



MICROWAVE THIN-LAYER DRYING KINETICS, DIFFUSIVITY, AND ENERGY EFFICIENCY OF MEDICINAL OCIMUM GRATISSIMUM AND VERNONIA AMYGDALINA LEAVES

Oladele, S. O.

Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure, Nigeria

Correspondence: sooladele@futa.edu.ng

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Abstract

Thin-layer microwave drying was applied to highly perishable medicinal herbs, *Ocimum gratissimum* (scent leaf) and *Vernonia amygdalina* (bitter leaf), to generate a comprehensive kinetic and energy dataset for these species. Increasing microwave power significantly reduced drying time from 19 minutes to 7 minutes for scent leaf and from 17 minutes to 4 minutes for bitter leaf, thereby avoiding the multi-hour durations required by convective or solar methods. Moisture-ratio curves exhibited only a falling-rate period. Seven thin-layer drying models were evaluated; the Midilli model provided the optimal fit ($R^2 \geq 0.990$, root mean square error (RMSE) ≤ 0.030). Effective moisture diffusivity increased by an order of magnitude with applied power, reaching $1.84 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ for scent leaf and $1.54 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ for bitter leaf. An Arrhenius-type analysis yielded activation energies of 31.8 W g^{-1} and 28.1 W g^{-1} for scent leaf and bitter leaf, respectively. Specific energy consumption decreased to $4.09 \text{ MJ per kg of water removed}$ ($4.09 \text{ MJ kg}^{-1} \text{ H}_2\text{O}$) at 900 W , while drying efficiency exceeded 97%. These results demonstrate that appropriately selected microwave power levels achieve rapid, energy-efficient dehydration without prolonged thermal exposure, offering a promising preservation approach for nutraceutical herbs in tropical regions. The reported kinetic and diffusivity parameters facilitate scale-up calculations for industrial microwave units targeting bioactive-compound retention.

Keywords: Thin-layer, microwave-drying, modeling, activation energy, moisture diffusivity

Introduction

Medicinal leafy herbs constitute a vital component of Sub-Saharan Africa cuisine and primary health care. Scent leaf (*Ocimum gratissimum*), an aromatic perennial of the Lamiaceae family, and bitter leaf (*Vernonia amygdalina*), a bitter shrub of the Asteraceae family. They are consumed as soups, seasonings and herbal infusions; both exhibit broad antimicrobial, antidiabetic and antioxidant activities and are formally recognised as nutraceuticals by recent FAO and WHO monograph (Nakra *et al.*, 2025; Idris *et al.*, 2011). Both leaves contain moisture content greater than 85 % moisture (wet basis), so enzymatic browning and microbial spoilage commence within 24 h of harvest, causing post-harvest losses exceeding 30 % in humid regions.

Drying extends shelf life, lowers packaging mass and volume, and facilitates year-round availability (Maroulis and Saravacos, 2003). Traditional sun-

drying or hot-air drying of leafy vegetables is hampered by long residence times, airborne contamination, and non-uniform quality (Soysal, 2004). Hot-air systems additionally suffer low thermal efficiency because heat must conduct from the surface to the core through tissue of poor thermal conductivity (Maskan, 2000). Recent reviews confirm that applying microwave (MW) energy yields volumetric heating, accelerates moisture migration, and can shorten drying time by 80–90 % relative to convective methods while retaining greener colour and aroma (Zahoor *et al.*, 2023). Nevertheless, excessively high MW power can provoke localised overheating, cell-wall rupture and case-hardening; optimal power schedules are therefore commodity-specific (Kalinke *et al.*, 2025).

Thin-layer MW-drying kinetics and modelling have been reported for parsley, basil, spinach and selected fruit slices (Soysal, 2004; Dadali *et al.*, 2007). Isolated studies on *O. gratissimum* used narrow

power ranges lesser than 264 W (Kusuma *et al.*, 2023) and published work on *V. amygdalina* focuses on convective or sun-drying only (Alara *et al.*, 2018).

To date, no study has systematically examined the microwave drying behaviour of *Ocimum gratissimum* and *Vernonia amygdalina* across a comprehensive range of power levels. Existing literature also lacks comparative benchmarking of multiple thin-layer drying models using robust goodness-of-fit statistics, alongside simultaneous quantification of effective moisture diffusivity (Deff), Arrhenius activation energy (Ea), specific energy consumption (SEC), and drying efficiency (η); all of which are critical for process scale-up and techno-economic evaluation. Addressing these gaps is essential for the rational design of industrial-scale microwave dryers that enable rapid, energy-efficient stabilisation of nutraceutical herbs without compromising their bioactive integrity. Accordingly, the present study aims to characterise the microwave thin-layer drying kinetics of scent and bitter leaves across six microwave power levels, apply mathematical models to describe the drying process, and evaluate the associated energy performance indicators.

