Drying Kinetics and Moisture Diffusion Behaviour of Selected Medicinal Leaves Under Electrically Controlled and Ambient Atmospheric Conditions

Afolabi Bukola Olanrewaju[1]*, Onatola Iyiola Tope[2] and Fadele Noah Taiwo[3]

Department of Agricultural and Bio-Environmental Engineering Federal College of Agriculture, Ibadan, Oyo, Nigeria

***Corresponding Author**

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ABSTRACT

Drying remains one of the most important postharvest engineering operations required for the preservation of medicinal leaves through effective moisture reduction while maintaining product quality, storability, and process reliability. This study investigated the time–temperature dependent drying kinetics and moisture diffusion behaviour of guava (*Psidium guajava*), bitter (*Vernonia amygdalina*), and scent (*Ocimum gratissimum*) leaves under ambient sun drying and electrically controlled oven drying conditions. Emphasis was placed on moisture content reduction, moisture ratio (MR), drying rate, moisture retention capacity, and thin-layer kinetic modelling as influenced by leaf type and drying environment. Drying experiments were conducted over an 8-hour period with hourly measurements of mass, temperature, and relative humidity. Sun drying was carried out under fluctuating atmospheric conditions (32–37 °C; 59–80% RH), whereas oven drying was maintained at 60 ± 1 °C. Results showed that sun drying reduced moisture content to safe storage levels (<10%) but exhibited irregular drying patterns characterized by fluctuating MR profiles, lower drying constants, and unstable falling-rate behaviour. In contrast, oven drying achieved rapid and uniform moisture reduction within 6 hours, with smooth MR decay curves and higher drying constants, indicating enhanced internal moisture diffusivity. Among the leaves, bitter leaf exhibited the fastest drying response, while guava leaf showed greater resistance to moisture migration. Thin-layer model fitting revealed that the Page model provided the best predictive performance with coefficient of determination (R^2) values up to 0.998. Overall, electrically controlled drying demonstrated superior efficiency, predictability, and engineering suitability for large-scale medicinal leaf preservation.

Keywords: Thin-Layer Drying, Medicinal Leaves, Moisture Diffusivity, Postharvest Engineering, Drying Kinetics

INTRODUCTION

Medicinal plant leaves constitute a highly valuable strategic bioresource within primary healthcare systems, traditional medicine, food fortification, and the rapidly expanding phytopharmaceutical industry, particularly in developing economies where plant-based therapies remain affordable, accessible, culturally accepted, and therapeutically relevant (WHO, 2013; Ekor, 2014; Sofowora, 2008; Akinyemi *et al.*, 2005). Across sub-Saharan Africa, especially Nigeria, medicinal leaves such as guava (Psidium guajava), bitter leaf (Vernonia amygdalina), and scent leaf (Ocimum gratissimum) are widely utilized for their nutritional, pharmacological, and ethnomedicinal importance (Ijeh and Ejike, 2011; Erukainure *et al.*, 2011; Akinmoladun *et al.*, 2007).

These leaves are rich sources of phenolic compounds, flavonoids, alkaloids, tannins, essential oils, saponins, terpenoids, and antioxidant metabolites, which contribute to their reported antimicrobial, anti-inflammatory, hypoglycemic, antimalarial, and antioxidant activities (Prakash and Gupta, 2005; Eleyinmi, 2007; Oboh, 2006;

Okwu, 2004; Trease and Evans, 2002). For instance, *Vernonia amygdalina* has been extensively reported as a functional medicinal vegetable with significant therapeutic applications in gastrointestinal regulation, diabetes management, liver protection, and immune enhancement (Farombi and Owoeye, 2011; Igile *et al.*, 1994). Similarly, *Ocimum gratissimum* has demonstrated pronounced antibacterial and antifungal activities, largely attributed to its volatile oil fractions and phenolic compounds such as eugenol and thymol (Matasyoh *et al.*, 2007; Pessoa *et al.*, 2002). Guava leaves (*Psidium guajava*) have also received considerable attention for their anti-diarrheal, antioxidant, anti-inflammatory, and antimicrobial properties, which support their extensive use in herbal medicine and nutraceutical formulations (Arima and Danno, 2002; Gutierrez *et al.*, 2008).

Despite these important medicinal attributes, freshly harvested leaves typically possess high initial moisture contents ranging between 70–85% wet basis, which predispose them to rapid enzymatic deterioration, microbial spoilage, biochemical instability, pigment degradation, and oxidative reactions, thereby significantly reducing postharvest quality and therapeutic efficacy (Mujumdar, 2014; Fellows, 2009; Vega-Gálvez *et al.*, 2012). High moisture levels enhance water activity, which facilitates microbial proliferation and accelerates enzymatic reactions such as polyphenol oxidation and chlorophyll degradation (Doymaz, 2011; Krokida *et al.*, 2000). Consequently, immediate postharvest moisture reduction becomes essential for preserving medicinal potency and extending shelf stability.

Drying is therefore recognized as one of the most critical postharvest engineering operations for medicinal plant processing, aimed at reducing moisture content, minimizing transport weight, enhancing storability, lowering packaging costs, and preserving phytochemical integrity (Mujumdar, 2014; Fellows, 2009; Erbay and Icier, 2010). In rural and semi-urban African settings, open sun drying remains the most commonly employed technique due to its low capital requirement, simplicity, and energy independence (Doymaz, 2011; Togrul and Pehlivan, 2002). However, sun drying is strongly affected by fluctuating ambient temperature, solar radiation intensity, relative humidity, wind speed, and atmospheric turbulence, all of which directly influence the coupled heat and mass transfer mechanisms governing moisture migration (Akpinar, 2006; Togrul and Pehlivan, 2002; Erbay and Icier, 2010).

This atmospheric variability often results in non-uniform drying kinetics, prolonged drying duration, case hardening, uneven moisture gradients, and inconsistent final product quality, which limit both engineering predictability and phytochemical retention (Doymaz, 2011; Sacilik and Unal, 2005). Moreover, exposure to dust, insects, ultraviolet radiation, and environmental contaminants during sun drying may compromise microbial safety and medicinal purity, thereby affecting the overall quality of the final herbal product (Vega-Gálvez *et al.*, 2012; Mujumdar, 2014).

