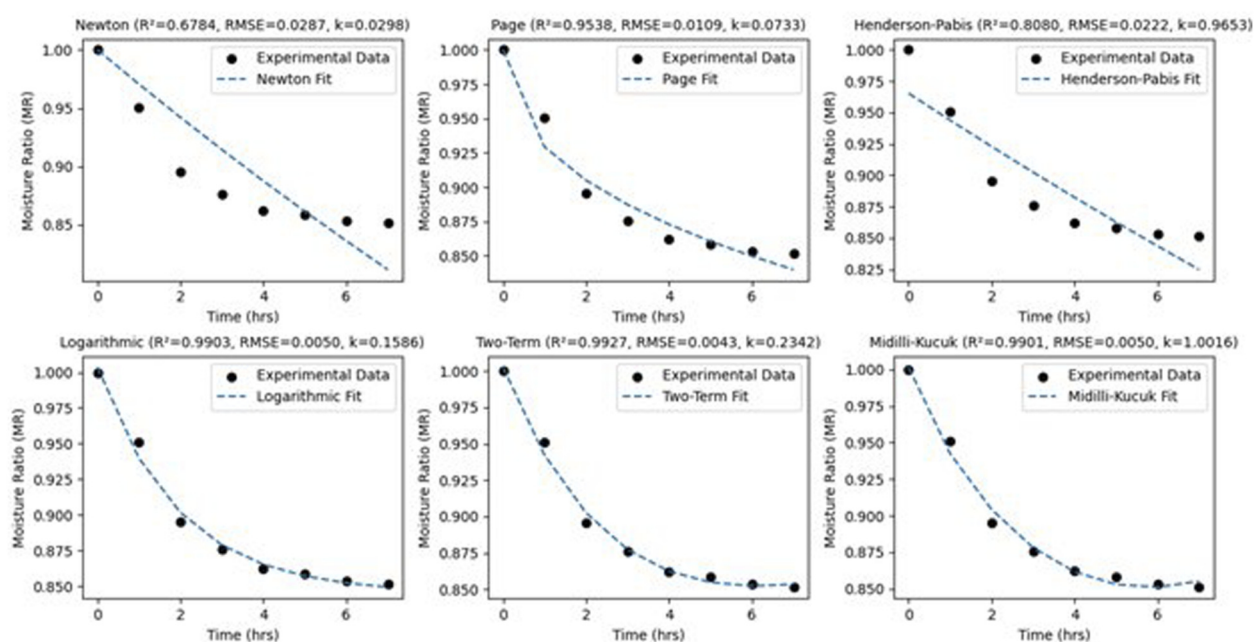


FIGURE 2

Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Oven drying of shelled walnuts at 50 °C.

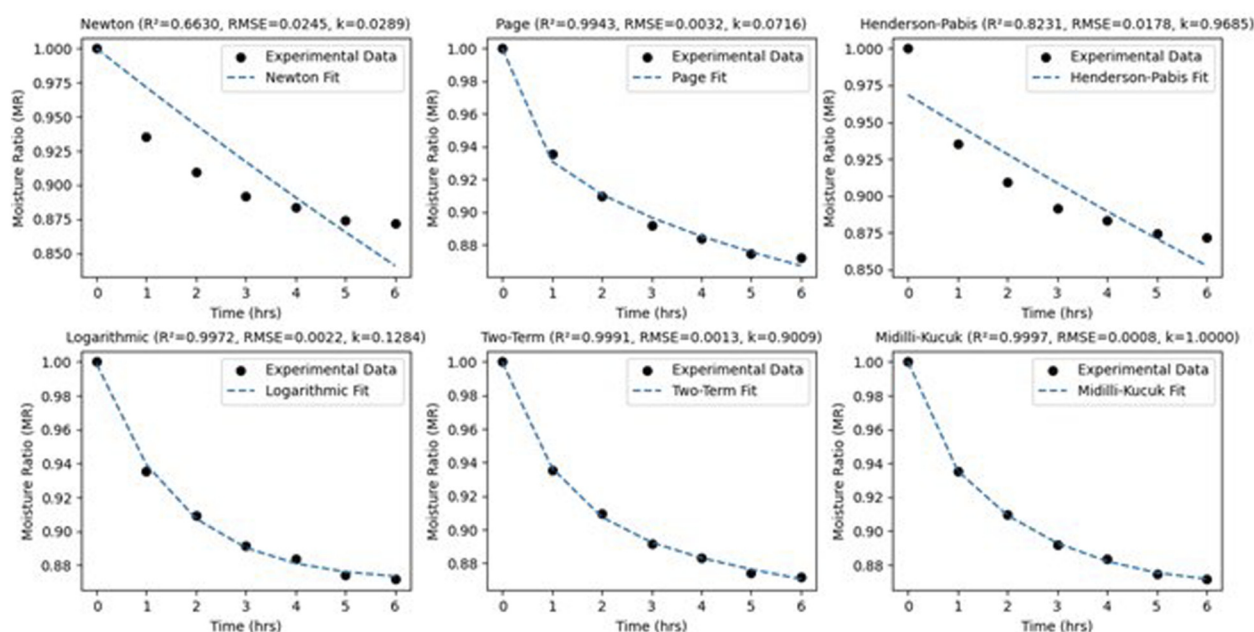


FIGURE 3

Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Oven drying of whole walnuts at 65 °C.

Henderson-Pabis equations were consistently poor, with R^2 values below 0.80 at times. This suggests that basic exponential equations cannot model the complex diffusion of moisture in oil-rich nuts with uneven internal composition. This

has also been observed for the seeds of fruits and other biological materials, where joint linear and exponential equations model the drying process at both stages (Benestante et al., 2024; Metwally et al., 2024).