Material and Methods

Material Procurement and Conditioning

Fresh scent leaf (*Ocimum gratissimum*) and bitter leaf (*Vernonia amygdalina*) were harvested at physiological maturity from a certified organic farm in Akure, Nigeria (7°17' N, 5°13' E). Within 2 h of harvest, leaves were sorted to remove extraneous matter, rinsed with potable water (15 °C), surface-blotted, packed (≤ 300 g kg⁻¹ void space) in low-density polyethylene bags, and held at 4 ± 1 °C for 24 h to equalise internal moisture.

Microwave Drying Apparatus

Drying was performed in a domestic-grade microwave oven (Sanyo EM-G4753AW, 2.65 kW, 2 450 MHz; cavity 340 × 220 × 320 mm). Output power was programmed at 90, 180, 360, 540, 720 and 900 W.

Experimental Design and Procedure

A randomised complete block design was adopted, with leaf species as blocks and power level as treatment (six levels). Each treatment was replicated three times (n = 3). For every run, 25.0 ± 0.2 g of destemmed leaves were spread in a single layer on the 300 mm glass turntable. Runs were scheduled in random order; a 10-min cool-down prevented carry-over heating. The oven was paused every 30 s; the sample was removed, weighed on a calibrated 0.01 g balance (Mettler Toledo PB203), and returned. Drying ceased when the mass change over two successive readings was lesser than 0.02 g.

Moisture Content Determination

Initial and final weights of the samples were measured using hot-air-oven method (70 °C, 12 h). Results were expressed in wet basis (%b). The instantaneous moisture content of the samples was obtained using Equation 1.

$$M_t = \frac{m_w - m_d}{m_d} \tag{1}$$

where M_t is the moisture content (g water/ g dry matter), m_w the wet mass of sample at a time (g), and m_d is the corresponding dry mass of the sample (g).

The initial moisture content, M_o , and final moisture content, M_f were used to compute the moisture ratio (MR), Equation 2.

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{2}$$

where M_e is the equilibrium moisture contents (% db) and it is assumed to be negligible.

Kinetic Modelling Content Determination

Seven thin-layer models (Lewis, Page, Henderson–Pabis, Logarithmic, Two-term exponential, Verma, Midilli) – Table 1 were fitted to MR–time data using non-linear least-squares (Levenberg–Marquardt) in STATISTICA 12.

Goodness-of-fit was judged by coefficient of determination (R²), root-mean-square error (RMSE), sum-of-squared errors (SSE) and root-mean-square-error (RMSE) of the empirical models to account for parameters count. These parameters were calculated using Equations 3-6.

Table 1: Thin-layer drying mathematical models employed for the fitting of experimental data

Models	Equations	Reference
Lewis	$MR = \exp(-at)$	McMinn (2006)
Page	$MR = \exp(-at^b)$	Kaleemullah and Kailappan, (2006)
Henderson and Pabis	$MR = b \exp(-at)$	Akpinar <i>et al.</i> , (2004).
Two-term exp.	$MR = a \exp(-bt) + (1 - a) \exp(-abt)$	Togrul and Pehlivan (2004)
Logarithmic	$MR = c + a \exp(-bt)$	Akgun and Doymaz (2005)
Verma <i>et al.</i>	$MR = a \exp(-bt) + (1 - a) \exp(-ct)$	Akpinar <i>et al.</i> , 2006)
Midilli <i>et al.</i>	$MR = a \exp(-bt^d) + ct$	Midilli <i>et al.</i> (2002); Sacilik <i>et al.</i> (2006)

a, b, c and d are constants and coefficients in the drying models

$$R^2 = \frac{\sum_{i=1}^N (\overline{MR}_{exp} - MR_{pre,i}) \cdot \sum_{i=1}^N (\overline{MR}_{exp} - MR_{exp,i})}{\sqrt{[\sum_{i=1}^N (\overline{MR}_{exp} - MR_{pre,i})^2][\sum_{i=1}^N (\overline{MR}_{exp} - MR_{exp,i})^2]}} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (4)$$

$$NRMSE = \sqrt{\frac{1}{N} \left(\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{MR_{exp,max} - MR_{exp,min}} \right)} \quad (5)$$

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

Goodness-of-fit was judged by coefficient of determination (R^2), root-mean-square error (RMSE), sum-of-squared errors (SSE) and root-mean-square-error (RMSE) of the empirical models to account for parameters count. These parameters were calculated using Equations 3-6.

$$R^2 = \frac{\sum_{i=1}^N (\overline{MR}_{exp} - MR_{pre,i}) \cdot \sum_{i=1}^N (\overline{MR}_{exp} - MR_{exp,i})}{\sqrt{[\sum_{i=1}^N (\overline{MR}_{exp} - MR_{pre,i})^2][\sum_{i=1}^N (\overline{MR}_{exp} - MR_{exp,i})^2]}} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (4)$$

$$NRMSE = \sqrt{\frac{1}{N} \left(\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{MR_{exp,max} - MR_{exp,min}} \right)} \quad (5)$$