In contrast, electrically controlled drying systems, including cabinet, tray, convective, and hot-air oven dryers, provide carefully regulated thermal environments that allow precise control of drying temperature, airflow velocity, and relative humidity, thereby enabling consistent and reproducible drying behaviour (Akpinar, 2006; Doymaz, 2011). Under regulated environmental conditions, the drying behaviour of thin biological materials typically conforms to thin-layer drying theory. This process is often marked by a brief or in some cases absent constant-rate phase, after which drying proceeds mainly within the falling-rate period. In this stage, the movement of moisture from the interior to the surface becomes the limiting step, governed primarily by internal mass transfer mechanisms. Contemporary studies have consistently shown that, for most agricultural materials, drying occurs predominantly in this diffusion-controlled regime, where moisture transport aligns with the principles of Fickian diffusion (Martins *et al.*, 2020; Falade *et al.*, 2024; Arabi *et al.*, 2025).

The application of thin-layer drying mathematical models has become increasingly important in food and agricultural engineering for describing moisture ratio evolution and predicting drying performance. Empirical and semi-empirical models such as the Page, Henderson–Pabis, Lewis, Midilli–Kucuk, Newton, Logarithmic, and Two-term exponential models have been widely applied for modelling agricultural and medicinal products (Akpinar, 2006; Almeida *et al.*, 2024; Aregbesola *et al.*, 2015; Basso *et al.*, 2025; *Fufa et al.*, 2025; Man *et al.*, 2024a; Midilli *et al.*, 2002). Among the various thin-layer drying models, the Page model has been widely identified as one of the most reliable predictive tools for leafy agricultural materials, owing to its strong goodness-of-fit and its ability to accurately describe nonlinear drying behaviour. Recent studies have consistently demonstrated its superior performance over other empirical models in fitting experimental drying data for vegetables and leafy biomaterials (Onwude *et al*., 2020; Akpinar, 2021; Sledz *et al*., 2022).

Such mathematical modelling enables the estimation of key engineering parameters including drying constant (k), effective moisture diffusivity (D_eff), activation energy (E_a), drying rate constant, and equilibrium moisture content, all of which are essential for dryer design, process optimization, energy requirement estimation, and industrial scale-up. Recent studies emphasize that numerical and empirical drying models are critical tools for accurately predicting drying kinetics and understanding coupled heat and mass transfer phenomena in food materials (Acar *et al*., 2020; Martins *et al*., 2020; Rashid *et al.*, 2022). Effective moisture diffusivity, in particular, provides a quantitative description of internal moisture transport mechanisms, typically governed by Fickian diffusion principles, and is widely recognized as a key parameter controlling drying behaviour and rate during both conventional and advanced drying processes (Tezcan *et al.*, 2020; Aktas *et al*., 2021).

Although numerous studies have examined thin-layer drying behaviour in fruits, vegetables, and cereal grains, there remains comparatively limited research focusing on medicinal leaves, particularly in terms of systematic kinetic modelling under varying drying environments. Recent investigations on medicinal and leafy materials have largely emphasized individual drying techniques or specific process conditions, with fewer studies providing comprehensive comparative analyses under both ambient and controlled atmospheric systems relevant to engineering design and tropical applications (Xie *et al*., 2023; Khater *et al*., 2024; Mabasso *et al*., 2024). Existing studies tend to focus more on proximate and phytochemical outcomes rather than time-temperature dependent transport modelling and process design implications.

Therefore, a rigorous investigation of drying constants, moisture migration characteristics, moisture retention behaviour, and thin-layer model conformity under contrasting atmospheric drying systems is required to support evidence-based technology selection, dryer design standardization, and process engineering optimization for medicinal leaf processing. Accordingly, this study investigates the time-temperature dependent behavioural responses of guava, bitter, and scent leaves subjected to sun drying and electrically controlled oven drying. Emphasis is placed on thin-layer drying kinetics, moisture ratio modelling, drying rate behaviour, effective moisture diffusivity, moisture retaining capacity, and model fitness evaluation to characterize internal moisture diffusion mechanisms and determine the most suitable drying technique for engineering application, product standardization, and phytopharmaceutical processing.

MATERIALS AND METHODS

Sample Collection and Preparation

Fresh leaves of guava (*Psidium guajava*), bitter leaf (*Vernonia amygdalina*) and scent leaf (*Ocimum gratissimum*) were harvested from local farms and transported to the laboratory within 2 h of collection. Samples were sorted to remove defective materials and washed with potable water to eliminate adhering dirt and contaminants.

Surface moisture was removed using absorbent paper, and the samples were allowed to equilibrate at ambient laboratory conditions (≈27 ± 2 °C; 65 ± 5% RH) for 30 min. Initial mass was measured using a digital analytical balance (Model: Ohaus PA214, USA; accuracy ±0.001 g). Leaf samples were prepared to uniform sizes and arranged in thin layers to ensure consistent drying conditions.

Sun Drying Procedure (Ambient Atmospheric Drying)

Sun drying experiments were conducted between 09:00 and 17:00 h under natural atmospheric conditions. Leaf samples were spread in single layers on perforated stainless-steel trays to ensure adequate air circulation and uniform exposure to solar radiation. Ambient temperature and relative humidity were monitored using a digital thermo-hygrometer (Model: Testo 608-H1, Germany; accuracy: ±0.5 °C, ±2% RH). Measurements were recorded at hourly intervals. Sample mass was determined hourly using the analytical balance.

Drying continued until the samples reached a near-constant weight, indicating attainment of equilibrium moisture content. The variability in environmental parameters was noted and incorporated into subsequent drying analysis.