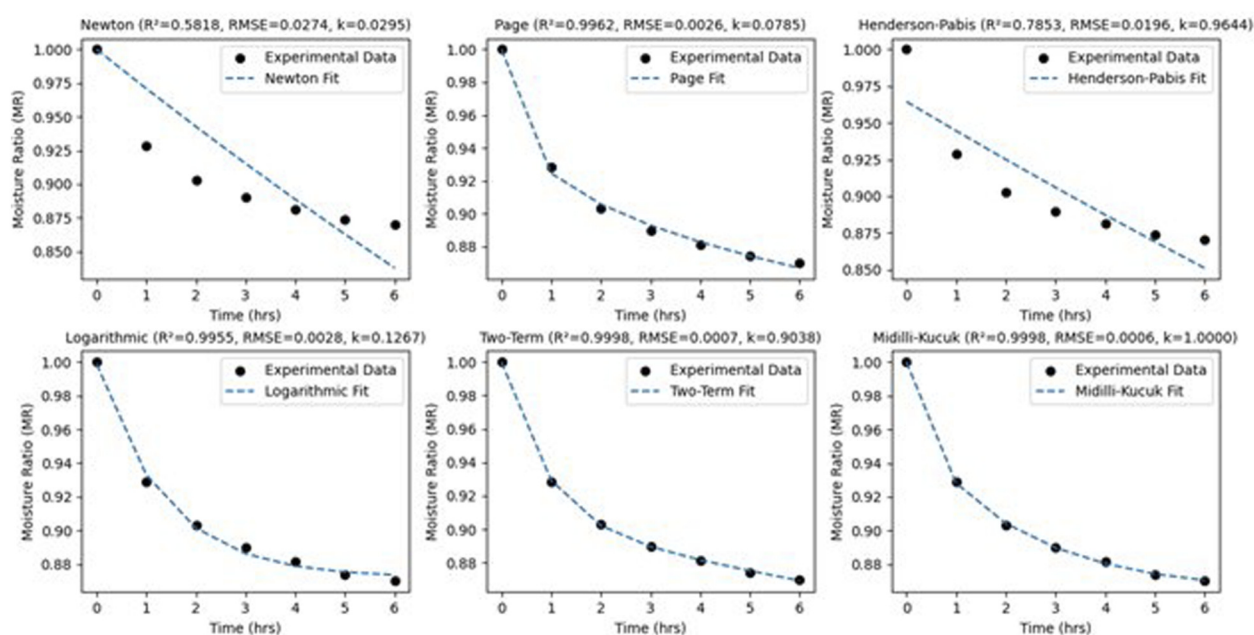


FIGURE 4
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Oven drying of shelled walnuts at 65 °C.

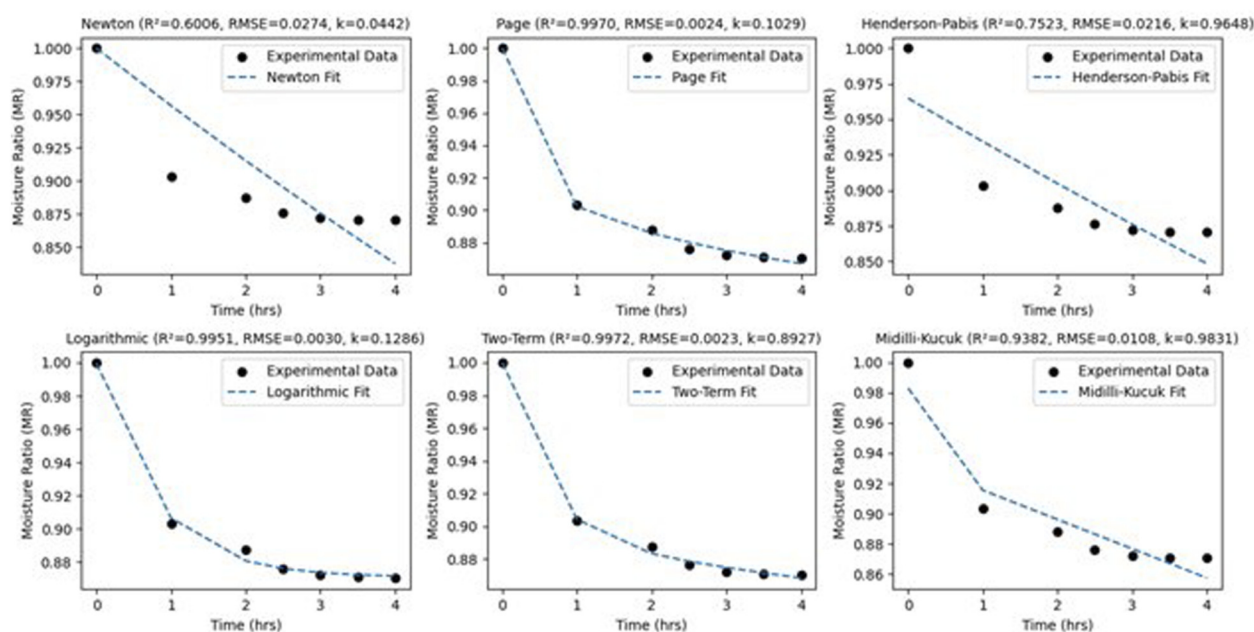


FIGURE 5
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Oven drying of whole walnuts at 80 °C.

3.4 Effective moisture diffusivity

The values of the effective diffusivity (D_{eff}) were determined using Fick's second law and are given in Table 4.

The D_{eff} increased with the increase in drying temperatures in both drying methods, indicating increased ease of diffusivity with higher temperatures (Abbaspour-Gilaneh et al., 2020).