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

Effective Moisture Diffusivity and Activation Energy

The Assuming one-dimensional Fickian diffusion in an infinite slab of half-thickness $L = 0.25$ mm, the long-time analytical solution yields. Plots of $\ln(MR)$ versus t provided the slope (Equation 7), from which effective diffusivity (D_{eff}) – Equation 4 was calculated.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{4L^2} \quad (7)$$

The Arrhenius-type relation (Equation 8) was linearised as $\ln D_{eff}$ vs $1/P$ (power per gram sample) to extract the pre-exponential factor (D_0) and activation energy (E_a) (Dadali *et al.*, 2007b).

$$D_{eff} = D_0 \exp^{-E_a P^{-1}} \quad (8)$$

The diffusion coefficient, D_0 for each microwave drying power was calculated using Equation (9). The coefficient was determined by the plotting experimental data against drying time, and fitting a straight line to $\ln(MR)$, the slope of the straight line was expressed as Equation 10.

$$\text{slope}(\phi) = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

$$\text{Therefore, } D_{eff} = \frac{4L^2 \phi}{\pi^2} \quad (10)$$

Energy Performance Metrics

The specific energy consumption, SEC (Equation 9) and microwave drying efficiency, η (Equation 11) were derived.

$$SEC = \frac{P_{in} t_{on}}{m_w} \quad (11)$$

$$\eta = \frac{m_w \lambda_{100}}{P_{in} t_{on}} \times 100 \quad (12)$$

where P_{in} is measured input power (kW), t_{on} is drying time (s), m_w is water removed (kg) and $\lambda_{100} = 2.257$ kJ kg⁻¹.

Statistical Analysis

Data were reported as mean \pm standard deviation (SD). Differences among power levels were evaluated by one-way ANOVA; Tukey's HSD test ($\alpha = 0.05$) identified significant pairwise differences.

Results and Discussion

The influence of microwave output power on the drying characteristics (moisture content, moisture ratio, drying rate, and drying time) of leaf samples was investigated at power levels of 90, 180, 360, 540, 720 and 900 W. Figure 1 illustrates the variation in moisture ratio with drying time for the different power settings. A consistent reduction in moisture content was observed with increasing drying time, with more rapid moisture loss occurring at higher microwave powers. The drying behaviour followed a typical falling-rate pattern, characterised by faster moisture removal at higher power levels and relatively steadier moisture loss at lower power settings.

Experimental results for both leaf types confirmed that drying occurred exclusively in the falling-rate period, as no constant-rate phase was observed. The critical moisture content was found to coincide with the initial moisture content, recorded as 86.22% (wb) for scent leaf and 87.36% (wb) for bitter leaf, indicating that internal moisture diffusion was the rate-controlling mechanism. This observation is consistent with the findings of Gogus and Maskan, (1999). The results also align with previous studies on banana (Maskan, 2000), black tea (Panchariya *et al.*, 2002), apple pomace (Wang *et al.*, 2007), spinach (Dadali *et al.*, 2007c) and basil leaves (Demirhan and Özbek, 2010).

The total drying time required to reduce the initial moisture contents of scent and bitter leaves to final values of $2.17 \pm 0.18\%$ and $2.46 \pm 0.12\%$ (wb), respectively, varied significantly with microwave power. Drying times recorded were 19, 10, 5, 5, 4 and 7 minutes for scent leaf, and 17, 12, 9, 8, 6 and 4 minutes for bitter leaf, at 90, 180, 360, 540, 720 and 900 W, respectively. This significant reduction in drying time with increased microwave power can be attributed to the volumetric heating effect of microwave energy. This mechanism creates a steep

The drying rate, defined as the change in moisture content per unit time, was analysed to further explain the drying behaviour. Figure 2 presents the drying rate versus drying time profiles at the different microwave power levels. As expected, the drying rate decreased with time due to progressive moisture depletion. Conversely, higher power levels generally produced higher drying rates, except at 900 W where a decline was observed. This reduction is attributed to possible structural damage and reduced porosity at very high-power levels, which