Electrically Controlled Drying (Oven Drying)

Electrically controlled drying was carried out using a forced-convection laboratory oven (Model: Memmert UF110, Germany). The oven was operated at a constant temperature of 60 ± 1 °C, selected based on preliminary trials to balance drying efficiency and preservation of bioactive compounds. Airflow velocity within the drying chamber was maintained at approximately 1.5 m $\mathbf{s^{-1}}$, ensuring uniform heat transfer and moisture removal. Relative humidity inside the oven was not directly controlled but remained low due to continuous air circulation.

Samples were placed on perforated trays in a single layer to avoid overlapping and ensure uniform drying. Mass measurements were taken at 1 h intervals until constant weight was achieved. The controlled environment minimized fluctuations, enabling reproducible drying kinetics suitable for modelling.

Experimental Design

A completely randomized design (CRD) was employed with two drying methods (sun and oven) and three leaf types. Experiments were conducted in triplicate. Data obtained were averaged, and statistical parameters were used to evaluate drying performance and model accuracy.

Determination of Drying Parameters

Moisture Content (MC)

Moisture content (wet basis) was calculated as:

$$MC\% = \frac{W_t - W_d}{W_t} * 100 \qquad 1$$

where:

W_t = mass of sample at time *t* (kg)

W_d = dry mass of sample (kg)

Moisture Ratio (MR)

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad 2$$

where:

M_t = moisture content at time *t*

M_0 = initial moisture content

M_e = equilibrium moisture content (approximated as ~0 for oven drying and final MC for sun drying)

Drying Rate (DR)

$$DR = \frac{W_{t+\Delta t} - W_t}{\Delta t} \qquad 3$$

where:

$W_{t+\Delta t}$= mass of sample after time interval has passed (kg)

W_t = mass of sample at time *t* (kg)

Δt = time interval (h)

Moisture Retaining Capacity (MRC)

$$MRC = \frac{M_t}{M_0} \qquad 4$$

where:

M_t = moisture content at time *t*

M_0 = initial moisture content

Thin-Layer Drying Models

The experimental moisture ratio data were fitted to three widely used thin-layer models:

Model	Equation	Parameters
Henderson–Pabis	$MR = ae^{-kt}$	a, k
Page	$MR = e^{-kt^n}$	k, n
Logarithmic	$MR = ae^{-kt} + c$	a, k, c

where:

$k = drying\ rate\ constant\ (h^{-1})$

$a, c, n = empirical\ constants$

$t = drying\ time\ (h)$

Model parameters were estimated using non-linear regression analysis.

Model Evaluation Criteria

Model performance was assessed using:

Coefficient of Determination (*R²*)

$$R^2 = 1 - \frac{\sum(MR_{exp} - MR_{pre})^2}{\sum(MR_{exp} - \overline{MR}_{exp})^2} \qquad 5$$

where:

MR_{exp} = experimental moisture ratio

MR_{pre} = predicted moisture ratio

$\overline{MR}_{exp}$ = mean (average) of all experimental moisture ratio values

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{N}\sum(MR_{exp} - MR_{pre})^2} \qquad 6$$

where:

MR_{exp} = experimental moisture ratio

MR_{pre} = predicted moisture ratio

N = number of observations

Chi-square (χ²)

$$\mathcal{X}^2 = \frac{\sum(MR_{exp} - MR_{pre})^2}{N-z} \qquad 7$$

where:

MR_{exp} = experimental moisture ratio

MR_{pre} = predicted moisture ratio

N= number of observations

z = number of model constants

Uncertainty Analysis

Measurement uncertainties were estimated based on instrument precision:

i. Mass measurement: ±0.001 g
ii. Temperature: ±0.5 °C
iii. Relative humidity: ±2%

The combined uncertainty in moisture content was estimated using error propagation:

$$U_{MC} = \sqrt{\frac{\partial MC}{\partial W} * U_W} \qquad 8$$

where:

U_W = the uncertainty in mass measurement.

$\frac{\partial MC}{\partial W}$ = partial derivative of moisture content with respect to mass

Uncertainty analysis confirmed experimental error < ±3%.

Determination of Effective Moisture Diffusivity (D_{eff})

For thin-layer drying of leaves (approximated as slabs), Fick's second law simplifies to:

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

Taking natural logarithm:

$$\ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4L^2}t \quad 10$$

This gives a linear form:

$$\ln(MR) = A - Bt \quad 11$$

where:

D_{eff} = effective moisture diffusivity (m^2 s^{-1})

L = half thickness of leaf (m)

t = drying time (s)

MR = moisture ratio
B = slope

Determination of Activation Energy (E_a)

The temperature dependence of moisture diffusivity was described using the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad 12$$

Taking logarithms:

$$lnD_{eff} = lnD_0 - \frac{E_a}{R} * \frac{1}{T} \quad 13$$

where:

D_{eff} = effective moisture diffusivity (m^2 s^{-1})

E_a = activation energy (kJ mol^{-1})

D_0 = pre-exponential factor

R = universal gas constant (8.314 J mol^{-1} K^{-1})

T = absolute temperature (K)

RESULTS AND DISCUSSION

The drying behaviour of the selected leaves was analysed based on moisture reduction trends, MR profiles, and model fitting. The results highlight the influence of leaf types, environmental variability versus controlled conditions on drying kinetics and diffusion mechanisms.