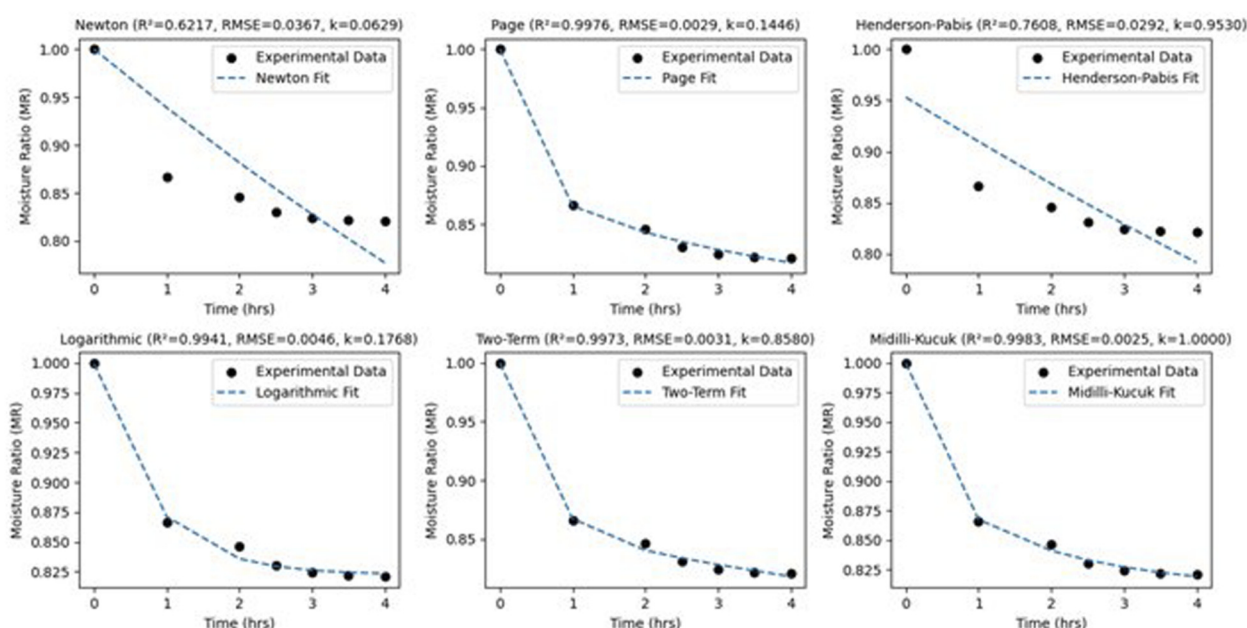


FIGURE 6
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Oven drying of shelled walnuts at 80 °C.

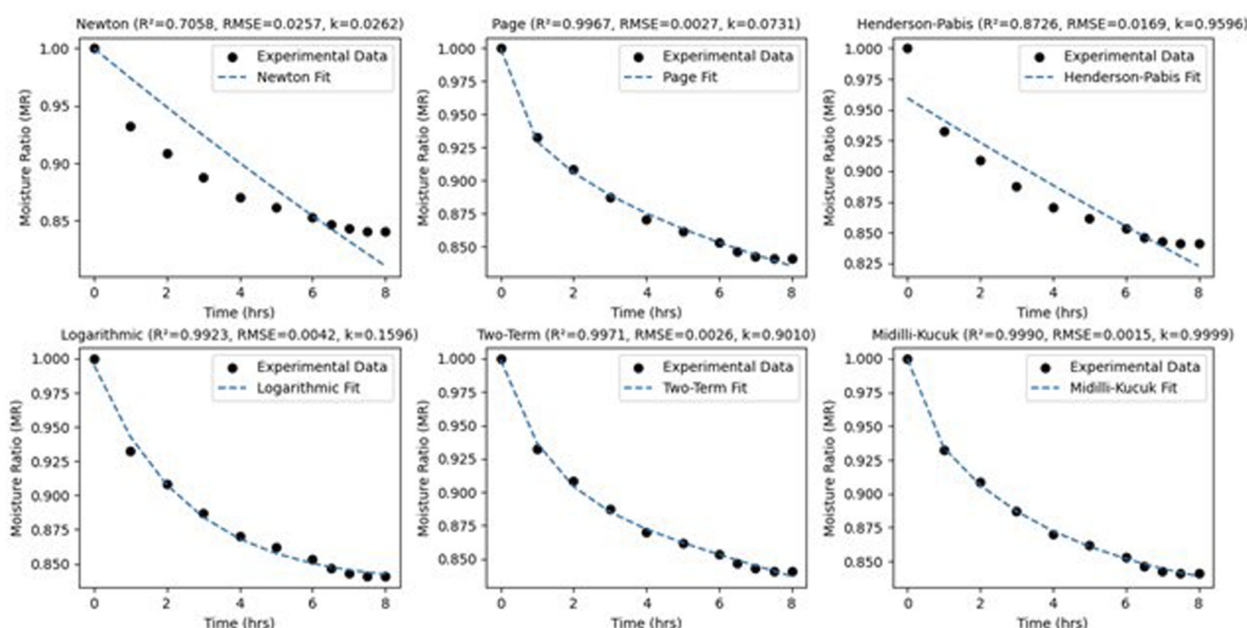


FIGURE 7
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Cabinet drying of whole walnuts at 50 °C.

The increase in temperature up to 80 °C, however, did not increase the effective diffusivity in all cases. This could be attributed to the hardening of the shell, the reduction in the moisture gradient, or the viscous resistance in the kernel, which limits the movement of the moisture (Ning et al., 2025).

The lowest D_{eff} ($6.23 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$) was found to be at the cabinet drying of shelled walnuts at 50 °C, and the highest ($4.72 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$) was at 65 °C. The obtained results for the effective moisture diffusivity are within the usual range for agricultural materials and nuts, which normally ranges from