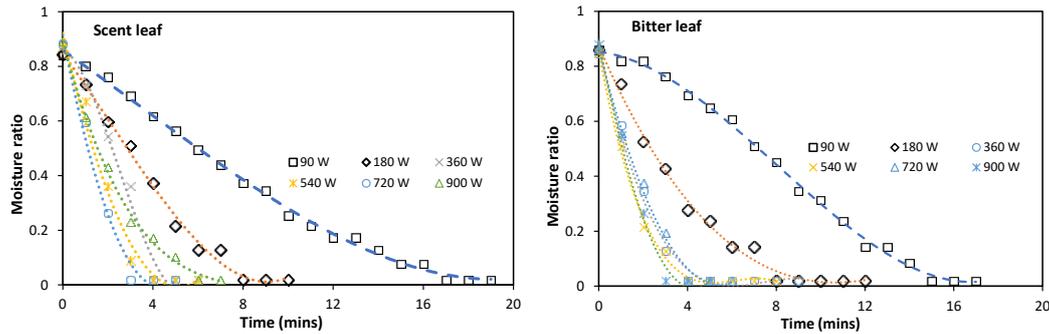


Figure 1: Moisture content against time at different microwave power outputs

vapour pressure gradient between the interior and surface of the material, thereby enhancing both heat and mass transfer and accelerating the drying process at higher power levels.

These findings are consistent with the work of Demirhan and Özbek, (2010) on basil leaves. They also highlight the efficiency of microwave drying when compared to conventional methods. For instance, drying durations reported by Akpınar, (2006) for solar-dried basil leaves and by Mepba *et al.* (2007) for sun-dried Nigerian leafy vegetables ranged from 5 hours to 2 days, which is substantially longer than the drying times observed in the present study.

hinder moisture migration from the core to the surface.

The drying rate values at each power level for scent leaf were 0.0384, 0.1089, 0.1423, 0.2005, 0.2879 and 0.4596 g water/g dry matter ·min, while for bitter leaf, values were 0.0405, 0.1238, 0.2589, 0.3363, 0.3054 and 0.1413 g water/g dry matter ·min at 90, 180, 360, 540, 720 and 900 W, respectively. The high initial drying rates were attributed to rapid microwave energy absorption and high moisture diffusivity, which enhanced the drying effect. As the drying progressed, moisture loss reduced the microwave absorption capacity of the samples, which in turn caused a fall in the drying rate.

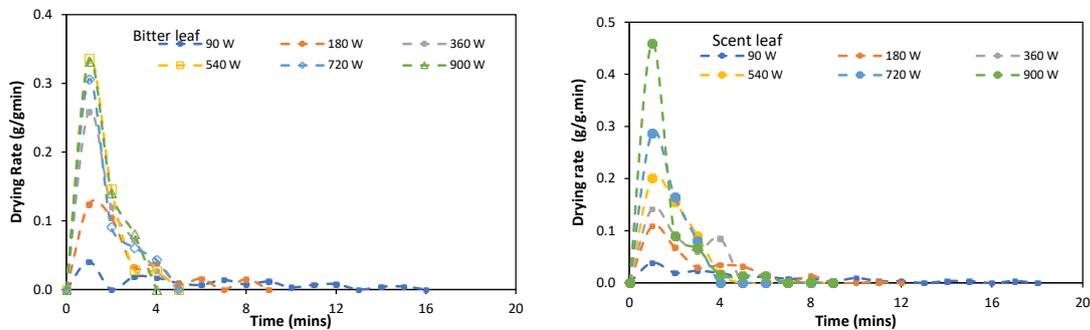


Figure 2: DR versus drying time of scent leaves samples at different drying microwave powers