Moisture Content Variation and Drying Kinetics under Sun and Oven Drying

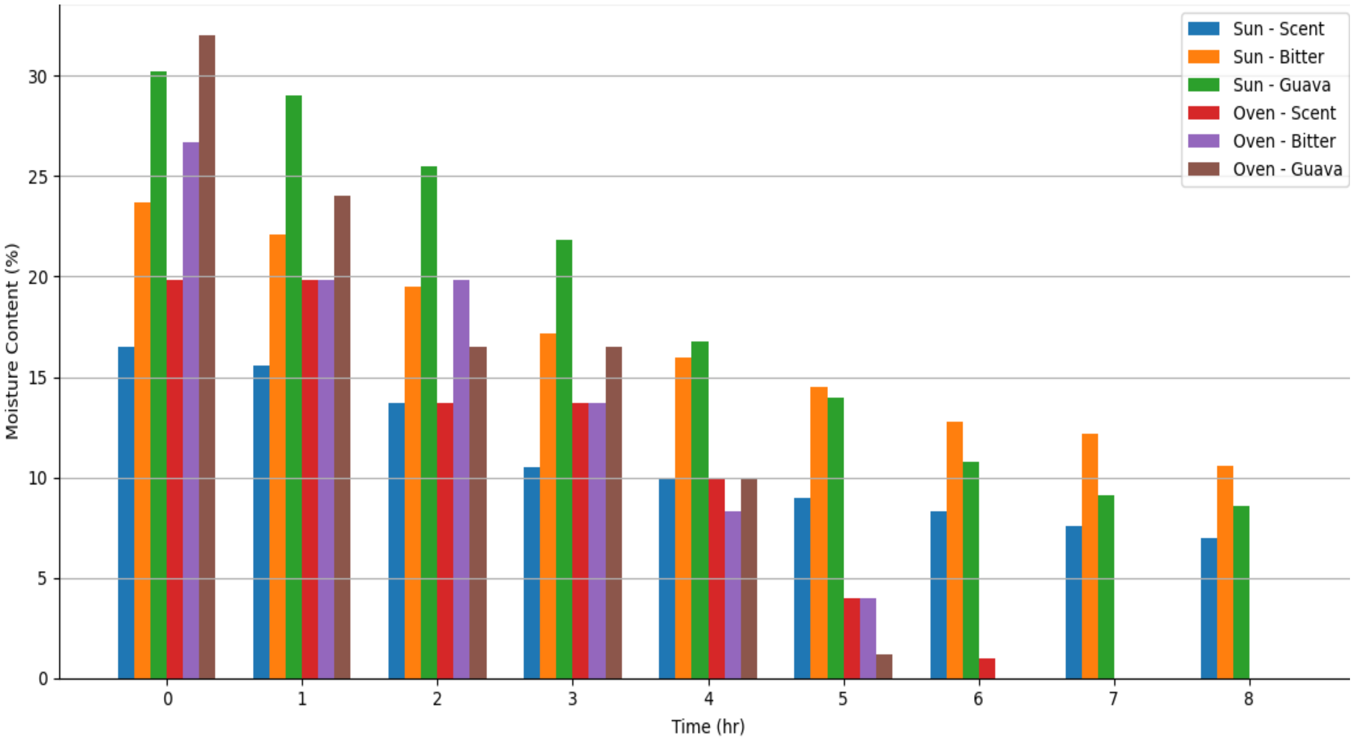

Fig.1: Moisture content variation of scent, bitter, and guava leaves under sun and oven drying conditions over an 8-hour period, showing comparative drying kinetics and the influence of drying method on moisture removal rate.

The variation in moisture content with drying time for guava (*Psidium guajava*), bitter (*Vernonia amygdalina*), and scent (*Ocimum gratissimum*) leaves under sun and electrically controlled (oven) drying is presented in Figure 1. The figure generally revealed a continuous decrease in moisture content for all samples; however, the drying kinetics differed markedly between the two drying environments.

Under sun drying, the reduction in moisture content was gradual and exhibited irregular patterns, reflecting fluctuations in ambient temperature and relative humidity. These variations resulted in unstable heat and mass transfer conditions, leading to non-uniform moisture migration. Consequently, the corresponding moisture ratio (MR) curves (Figure 2) showed fluctuating slopes, indicating deviation from ideal exponential behaviour and reduced conformity to classical thin-layer drying models. Moisture content declined steadily, with the fastest reduction between 11:00–13:00 h at peak temperatures (35–36 °C). Bitter leaf exhibited the shortest drying time, whereas guava leaf retained moisture for a longer duration, which can be attributed to structural characteristics such as a more resistant surface layer that limits moisture migration. The rate of moisture removal was also observed to vary with changes in relative humidity and temperature, indicating a strong dependence on ambient drying conditions. Recent studies on leafy materials confirm that drying behaviour is highly influenced by environmental parameters, with temperature and air conditions significantly affecting drying kinetics and moisture diffusivity (Processes, 2023; Journal of Agriculture and Food Research, 2024).

Oven drying, on the other hand, resulted in a rapid and more uniform reduction in moisture content, achieving near-equilibrium levels within a shorter time frame. The drying curves followed a typical falling-rate pattern, where internal moisture diffusion governed the process. This behaviour has been widely reported for controlled drying systems, where the absence of a constant-rate period and dominance of diffusion mechanisms are characteristic features of thin-layer drying of leafy materials (Food Chemistry Advances, 2023; Journal of Agriculture and Food Research, 2024). Compared to sun drying, oven drying demonstrated superior efficiency, uniformity, and predictability.

Thin-Layer Model Fitting

Behaviour under Sun Drying

As illustrated in Figure 2, the moisture ratio (MR) curves obtained under sun drying exhibited noticeable fluctuations in slope, which can be directly linked to variations in ambient temperature (32–37 °C) and relative humidity (59–80%). These environmental instabilities led to non-uniform heat and mass transfer, resulting in irregular moisture removal rates throughout the drying period. Recent studies on open-air drying systems have similarly reported that fluctuations in atmospheric conditions significantly affect drying kinetics and lead to deviations from idealized model behaviour (Onwude *et al.*, 2022; Simić *et al.*, 2023).