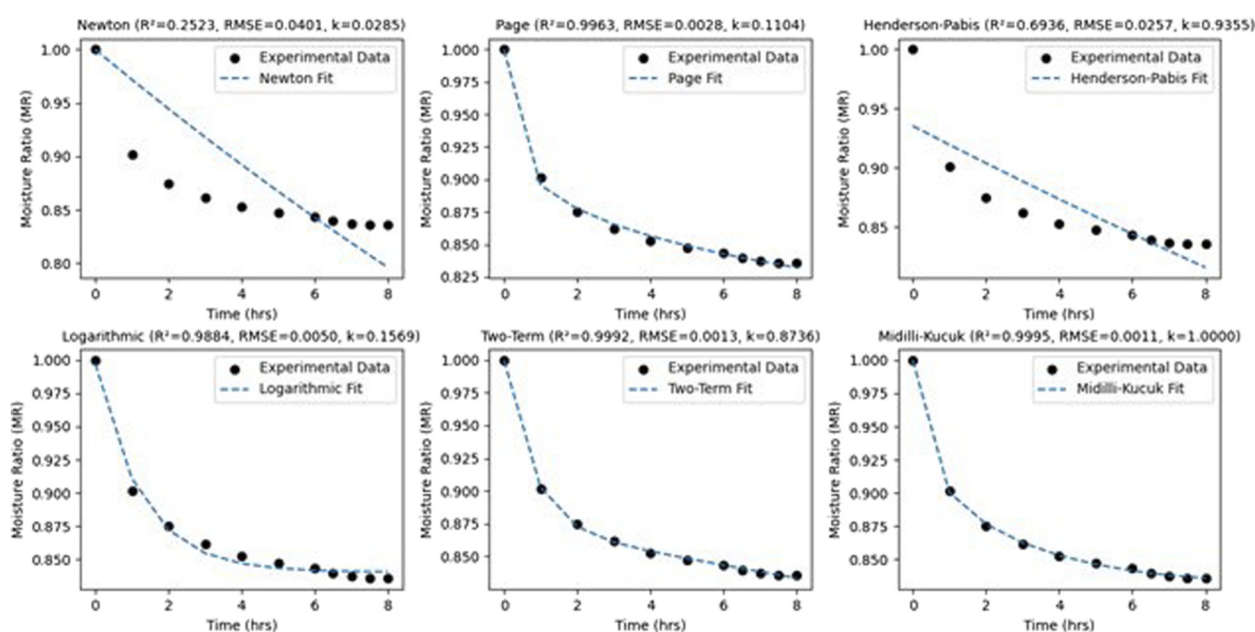


FIGURE 8
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Cabinet drying of shelled walnuts at 50 °C.

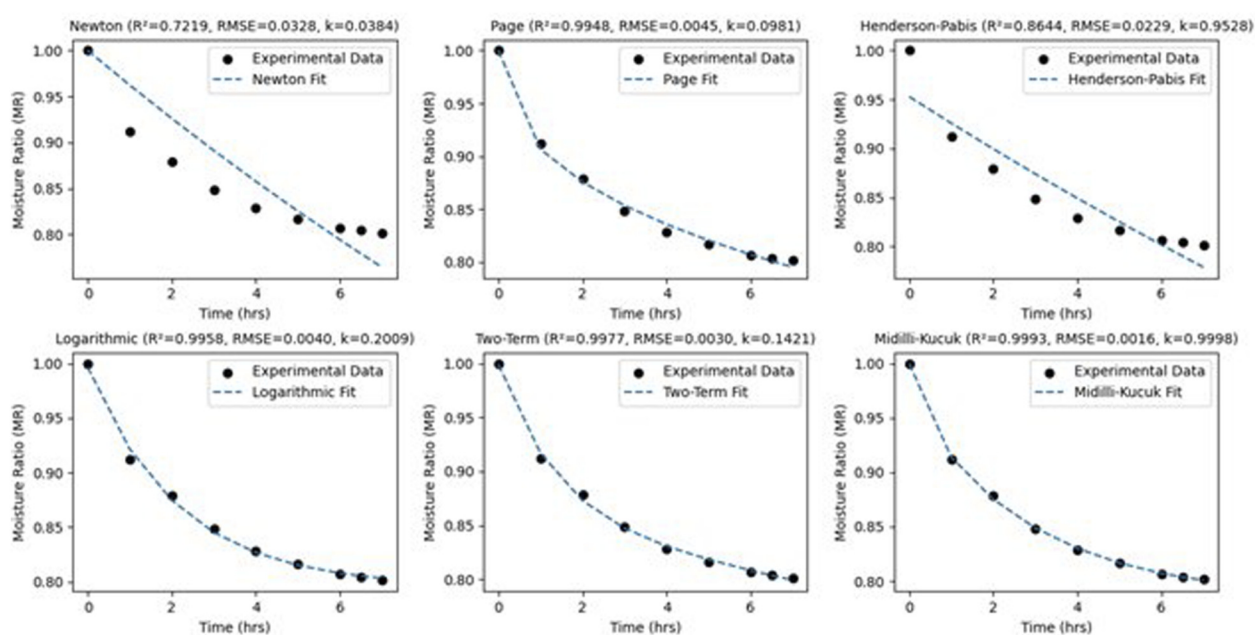


FIGURE 9
Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Cabinet drying of whole walnuts at 65 °C.

10^{-12} to $10^{-7} \text{ m}^2 \text{ s}^{-1}$, and increases with increasing drying temperature (Chen et al., 2020b; Man et al., 2024b; Öztekin et al., 2022; Pinheiro and Castro, 2023; Taskin et al., 2024). This confirms the accuracy of the experimental and theoretical procedure.

3.5 Activation energy for moisture diffusion

Further analysis of the effect of temperature on the diffusivity of moisture was carried out using the Arrhenius equation. The activation energy was calculated from the linear relationship

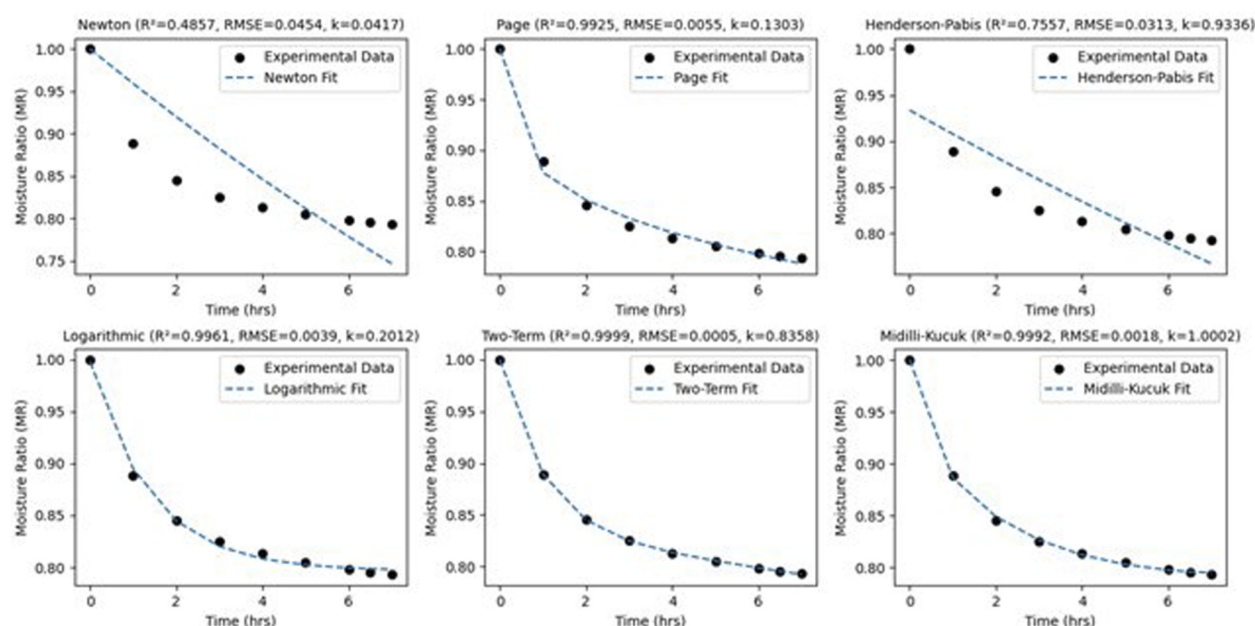


FIGURE 10 Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Cabinet drying of shelled walnuts at 65 °C.