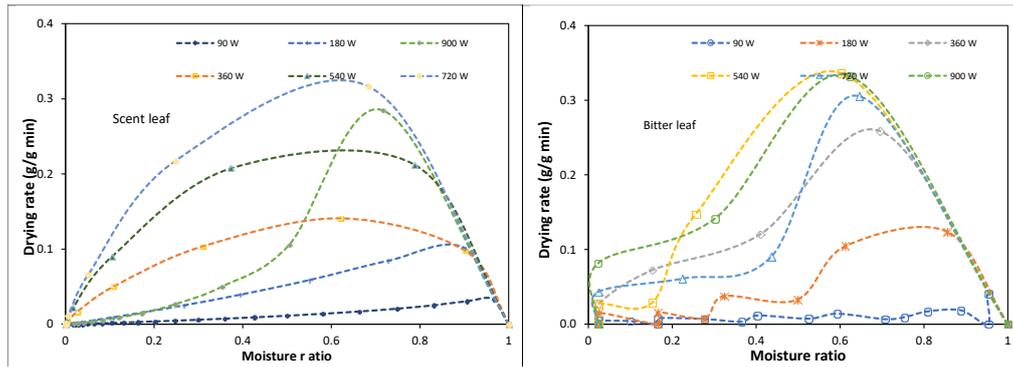


Figure 3: Drying rate vs moisture ratio at various microwave powers

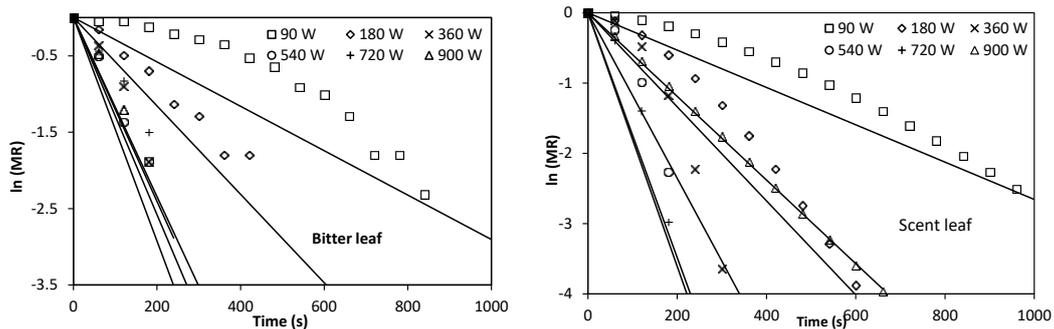


Figure 4: Microwave power effect on samples drying dependence on MR logarithmic scale

Figure 3 shows the relationship between moisture ratio and drying rate for scent and bitter leaf at the different power levels. At higher power settings, the drying rate increased sharply due to enhanced heat and mass transfer at the start of the process. However, the rate gradually declined with decreasing moisture ratio. This behaviour is explained by material shrinkage and the corresponding reduction in porosity, which increases resistance to moisture migration. These results agree with those reported by Doymaz *et al.* (2015).

Effective Moisture Diffusivity

To understand the mass transfer mechanism of the leaves under varying microwave output powers, the effective moisture diffusivity (D_{eff}) was determined from the drying kinetics. This was computed from the slopes of the plots of the natural logarithm of the moisture ratio ($\ln MR$) against drying time for each microwave power level. Figure 4 illustrates the relationship between $\ln MR$ and drying time for different microwave output powers. Although the plots show an overall linear trend, the relationship is not strictly linear across all power levels.

Table 2 presents the calculated effective moisture diffusivity values (D_{eff}), along with the corresponding coefficients of determination (R^2) and standard errors (SE) based on Equation (5). The results indicate that increasing the microwave power led to a marked increase in D_{eff} , as shown in Figure 5. This increase can be attributed to the intensified

activity of water molecules, driven by higher energy absorption, which enhanced moisture mobility and diffusion.

The effective moisture diffusivity values for microwave drying ranged from 7.67×10^{-11} to 1.84×10^{-9} m^2/s for scent leaf and from 9.21×10^{-11} to 1.54×10^{-9} m^2/s for bitter leaf. These findings are comparable to the range of 7.899×10^{-10} to 2.168×10^{-10} m^2/s reported by Demirhan and Özbek (2010) for microwave-dried basil leaves. However, the values were significantly higher than the 6.44×10^{-12} m^2/s reported by Akpınar (2006) for sun-dried basil leaves, highlighting the improved diffusivity associated with microwave heating.

Further agreement was observed with studies by Bakal *et al.* (2011), Lin *et al.* (2005), Aghbashlo *et al.* (2011), McMinn *et al.* (2003) and Khraisheh *et al.* (1997), who reported effective diffusivity values ranging from 5.612×10^{-9} to 1.317×10^{-8} m^2/s for fluidised bed dried potatoes; 4.606×10^{-6} to 7.065×10^{-6} m^2/s for far-infrared freeze-dried sweet potato cubes; 3.17×10^{-7} to 15.45×10^{-7} m^2/s for continuous band thin-layer dried carrot cubes; and 2.90×10^{-8} to 5.36×10^{-8} m^2/s for convective, microwave and combined dried potato cylinders. The reported values fall within the general range of 10^{-9} to 10^{-11} m^2/s typically observed for food materials.

The linear relationship between microwave power and effective moisture diffusivity for scent and bitter

Table 2: The estimated effective moisture diffusivity and statistical analysis of linear model at various microwave output powers

Sample	Power (W)	Slope	$D_{eff} \cdot 10^{-10} \text{ (m}^2/\text{s)}$	R^2	σ
Scent leaf	90	0.003	0.767	0.973	0.090
	180	0.007	4.488	0.971	0.080
	360	0.012	10.856	0.900	0.087
	540	0.017	14.574	0.916	0.070
	720	0.018	16.885	0.939	0.077
	900	0.027	18.445	0.998	0.083
Bitter leaf	90	0.004	0.921	0.906	0.556
	180	0.006	4.396	0.917	0.445
	360	0.009	9.606	0.912	1.143
	540	0.012	12.466	0.948	1.071
	720	0.014	14.200	0.895	0.536
	900	0.015	15.355	0.864	2.476