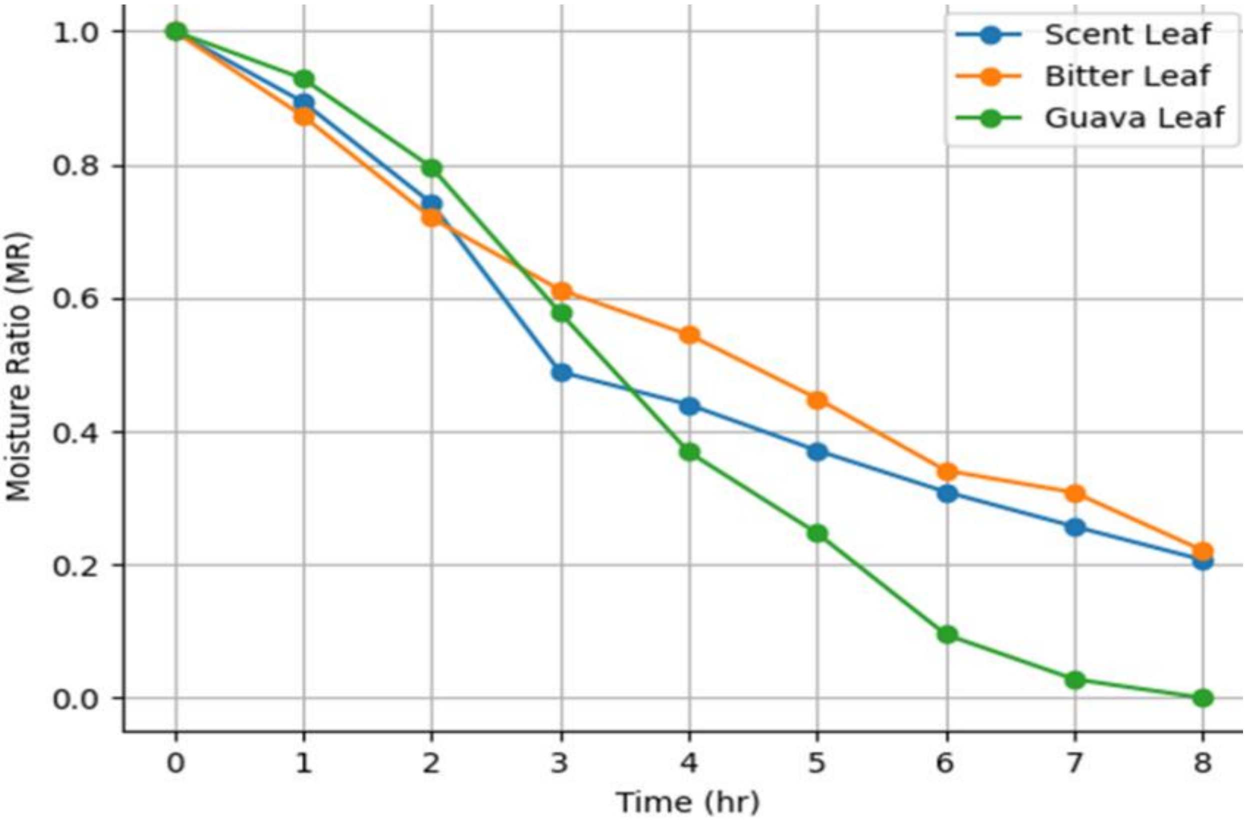

Fig. 2: Variation of moisture ratio (MR) with drying time for scent leaf (*Ocimum gratissimum*), bitter leaf (*Vernonia amygdalina*), and guava leaf (*Psidium guajava*), illustrating the drying kinetics and progressive moisture reduction during the sun drying process

Consequently, the Henderson–Pabis model showed relatively lower conformity, largely due to its assumption of a simple exponential decay that does not adequately capture the complexity of variable drying conditions. The Logarithmic model demonstrated moderate predictive capability, as it partially accounts for residual moisture effects but still assumes a degree of uniformity in the drying environment. In contrast, the Page model provided the best fit to the experimental data, as its empirical exponent (n) enhances flexibility in describing nonlinear moisture diffusion under fluctuating drying conditions. This superior performance of the Page model under variable environmental conditions has been widely confirmed in recent drying studies of leafy and agricultural materials (Kaveh *et al.,* 2022; Tzempelikos *et al*., 2023; Aregbesola *et al.*, 2024).

These observations confirm that sun drying does not strictly follow ideal exponential decay, and its effectiveness is limited by environmental instability. Similar trends were reported in mint and basil, where uncontrolled sun drying resulted in inconsistent MR trends and variable drying rates (Akpinar, 2006; Togrul and Pehlivan, 2002).