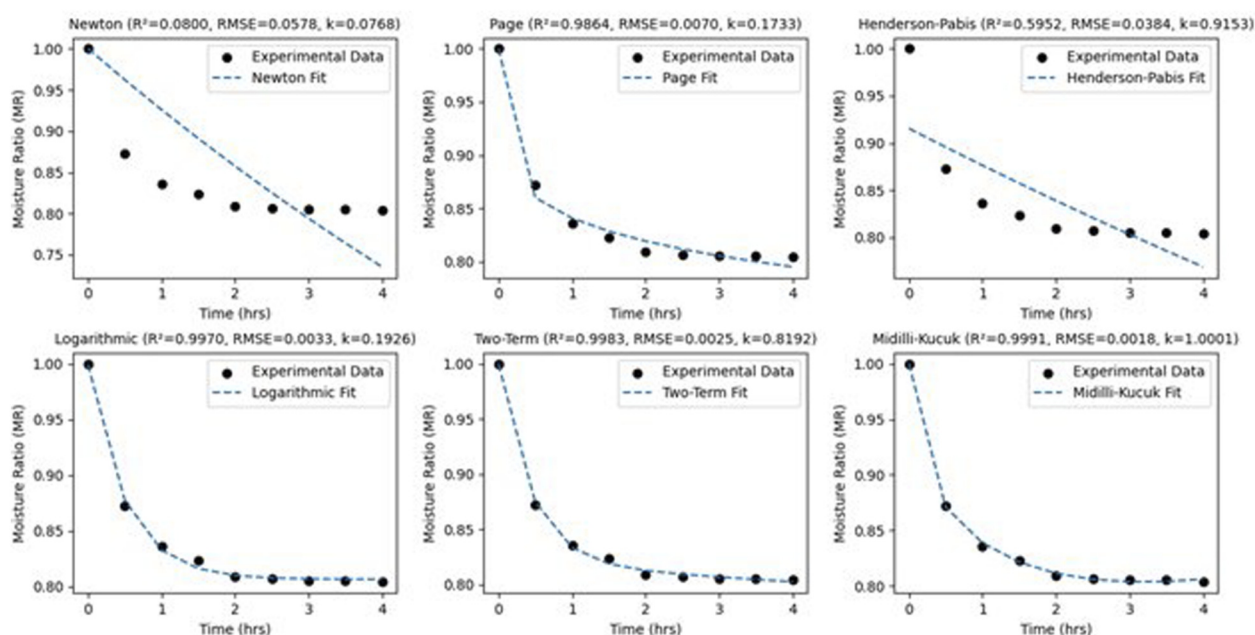


FIGURE 11 Experimental and predicted moisture ratio curves for six thin-layer models (Newton, Page, Henderson-Pabis, Logarithmic, Two-Term, and Midilli-Kucuk) under Cabinet drying of whole walnuts at 80 °C.

between the natural logarithm of the effective diffusivity of the moisture $\ln(D_{\text{eff}})$, and the reciprocal of absolute temperature ($\frac{1}{T}$).

Table 5 shows the calculated activation energy for the different drying processes. The calculated activation energy was influenced by

the type of drying method used as well as the shell condition of the product.

For the oven drying method, the calculated activation energy was 24.61 kJ/mol for the whole walnuts, while for the