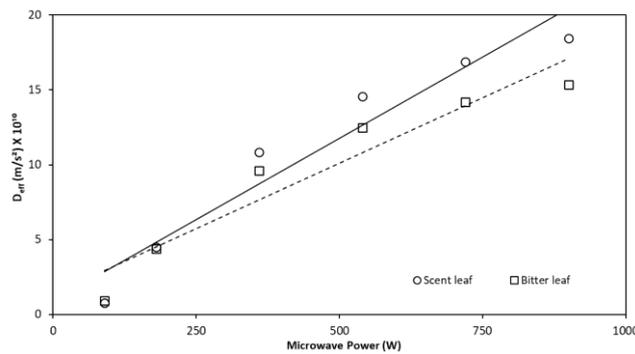


Figure 5: The effective diffusivity values for microwave drying

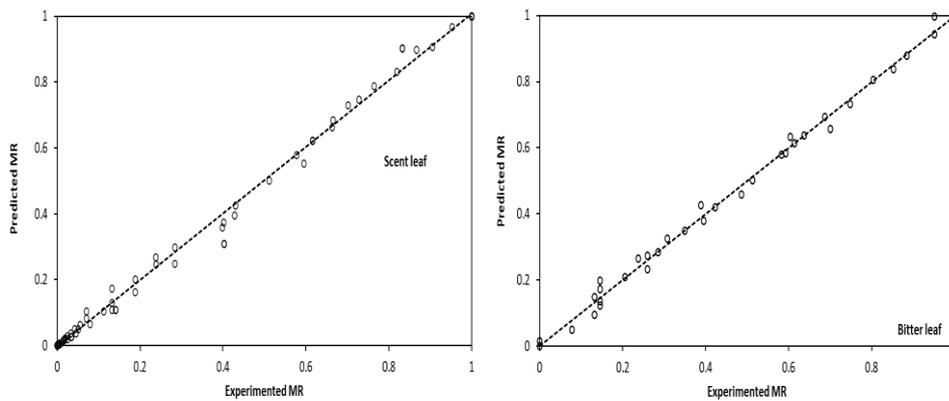


Figure 6: Predicted and experimentally observed moisture ratio values for both leaf types

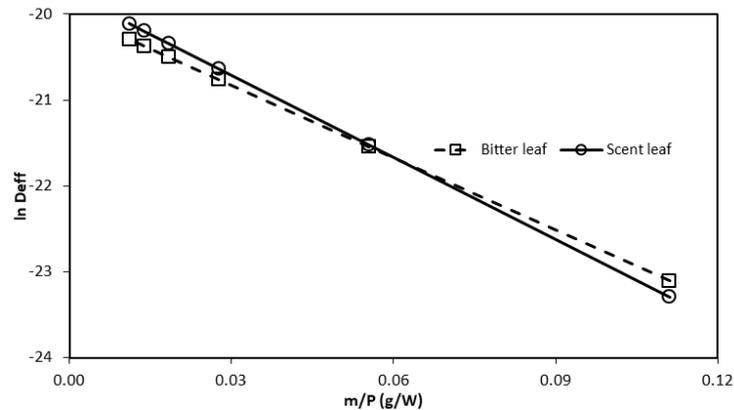


Figure 6: The $\ln(D_{eff})$ - amount/power Arrhenius relationship for the samples

respectively (Figure 7).

$$D_{eff} = 2.17 \times 10^{-12}(P) + 8.9 \times 10^{-11} \quad (R^2=0.9322) \quad (13)$$

$$D_{eff} = 1.75 \times 10^{-12}(P) + 1.35 \times 10^{-10} \quad (R^2=0.9322) \quad (14)$$

The estimated model parameters and the corresponding statistical performance indices under each drying condition are summarised in Tables 3 and 4. For scent leaf, the Midilli *et al.* (2002) model yielded R² values ranging from 0.9905 to 1.0000, RMSE between 0 and 3.03 × 10⁻², SSE from 0 to 0.74 × 10⁻², and NRMSE between 0 and 3.40 × 10⁻².