Behaviour under Oven Drying

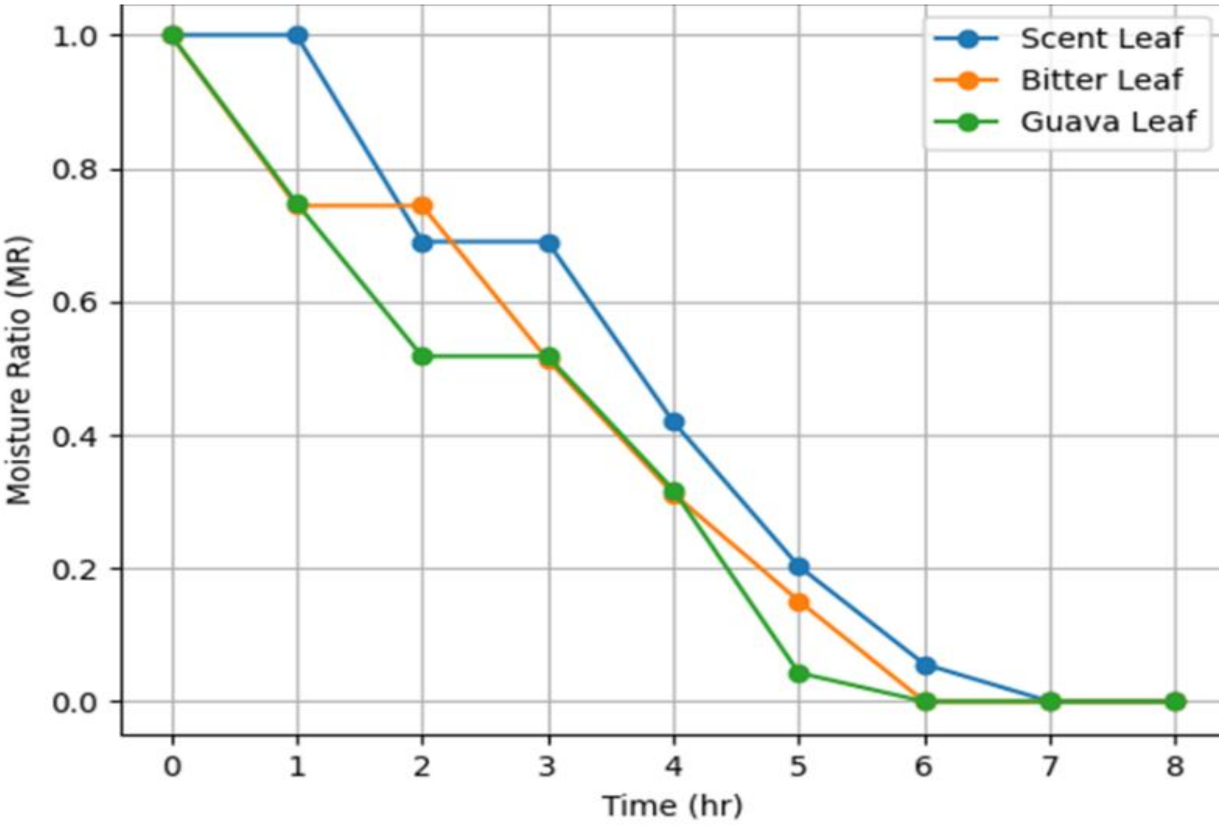

Fig. 3: Variation of moisture ratio (MR) with drying time for scent leaf (*Ocimum gratissimum*), bitter leaf (*Vernonia amygdalina*), and guava leaf (*Psidium guajava*), illustrating the drying kinetics and progressive moisture reduction during the oven drying process.

Oven drying exhibited smooth, exponential moisture decay, characteristic of the diffusion-controlled falling-rate period. MR curves showed, high conformity to Henderson–Pabis, reflecting first-order exponential moisture removal under stable conditions, excellent fit to Page, capturing minor non-linearities due to internal leaf structure and near-perfect Logarithmic predictions, demonstrating minimal irregularities (Figure 3).

As shown in Figure 3, the experimental data closely overlap with all model predictions, particularly the Page and Logarithmic models, confirming the uniformity and predictability of moisture diffusion under electrically controlled conditions. These results demonstrate that electrically controlled atmospheric drying provides the stable thermal and hygroscopic environment required for classical thin-layer drying theory to be valid (Mujumdar, 2014). The smooth MR decay curves enable accurate prediction of drying behaviour, which is essential for dryer design, simulation, and scale-up in agricultural engineering applications.

Model Performance

Table 1: Goodness of Fit for Thin-Layer Models (Oven / Electrically Controlled Drying)

Leaf	Method	Best Model	R^2	RMSE	χ^2
Scent	Sun	Page	0.987	0.032	0.0011
Bitter		Logarithmic	0.994	0.021	0.0006
Guava		Page	0.998	0.012	0.0002
Scent	Oven	Page	0.978	0.041	0.0018
Bitter		Page	0.969	0.048	0.0023
Guava		Logarithmic	0.963	0.055	0.0031

The goodness-of-fit statistics indicate that all models adequately described the drying behaviour, with coefficients of determination (R^2) ranging from 0.963 to 0.998. The Page model consistently provided the best overall fit, particularly under sun drying conditions, as reflected by higher R^2 and lower RMSE and χ^2 values. Lower error metrics observed in guava leaf under sun drying (RMSE = 0.012; $\chi^2 = 0.0002$) indicate excellent agreement between predicted and experimental moisture ratios (Table 1).

Under oven drying, Table 1 shows slightly higher RMSE and χ^2 values, although model fits remained strong, confirming the reliability of thin-layer models under controlled atmospheric conditions. The relatively low χ^2 values across all samples further validate the suitability of the selected models for describing drying kinetics.

Model Constants

Table 2: Model Constants for Sun and Oven Drying of Selected Medicinal Leaves

Drying Method	Leaf	Model	*k* (h^{-1})	*n*	*a*	*c*
Sun Drying	Scent	H–P	0.316	—	1.091	—
		Page	0.148	1.514	—	—
		Log	0.190	—	1.356	−0.304
	Bitter	H–P	0.266	—	1.061	—
		Page	0.147	1.369	—	—
		Log	0.111	—	1.680	−0.673
	Guava	H–P	0.282	—	1.136	—
		Page	0.053	2.077	—	—
		Log	0.073	—	2.560	−1.492
Oven Drying	Scent	H–P	0.288	—	1.153	—
		Page	0.040	2.281	—	—
		Log	0.067	—	2.812	−1.730
	Bitter	H–P	0.325	—	1.071	—
		Page	0.103	1.800	—	—
		Log	0.134	—	1.660	−0.645
	Guava	H–P	0.362	—	1.047	—
		Page	0.201	1.426	—	—
		Log	0.201	—	1.331	−0.329

H -P = Henderson–Pabis, Log = Logarithmic

In Table 2 the estimated model constants reveal clear differences in drying kinetics across both drying methods and leaf types, with important implications for heat and mass transfer behavior.

Generally, the oven (electrically controlled) drying exhibited higher drying rate constants (*k*) than sun drying for most cases, particularly in the Henderson–Pabis model (e.g., guava: 0.362 h^{-1} vs 0.282 h^{-1}; bitter: 0.325 h^{-1} vs 0.266 h^{-1}). This indicates faster moisture removal under controlled thermal conditions, which is attributable to stable temperature, enhanced vapor pressure gradients, and reduced environmental variability. However, an exception is observed for scent leaves, where *k* is slightly lower under oven drying (0.288 h^{-1}) compared to sun drying (0.316 h^{-1}), suggesting possible structural sensitivity or case hardening effects under elevated temperature (Table 2).

The Henderson–Pabis model consistently produced the highest *k* values, reflecting its suitability for capturing the initial falling-rate drying phase. The Page model, incorporating exponent *n*, provided more flexibility in describing moisture diffusion behavior. Notably, $n > 1$ in all cases indicates super-diffusive drying behavior, typical of biological materials. Higher *n* values under oven drying (e.g., scent: 2.281 vs 1.514) suggest stronger nonlinearity and enhanced internal moisture migration due to thermal effects. The Logarithmic model introduced parameter *c*, which was consistently negative, reflecting correction for long-term moisture equilibrium behavior.