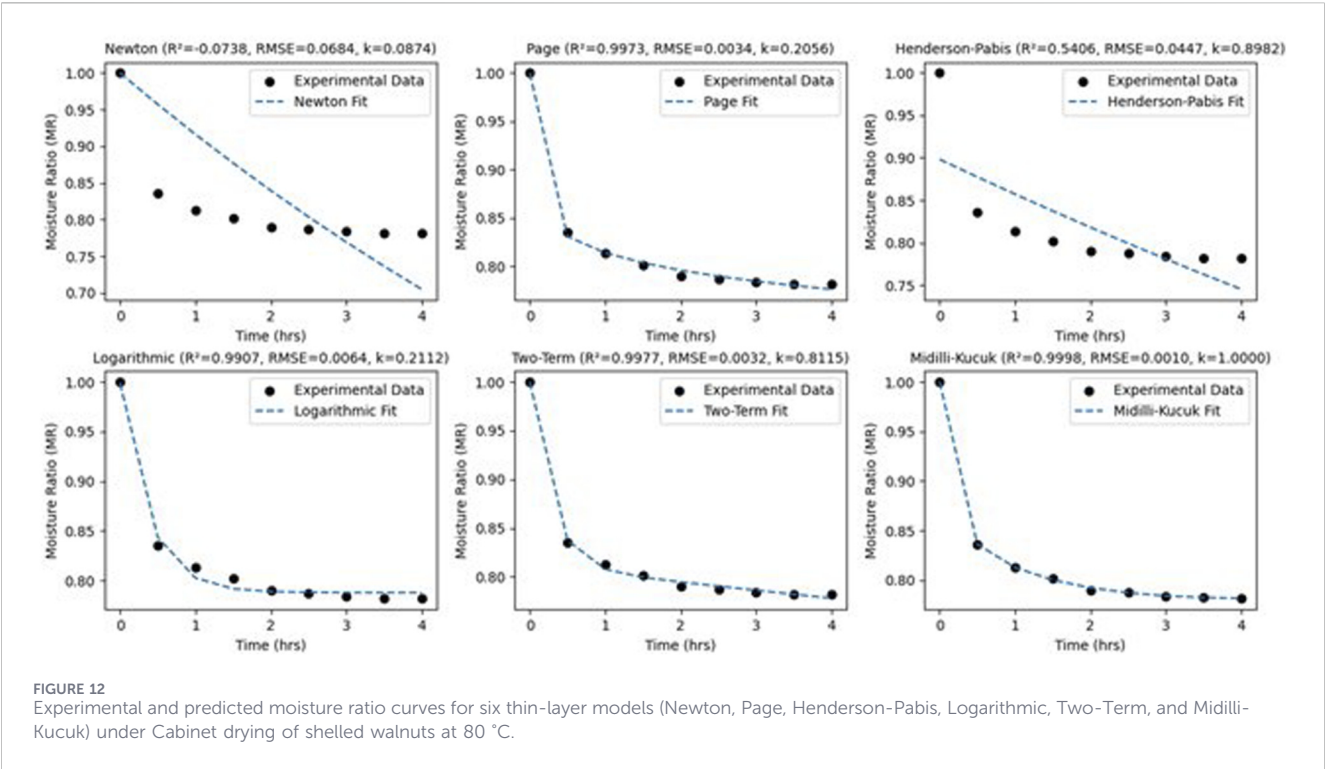


TABLE 4 Effective moisture diffusivity (D_{eff}) for walnut samples under different drying conditions.

Dryer & condition	Temperature (°C)	D_{eff} (m^2/s)	R^2
OD 50 W	50	1.34×10^{-7}	0.814
OD 50 S	50	1.03×10^{-7}	0.762
OD 65 W	65	3.12×10^{-7}	0.913
OD 65 S	65	8.08×10^{-8}	0.908
OD 80 W	80	2.88×10^{-7}	0.873
OD 80 S	80	1.21×10^{-7}	0.908
CA 50 W	50	3.31×10^{-7}	0.945
CA 50 S	50	6.23×10^{-8}	0.885
CA 65 W	65	4.72×10^{-7}	0.932
CA 65 S	65	1.08×10^{-7}	0.872
CA 80 W	80	4.48×10^{-7}	0.716
CA 80 S	80	1.13×10^{-7}	0.812

shelled ones, the activation energy was 4.79 kJ/mol. For the cabinet drying method, the calculated activation energy was 9.76 kJ/mol for the whole walnuts, while for the shelled ones, the calculated activation energy was 19.05 kJ/mol.

This shows that the energy required for the movement of the moisture from the product can be affected by the type of drying method used as well as the shell condition of the product. The higher energy required for the movement of the moisture from the whole

walnuts as compared to the shelled ones shows that the shell acts as a resistance to the movement of the moisture from the product. The lower energy required for the movement of the moisture from the shelled walnuts as compared to the whole ones shows that the shell acts as a resistance to the movement of the moisture from the product.

The calculated activation energy lies within the range reported for agricultural and biological materials during convective drying process which is typically between the values of 12–110 kJ/mol, as reported by [Chen et al. \(2020b\)](#); [Pinheiro and Castro \(2023\)](#); and [Taskin et al. \(2024\)](#) for the drying of agricultural products. This confirms the effect of temperature on the moisture diffusion mechanism from the product.

3.6 Energy analysis

Specific energy consumption (SEC) values corresponding to all drying conditions are given in [Table 6](#). Specific energy consumption was found to decrease with increasing drying temperature in both cabinet and oven dryers, which could be due to shorter drying times with higher temperatures.

Oven drying SEC values ranged from 2.93 kWh/kg at 50 °C for shelled to 0.11 kWh/kg at 80 °C for whole, while for cabinet drying, values ranged from 0.95 kWh/kg at 50 °C for shelled to 0.51 kWh/kg at 80 °C for whole. The energy performance was found to be a function of both the method of drying and temperature used in the process. Although the results of the cabinet dryer indicated promising SEC results in certain cases, the oven dryer at 80 °C was found to offer the best compromise in terms of time and energy efficiency ([Sethi et al., 2021](#)).

The shelled walnuts consistently showed lower SEC values than whole walnuts under similar conditions, and it is clear that shell

TABLE 5 Activation energy for moisture diffusion of Nigerian walnut under different drying conditions.

Drying method	Sample condition	Activation energy (kJ/mol)
Oven drying	Whole walnut	24.61
Oven drying	Shelled walnut	4.79
Cabinet drying	Whole walnut	9.76
Cabinet drying	Shelled walnut	19.05

TABLE 6 Specific energy consumption (SEC) of oven (OD) and cabinet (CA) drying of Nigerian walnut.

Drying condition	Drying time (h)	SEC (kWh/kg)
OD 50 W	7	2.93
OD 50 S	7	2.07
OD 65 W	6	0.11
OD 65 S	6	0.15
OD 80 W	4	0.11
OD 80 S	4	0.14
CA 50 W	8	0.67
CA 50 S	8	0.95
CA 65 W	7	0.54
CA 65 S	7	0.76
CA 80 W	4	0.51
CA 80 S	4	0.62

removal enhances diffusion rates and improves energy efficiency. The same trends have been found in previous studies on nut and fruit seed drying processes (Darvishi et al., 2016; Taskin et al., 2024). Although it is difficult to predict exact SEC under similar conditions for dryers of different designs and operating modes, it can be concluded that further improvement in energy efficiency is possible based on optimal drying conditions.

4 Conclusion

This research assessed the drying characteristics, kinetic analysis, and energy efficiency of African (Nigerian) walnut (*T. conophorum*) at various temperature levels for cabinet and oven drying methods. The thin-layer drying models were employed on the experimental moisture ratio results, and the appropriateness of the models for the experimental results was determined based on statistical parameters (R^2 , RMSE, and SSE). Of the drying models employed, the Midilli and Kucuk model performed best.