Table 3: Curve fitting criteria for the thin-layer models of Scent leaves

Microwave power	Thin-layer model	Statistical parameter			
		SSE	R ²	RMSE	NMRSE
90	Lewis	0.0920	0.9745	0.0736	0.0816
	Page	0.0047	0.9972	0.0167	0.0185
	Henderson and Pabis	0.0602	0.9659	0.0595	0.0587
	Two_term exp.	0.0920	0.9745	0.0736	0.0728
	Logarithmic	0.0105	0.9935	0.0249	0.0221
	Verma <i>et al</i>	0.0085	0.9949	0.0224	0.0222
	Midili <i>et al</i>	0.0036	0.9978	0.0145	0.0144
180	Lewis	0.0447	0.9609	0.0748	0.0921
	Page	0.0079	0.9901	0.0314	0.0387
	Henderson and Pabis	0.0370	0.9551	0.0680	0.0778
	Two_term exp.	0.0447	0.9609	0.0748	0.0852
	Logarithmic	0.0115	0.9852	0.0380	0.0424
	Verma <i>et al</i>	0.0103	0.9870	0.0358	0.0408
	Midili <i>et al</i>	0.0074	0.9905	0.0303	0.0340
360	Lewis	0.0943	0.8747	0.1374	0.1536
	Page	0.0254	0.9609	0.0713	0.0797
	Henderson and Pabis	0.0867	0.8646	0.1317	0.1421
	Two_term exp.	0.0943	0.8747	0.1374	0.1426
	Logarithmic	0.0189	0.9689	0.0615	0.0582
	Verma <i>et al</i>	0.0405	0.9375	0.0900	0.0934
	Midili <i>et al</i>	0.0004	0.9993	0.0090	0.0092
540	Lewis	0.0634	0.9367	0.1126	0.1259
	Page	0.0021	0.9975	0.0206	0.0230
	Henderson and Pabis	0.0581	0.9302	0.1078	0.1157
	Two_term exp.	0.0634	0.9367	0.1126	0.1180
	Logarithmic	0.0146	0.9803	0.0541	0.0548
	Verma <i>et al</i>	0.0076	0.9915	0.0389	0.0408
	Midili <i>et al</i>	0.0017	0.9982	0.0179	1.5769
720	Lewis	0.0407	0.9432	0.1008	0.1164
	Page	0.0042	0.9935	0.0323	0.0373
	Henderson and Pabis	0.0387	0.9393	0.0983	0.1109
	Two_term exp.	0.0407	0.9432	0.1008	0.1117
	Logarithmic	0.0011	0.9981	0.0165	0.0179
	Verma <i>et al</i>	0.0071	0.9891	0.0422	0.0467
	Midili <i>et al</i>	0.0000	0.9989	0.0000	0.0000
900	Lewis	0.0029	0.9961	0.0190	0.0226
	Page	0.0027	0.9963	0.0184	0.0219
	Henderson and Pabis	0.0028	0.9961	0.0189	0.0223
	Two_term exp.	0.0029	0.9961	0.0190	0.0225
	Logarithmic	0.0028	0.9961	0.0188	0.0221
	Verma <i>et al</i>	0.0028	0.9962	0.0186	0.0220
	Midili <i>et al</i>	0.0025	0.9965	0.0178	0.0210

Modelling of Drying Curve

The drying kinetics of scent and bitter leaves were evaluated using seven widely accepted thin-layer drying models across the range of applied microwave output powers. Among these, the Midilli *et al.* (2002) model provided the best fit for the experimental data. This was based on its consistently higher values of the coefficient of determination (R²), as well as lower values of normalised root mean square error (NRMSE), sum of squared errors (SSE), and root mean square error (RMSE), when compared with other tested models.

Similarly, for bitter leaf, the model achieved R² values between 0.9930 and 1.0000, RMSE from 0 to 2.62 × 10⁻², SSE within 0 to 1.03 × 10⁻², and NRMSE ranging from 0 to 2.53 × 10⁻².

Figure 6 illustrates the agreement between the predicted and experimentally observed moisture ratio values for both leaf types. The results demonstrate high predictive accuracy, with degrees of agreement of 99.81% for scent leaf and 99.65% for bitter leaf.