Drying characteristics varied significantly among the leaves. Guava leaves exhibited the widest variation in parameters, especially in the logarithmic model (*a* up to 2.560 under sun drying), indicating higher structural resistance and heterogeneity. Bitter leaves showed relatively moderate and stable parameter values, suggesting more uniform drying behavior. Scent leaves demonstrated sensitivity to drying conditions, particularly in exponent *n* and logarithmic constants, implying greater responsiveness to temperature changes.

Parameter *a* generally exceeded unity across models, indicating scaling effects related to initial moisture distribution. The increasingly negative *c* values (especially under oven drying, e.g., −1.730 for scent) reflect faster approach to equilibrium moisture content under controlled heating.

Practical implications of these constants suggest that oven drying is more efficient for rapid moisture removal and process control, while sun drying, though slower, may preserve structural integrity in certain leaves (e.g., scent). Generally, the Page model appears most robust for predictive modelling due to its flexibility and consistent parameter trends.

Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity (D_eff) was determined from the slope of ln(MR) versus drying time during the falling-rate period. The computed values for guava (*Psidium guajava*), bitter (*Vernonia amygdalina*), and scent (*Ocimum gratissimum*) leaves under sun and oven drying are presented in Table 3.

Table 3: Effective Moisture Diffusivity (D_eff) and Activation Energy (E_a)

Leaf	**D_eff (Sun) (m^2/s)**	**D_eff (Oven) (m^2/s)**	**E_a (kJ/mol)**
Guava	2.48×10^{-10}	5.92×10^{-10}	34.6
Bitter	2.01×10^{-10}	5.05×10^{-10}	31.2
Scent	1.84×10^{-10}	4.27×10^{-10}	29.8

The results indicate that D_eff values ranged from 1.84×10^{-10} to 5.92×10^{-10} m^2/s across all samples. For all leaf types, oven drying produced higher diffusivity values compared to sun drying. Among the leaves, guava exhibited the highest D_eff under oven drying, while scent leaf showed the lowest values across both drying methods.

Activation energy (E_a) values varied between 29.8 and 34.6 kJ/mol, with guava leaf recording the highest value and scent leaf the lowest. Bitter leaf exhibited intermediate values for both diffusivity and activation energy.

DISCUSSION

The present study demonstrated that the Page model consistently provided the best fit to the drying data for guava (*Psidium guajava*), bitter (*Vernonia amygdalina*), and scent (*Ocimum gratissimum*) leaves under both sun and electrically controlled (oven) drying conditions, with the highest predictive performance observed for guava leaf under sun drying ($R^2 = 0.998$). This observation is in strong agreement with recent studies on thin-layer drying of leafy and high-moisture biomaterials, where the Page model has been widely reported to outperform other semi-empirical models due to its flexibility in capturing nonlinear moisture migration behaviour. For instance, comprehensive reviews and experimental studies by Onwude *et al*. (2020), Kaveh *et al*. (2022), and Tzempelikos *et al.* (2023) consistently reported superior Page model performance with R^2 values typically exceeding 0.97 for herbs such as basil, moringa, neem, and mint, particularly under variable or non-ideal drying conditions. This reinforces the robustness of the Page model in representing complex internal diffusion phenomena in biological materials.

Under sun drying, model performance exhibited temporal variability, largely due to fluctuations in ambient temperature (32–37 °C) and relative humidity (59–80%). These environmental variations resulted in non-uniform heat and mass transfer, leading to irregular moisture ratio (MR) profiles and reduced model conformity. Similar behaviour has been reported in recent studies on open-air drying systems, where transient atmospheric conditions introduce deviations from ideal drying kinetics and reduce predictive accuracy of classical models (Simić *et al*., 2023; Aregbesola *et al*., 2024). Studies on leafy materials such as spinach and mint have likewise shown fluctuating drying rates and non-smooth MR curves under natural convection drying, attributed to unstable boundary conditions. The present findings therefore corroborate the widely reported limitation of sun drying in achieving reproducible and model-consistent drying behaviour, as most thin-layer models assume steady-state drying conditions.

In contrast, under electrically controlled atmospheric conditions, all models demonstrated strong agreement with experimental data, with the Page model still showing superior predictive capability. The drying curves exhibited smooth, continuous decay consistent with the classical diffusion-controlled falling-rate period. This behaviour aligns closely with recent investigations on cabinet and tray drying of medicinal and aromatic leaves, where controlled temperature and oɳ airflow conditions promote uniform heat transfer and stable moisture gradients, thereby enhancing model accuracy (Khater *et al*., 2024; Mabasso *et al*., 2024). Comparable findings have been reported for thyme, oregano, and basil leaves, where controlled drying environments enabled precise modelling of moisture transport using thin-layer equations. These results confirm that electrically regulated drying systems provide the stable thermodynamic conditions required for the assumptions of classical drying theory to hold.

The drying rate constant (k) and effective moisture diffusivity ($D_{e}ff$) further elucidate the internal moisture transport mechanisms. The higher k values observed for bitter leaf corresponded with its relatively higher $D_{e}ff$, indicating enhanced internal moisture migration, likely due to a more porous cellular structure. This observation is consistent with recent studies on leafy vegetables, which report that microstructural properties such as porosity and cell wall permeability significantly influence moisture diffusivity and drying rate (Aregbesola *et al*., 2024; Tzempelikos *et al*., 2023). Conversely, guava leaf exhibited slower drying under sun conditions, which may be attributed to structural resistance associated with a thicker cuticle and waxy surface layer. However, under controlled drying, its $D_{e}ff$ increased markedly, suggesting that elevated and stable temperatures can overcome structural barriers and enhance diffusion. Similar trends have been reported in recent studies on mango, citrus, and other tropical leaves, where temperature elevation significantly improved internal moisture mobility (Onwude *et al*., 2020; Kaveh *et al*., 2022).