The drying temperature was a major factor affecting the removal of moisture. As the temperature increased, the drying time was significantly lowered. The effective moisture diffusivity, D_{eff} , was found to increase with an increase in temperature, though in some instances it was found to remain constant at the highest temperature, possibly because of the hardening of the material

on the surface, which reduced the moisture gradient. The activation energy analysis revealed that temperature plays a key role in the moisture diffusivity during drying. The presence of shells and type of dryer were observed to affect the moisture transportation. The results of the energy analysis revealed that the specific energy consumption was lower at higher temperatures because of the reduced drying time. The oven drying at 80 °C was found to be the most efficient drying process, possibly because of the combined effect of the forced convection, uniform air distribution and the reduced drying time.

Generally, it can be deduced that oven drying at a temperature of 80 °C provides a best possible combination of drying rate and energy efficiency for Nigerian walnut processing. The results have important implications for small to medium-scale processors to enhance drying efficiency for this non-commercial oil-rich nut.

The limitations of this research include the lack of air velocity measurement and the possibility of varying sample size and shape that could affect heat and mass transfer. Future research should include the characterization of airflow, further enhancement of the experimental work, and innovative drying techniques to further develop the model for drying Nigerian walnuts.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AA: Methodology, Data curation, Software, Writing – review and editing, Writing – original draft, Formal Analysis. SJ: Validation, Conceptualization, Supervision, Writing – review and editing. DI: Supervision, Writing – review and editing. ML: Supervision, Writing – review and editing, Validation. HM: Writing – review and editing. MA: Supervision, Writing – review and editing. EA: Validation, Supervision, Writing – review and editing.

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Conflict of interest

Author EA was employed by Nice-Pak Products Inc.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Abano, E. (2020). Microwave and blanching pretreatments for hot air drying of orange-fleshed sweet potato slices (*Ipomoea batatas*). *Int. J. Food Sci.* 2020, 8872429. doi:10.1155/2020/8872429
- Abbaspour-Gilandeh, Y., Jahanbakhshi, A., and Kaveh, M. (2020). Prediction kinetic, energy and exergy of quince under hot air dryer using ANNs and ANFIS. *Food Sci. Nutr.* 8 (1), 594–611. doi:10.1002/fsn3.1347
- Almeida, R. D., Martins Duarte, M. E., Mata, M. E. R. M. C., Martins Duarte da Costa, M. E., Pessoa Melo, M. O., Almeida, R. D., et al. (2024). Drying behavior and thermodynamic properties of cashew nut almonds in thin layers: a mathematical modeling approach. *Heliyon* 11 (1), e41417. doi:10.1016/j.heliyon.2024.e41417
- Anajekwu, E. O., Maziya-Dixon, B., Akinoso, R., Awoyale, W., and Alamu, E. O. (2020). Physicochemical properties and total carotenoid content of high-quality unripe plantain flour from varieties of hybrid plantain cultivars. *J. Chem.* 2020, 1–7. doi:10.1155/2020/5960346
- AOAC International (2023). "AOAC official method 925.10Solids (total) and loss on drying (moisture) in flour: air oven method," in *Official methods of analysis of AOAC international*. Editor Latimer, Jr., G. W. 22nd ed. (New York: Oxford University Press). doi:10.1093/9780197610145.003.2927
- Aregbesola, O. A., Ogunsina, B., Sofolahan, A. E., and Chime, N. N. (2015). Mathematical modeling of thin layer drying characteristics of dika (*Irvingia gabonensis*) nuts and kernels. *Niger. Food J.* 33 (1), 83–89. doi:10.1016/j.nifo.2015.04.012
- Basso, A. N. S., Erdem, T., and Öztekin, S. (2025). Analysis of drying kinetics and mathematical modelling of peanut pods using sunlight, hot air, and microwaves drying processes. *Turk. J. Agric. - Food Sci. Technol.* 13 (2), 368–375. doi:10.24925/turjaf.v13i2.368-375.7192
- Benestante, A., Bäuml, E., and Carrin, M. E. (2024). Drying kinetics of lemon (*Citrus lemon*) seeds on forced-air convective processing. *Bioresour. Technol. Rep.* 26, 101843. doi:10.1016/j.biteb.2024.101843
- Chen, C., Venkatasamy, C., Zhang, W., Khir, R., Upadhyaya, S., and Pan, Z. (2020a). Effective moisture diffusivity and drying simulation of walnuts under hot air. *Int. J. Heat Mass Trans.* 150, 119283. doi:10.1016/j.ijheatmasstransfer.2019.119283
- Chen, C., Weipeng, Z., Venkatasamy, C., Khir, R., McHugh, T., and Pan, Z. (2020b). Walnut structure and its influence on the hydration and drying characteristics. *Dry. Technol.* 38 (8), 975–986. doi:10.1080/07373937.2019.1605610
- Darvishi, H., Zarein, M., and Farhudi, Z. (2016). Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices. *J. Food Sci. Technol.* 53 (5), 2317–2333. doi:10.1007/s13197-016-2199-7
- Fufa, D. D., Bekele, T., Tamene, A., and Bultosa, G. (2025). Drying kinetic models, thermodynamics, physicochemical qualities, and bioactive compounds of avocado (*Persea americana* mill. Hass variety) seeds dried using various drying methods. *Heliyon* 11 (1), e41058. doi:10.1016/j.heliyon.2024.e41058
- Gama, T., Wallace, H. M., Trueman, S. J., and Hosseini-Bai, S. (2018). Quality and shelf life of tree nuts: a review. *Sci. Hortic.* 242 (May), 116–126. doi:10.1016/j.scienta.2018.07.036
- Jayasuriya, H., Pathare, P. B., Al-Attabi, Z., and Al-Hamdani, A. (2023). Drying kinetics and quality analysis of coriander leaves dried in an indirect, stand-alone solar dryer. *Processes* 11 (6), 1–15. doi:10.3390/pr11061596
- Kusuma, H. S., Nasution, R. A., and Permatasari, D. (2023). Drying process on kaffir lime leaves using microwave: evaluation of the drying performance and energy analysis of different microwave powers and sizes of leaves. *Appl. Food Res.* 3 (2), 100317. doi:10.1016/j.afres.2023.100317
- Li, L., Gan, T., Xie, L., Yi, P., Long, Y., Huang, M., et al. (2026). Influence of drying temperature on quality characteristics and drying kinetics of *Siraitia grosvenorii* fruit. *Foods* 15 (2), 335. doi:10.3390/foods15020335
- López, L. C., and Hincapié-Llanos, G. A. (2024). Comparison of mango (*Mangifera indica*) dehydration technologies: a systematic review. *AgriEngineering* 6 (3), 2694–2717. doi:10.3390/agriengineering6030157
- Macedo, L. L., Vimercati, W. C., da Silva Araújo, C., Saraiva, S. H., and Teixeira, L. J. Q. (2020). Effect of drying air temperature on drying kinetics and physicochemical characteristics of dried banana. *J. Food Process Eng.* 43 (9), 1–10. doi:10.1111/jfpe.13451
- Man, X., Li, L., Fan, X., Zhang, H., Lan, H., Tang, Y., et al. (2024a). Drying kinetics and mass transfer characteristics of walnut under hot air drying. *Agric. Switz.* 14 (2), 182. doi:10.3390/agriculture14020182
- Man, X., Li, L., Fan, X., Zhang, H., Lan, H., Tang, Y., et al. (2024b). Evolution and modelling of the moisture diffusion in walnuts during the combination of hot air and microwave–vacuum drying. *Agric. Switz.* 14 (2), 190. doi:10.3390/agriculture14020190
- Metwally, K. A., Oraith, A. A., Elzein, I. M., El-Messery, T. M., Nyambe, C., Mahmoud, M. M., et al. (2024). The mathematical modeling, diffusivity, energy, and environmental analysis (MD3E) of an automatic solar dryer for drying date fruits. *Sustainability* 16 (8), 3506. doi:10.3390/su16083506
- Midilli, A., and Kucuk, H. (2023). Development of a new curve equation representing thin layer drying process. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 45 (4), 9717–9730. doi:10.1080/15567036.2023.2240740
- Ni, Z., Zhang, Y., Chen, S., Thakur, K., Wang, S., Zhang, J., et al. (2021). Exploration of walnut components and their association with health effects. *Crit. Rev. Food Sci. Nutr.* 0 (0), 1–17. doi:10.1080/10408398.2021.1881439
- Ning, Z., Khir, R., Niederholzer, F., and Pan, Z. (2025). Characteristics of moisture diffusivity and shrinkage evolution of in-hull almonds under hot air drying. *LWT* 232, 118455. doi:10.1016/j.lwt.2025.118455
- Nkwonta, C. G., Auma, C. I., and Gong, Y. (2023). Underutilised food crops for improving food security and nutrition health in Nigeria and Uganda—A review. *Front. Sustain. Food Syst.* 7 (July), 1126020. doi:10.3389/fsufs.2023.1126020
- Nwakuba, N., Okafor, V. C. C., Abbah, C., Ofoma, A. N., and Onuruka, A. U. (2025). Investigating the impact of process variables on dehulling energy demand of african breadfruit seeds: a response surface optimization. *Niger. J. Technol. Dev.* 22, 27–38. doi:10.4314/njtd.v22i1.3165
- Obeng-Akrofi, G., Maier, D. E., White, W. S., Akowuah, J. O., Bartosik, R., and Cardoso, L. (2023). Effectiveness of hermetic bag storage technology to preserve physical quality attributes of shea nuts. *J. Stored Prod. Res.* 101, 102086. doi:10.1016/j.jspr.2023.102086
- Öztekin, Y. B., Aktaş, M., Dolgun, E. C., Bilim, H. I. C., and Sacilik, K. (2022). Drying kinetics and thermodynamic properties of uzun pistachios dried by convective drying. *J. Food Process. Preserv.* 46 (11), e17035. doi:10.1111/jfpp.17035
- Pinheiro, M. N. C., and Castro, L. M. M. N. (2023). Effective moisture diffusivity prediction in two Portuguese fruit cultivars (Bravo de Esmolfe Apple and Madeira banana) using drying kinetics data. *Heliyon* 9 (7), e17741. doi:10.1016/j.heliyon.2023.e17741
- Popescu, M., Iancu, P., Plesu, V., Bildea, C. S., and Manolache, F. A. (2023). Mathematical modeling of thin-layer drying kinetics of tomato peels: influence of drying temperature on the energy requirements and extracts quality. *Foods* 12 (20), 3883. doi:10.3390/foods12203883
- Rashid, M. T., Liu, K., Jatoti, M. A., Safdar, B., Lv, D., and Li, Q. (2022). Energy efficient drying technologies for sweet potatoes: operating and drying mechanism, quality-related attributes. *Front. Nutr.* 9, 1040314. doi:10.3389/fnut.2022.1040314

- Sethi, C. K., Acharya, S. K., Ghanem, S. R., Behera, A., and Patnaik, P. P. (2021). Exergy, energy and economic analysis of a V-groove assist rotating tray type solar cabinet dryer for drying potato chips. *J. Stored Prod. Res.* 93, 101861. doi:10.1016/j.jspr.2021.101861
- Singh, A., Sarkar, J., and Sahoo, R. R. (2020). Experimental energy-exergy performance and kinetics analyses of compact dual-mode heat pump drying of food chips. *J. Food Process Eng.* 43 (6), e13404. doi:10.1111/jfpe.13404
- Taskin, O., Khir, R., Ning, Z., Cao, L., Niederholzer, F., and Pan, Z. (2024). Drying and quality characteristics of intact-shell, cracked-shell and kernel walnuts under sequential infrared pre-drying and hot air drying. *Food control.* 165 (December 2023), 110669. doi:10.1016/j.foodcont.2024.110669
- Wu, W., Li, H., Chen, Y., Luo, Y., Zeng, J., Huang, J., et al. (2024). Recent advances in drying processing technologies for aquatic products. *Processes* 12 (5), 1–26. doi:10.3390/pr12050942
- Yasmin, S., Hasan, M., Sohany, M., and Sarker, M. S. H. (2022). Drying kinetics and quality aspects of bitter melon (*Momordica charantia*) dried in a novel cabinet dryer. *Food Res.* 6 (4), 180–188. doi:10.26656/fr.2017.6(4).437
- Zhang, D., Huang, D., Zhang, Y., Lu, Y., Huang, S., Gong, G., et al. (2023). Ultrasonic assisted far infrared drying characteristics and energy consumption of ginger slices. *Ultrason. Sonochemistry* 92 (September 2022), 106287. doi:10.1016/j.ultsonch.2022.106287