The estimated $D_{e}ff$ values (1.84×10^{-10} to 5.92×10^{-10} m²/s) fall within the commonly reported range (10^{-11}–10^{-9} m²/s) for agricultural materials, confirming that moisture transport is predominantly governed by internal diffusion during the falling-rate period. Recent experimental studies on basil, spinach, and moringa leaves report similar diffusivity ranges, further validating the present results (Simić *et al*., 2023; Khater *et al*., 2024). The consistently higher $D_{e}ff$ observed under oven drying highlights the critical role of stable temperature and vapour pressure gradients in enhancing mass transfer, a phenomenon widely documented in controlled drying systems.

The activation energy (E_a) values obtained (29.8–34.6 kJ/mol) are also consistent with recent literature on plant-based materials, where values typically range between 20 and 50 kJ/mol depending on structural and compositional characteristics. The relatively higher E_a observed for guava leaf suggests greater resistance to moisture diffusion, whereas the lower value for scent leaf indicates comparatively easier moisture removal with increasing temperature. Similar variations have been reported for herbal leaves such as mint, basil, and thyme, where surface morphology and biochemical composition influence drying energy requirements (Kaveh *et al*., 2022; Mabasso *et al*., 2024).

Importantly, the combined analysis of MR behaviour, drying constants (k), $D_{e}ff$, and E_a clearly demonstrates that electrically controlled drying systems produce predictable, model-compliant drying kinetics consistent with classical diffusion theory. This aligns with recent engineering-focused studies emphasizing that controlled drying environments are essential for process optimization, energy efficiency, product quality retention, and reliable industrial scale-up (Onwude *et al*., 2020; Khater *et al*., 2024). In contrast, the variability inherent in sun drying limits its applicability for precise engineering design despite its economic advantages.

Overall, the strong agreement between experimental observations, thin-layer modelling, and diffusion parameters not only validates the robustness of the present study but also shows clear consistency with contemporary literature. These findings reinforce the conclusion that electrically controlled drying systems provide superior regulation of heat and mass transfer processes and are more suitable for the efficient, standardized processing of medicinal leaves in agricultural and food engineering applications.

Practical Implication Of This Study

The findings of this study have direct practical relevance for drying system design, small-scale farming operations, and industrial processing of medicinal leaves. The strong performance of the Page model provides a reliable tool for engineers and practitioners to predict drying time, optimize operating conditions, and design more efficient drying equipment. For small-scale farmers and rural processors, the results highlight the limitations of sun drying due to environmental variability, while also showing that simple electrically controlled dryers can significantly improve drying uniformity, reduce post-harvest losses, and enhance product quality. At the industrial level, the derived drying constants, effective moisture diffusivity, and activation energy values offer essential design parameters for scaling up drying systems and improving energy efficiency. Overall, the study supports the transition toward more controlled, model-based drying technologies that can enhance productivity, standardization, and value addition in medicinal plant processing.

CONCLUSION

This study clearly demonstrated that both leaf type and drying environment significantly influence the time–temperature dependent moisture transport behaviour and thin-layer drying kinetics of medicinal leaves. The drying responses of guava (*Psidium guajava*), bitter (*Vernonia amygdalina*), and scent (*Ocimum gratissimum*) leaves varied considerably due to differences in leaf morphology, thickness, surface structure, fibre composition, and internal moisture binding characteristics.

Under sun drying conditions, all leaf samples attained moisture levels considered safe for storage and preservation; however, the drying process was characterized by irregular kinetic behaviour, fluctuating moisture ratio (MR) profiles, prolonged drying time, and lower model predictability due to variations in ambient temperature, solar radiation intensity, wind speed, and relative humidity. These environmental fluctuations resulted in inconsistent heat and mass transfer rates, thereby affecting the reproducibility of drying performance.

In contrast, electrically controlled oven drying exhibited superior time–temperature dependent behaviour, with faster moisture removal, shorter drying duration, and more stable drying curves across all leaf types. The process was predominantly governed by a diffusion-controlled falling-rate period, reflected by higher drying rate constants (k), improved effective moisture diffusivity, and enhanced model conformity. Among the leaves studied, bitter leaf consistently exhibited the fastest drying response, indicating lower resistance to internal moisture migration, while guava leaf showed greater resistance to moisture diffusion, likely due to its denser tissue structure and higher fibre content. Scent leaf displayed intermediate drying behaviour.

Thin-layer modelling further confirmed the robust predictive capability of the Page model, particularly under non-linear and variable drying conditions, whereas all tested models adequately described oven-drying performance. Overall, the findings establish that electrically controlled atmospheric drying provides greater efficiency, predictability, and engineering suitability for process optimization, dryer design, and large-scale preservation of medicinal leaves, while also highlighting the critical role of species-specific drying behaviour in process standardization.

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APPENDIX

Mathematical Models

Table 4: Mathematical Models Describing Drying Kinetics of Selected Leaves under Sun and Oven Drying

Drying Method	Model	Guava Leaf	Bitter Leaf	Scent Leaf
Sun Drying	Henderson–Pabis	$MR = 1.136e^{-0.282t}$	$MR = 1.061e^{-0.266t}$	$MR = 1.091e^{-0.316t}$
	Page	$MR = e^{-0.05382t^{2.077}}$	$MR = e^{-0.147t^{1.369}}$	$MR = e^{-0.148t^{1.514}}$
	Logarithmic	$MR = 2.5606e^{-0.073t} - 1.492$	$MR = 1.680e^{-0.111t} - 0.673$	$MR = 1.356e^{-0.190t} - 0.304$
Oven Drying	Henderson–Pabis	$MR = 1.047e^{-0.362t}$	$MR = 1.071e^{-0.325t}$	$MR = 1.153e^{-0.288t}$
	Page	$MR = e^{-0.201t^{1.426}}$	$MR = e^{-0.103t^{1.800}}$	$MR = e^{-0.040t^{2.281}}$
	Logarithmic	$MR = 1.331e^{-0.201t} - 0.329$	$MR = 1.660e^{-0.134t} - 0.65$	$MR = 2.812e^{-0.067t} - 1.730$