Figure 4: Curve fitting criteria for the thin-layer models of bitter leaves

Microwave power	Thin-layer model	Statistical parameter				Model constants			
		SSE	R2	RMSE	NMRSE	a	b	c	d
90	Lewis	0.1866	0.9292	0.1115	0.1252	0.0974			
	Page	0.0089	0.9945	0.0244	0.0274	0.0101	2.0513		
	HSP	0.1343	0.9128	0.0946	0.0980	0.1148	1.1415		
	Two_term exp.	0.1866	0.9292	0.1115	0.1085	1.0000	0.0974		
	Logarithmic	0.0210	0.9856	0.0375	0.0318	46.3116	0.0016	-45.2409	
	Verma <i>et al</i>	0.0312	0.9799	0.0456	0.0444	20.6726	0.2455	0.2610	
	Midili <i>et al</i>	0.0103	0.9930	0.0262	0.0253	0.9871	-0.1600	-0.1605	0.6303
360	Lewis	0.0138	0.9869	0.0415	0.0519	0.2665			
	Page	0.0048	0.9935	0.0244	0.0306	0.1959	1.2343		
	HSP	0.0108	0.9856	0.0367	0.0413	0.2800	1.0455		
	Two_term exp.	0.0138	0.9869	0.0415	0.0493	0.9997	0.2665		
	Logarithmic	0.0078	0.9893	0.0312	0.0352	1.1759	0.2154	-0.1481	
	Verma <i>et al</i>	0.0035	0.9952	0.0209	0.0248	1.1645	0.3148	11.1196	
	Midili <i>et al</i>	0.0038	0.9948	0.0217	0.0257	1.0034	0.1927	0.0093	1.3461
540	Lewis	0.0316	0.9650	0.0794	0.0888	0.5362			
	Page	0.0041	0.9944	0.0286	0.0320	0.3361	1.6152		
	HSP	0.0294	0.9614	0.0766	0.0829	0.5566	1.0436		
	Two_term exp.	0.0316	0.9650	0.0794	0.0851	0.9997	0.5362		
	Logarithmic	0.0019	0.9971	0.0195	0.0204	1.8168	0.2082	-0.8079	
	Verma <i>et al</i>	0.0066	0.9915	0.0363	0.0388	12.2193	1.1036	1.2095	
	Midili <i>et al</i>	0.0006	0.9991	0.0110	0.0118	0.9985	0.3159	-0.0341	1.3444
600	Lewis	0.0118	0.9862	0.0486	0.0544	0.6595			
	Page	0.0027	0.9959	0.0233	0.0261	0.5313	1.3574		
	HSP	0.0112	0.9851	0.0474	0.0518	0.6721	1.0231		
	Two_term exp.	0.0118	0.9862	0.0486	0.0532	0.9999	0.6595		
	Logarithmic	0.0037	0.9944	0.0271	0.0293	1.1847	0.4730	-0.1772	
	Verma <i>et al</i>	0.0027	0.9959	0.0233	0.0254	12.7051	1.2286	1.3195	
	Midili <i>et al</i>	0.0024	0.9963	0.0220	0.0240	1.0016	0.5277	-0.0079	1.2678
700	Lewis	0.0223	0.9696	0.0484	0.0746	0.5145			
	Page	0.0113	0.9821	0.0459	0.0531	0.3857	1.3600		
	HSP	0.0215	0.9677	0.0456	0.0723	0.5266	1.0253		
	Two_term exp.	0.0223	0.9696	0.0536	0.0728	0.9998	0.5145		
	Logarithmic	0.0018	0.9971	0.0445	0.0197	1.8002	0.1954	-0.8118	
	Verma <i>et al</i>	0.0121	0.9812	0.0371	0.0537	11.2085	0.9169	0.9852	
	Midili <i>et al</i>	0.0000	1.0000	0.0480	0.0020	1.0000	0.1734	-0.2026	0.1451
900	Lewis	0.0287	0.9582	0.0848	0.0979	0.6572			
	Page	0.0062	0.9897	0.0395	0.0456	0.4555	1.6570		
	HSP	0.0276	0.9556	0.0831	0.0943	0.6748	1.0315		
	Two_term exp.	0.0287	0.9582	0.0848	0.0949	0.9999	0.6572		
	Logarithmic	0.0000	1.0000	0.0007	0.0008	2.7041	0.1538	-1.7042	
	Verma <i>et al</i>	0.0000	1.0000	0.0009	0.0010	7.2998	0.1053	0.0562	
	Midili <i>et al</i>	0.0000	1.0000	0.0000	0.0000	1.0000	0.2746	-0.1463	0.9998

Figure 5: Energy indices for the samples

Sample	Power (W)	Specific energy consumption (MJkg ⁻¹)	Drying efficiency (%)
Bitter leaf	90	2.65	75.00
	180	5.29	91.67
	360	11.02	96.77
	540	16.52	97.30
	720	21.60	97.14
	900	24.82	98.18
	Scent leaf	90	4.09
180		5.29	95.65
360		11.02	96.88
540		16.52	97.14
720		14.40	95.65
900		13.23	94.44

Activation Energy

A modified form of the Arrhenius equation was employed to estimate the activation energy and to

characterise the relationship between the drying rate constant and the ratio of microwave output power to sample mass, in lieu of temperature. This

formulation was adapted from the approach proposed by Dadali *et al.* (2007a, 2007b), which allows for the evaluation of effective moisture diffusivity and drying rate constants under microwave drying conditions at varying sample masses and power levels.

For scent leaf, the calculated activation energy (E_a) was 31.801 W/g. The estimation was obtained from the linear regression of the natural logarithm of effective moisture diffusivity ($\ln D_{eff}$) plotted against the mass-to-power ratio, expressed as m/P (g/W). The plot showed a strong linear relationship across the microwave power range studied, confirming an Arrhenius-type dependence.

Accordingly, the slope of the regression line represents the negative activation energy ($-E_a$), while the intercept corresponds to the natural logarithm of the pre-exponential factor ($\ln D_0$). The generalised expression is presented in Equation 15 while the specific expressions are presented in Equations 16-17.

$$D_{eff} = D_0 \exp\left(-\frac{E_a m}{P}\right) \quad (15)$$

The specific expressions derived for the leaf samples are as follows:

$$D_{eff} = 2.63 \times 10^{-9} \exp\left(-\frac{31.801m}{P}\right) \quad (16)$$

$$D_{eff} = 2.10 \times 10^{-9} \exp\left(-\frac{28.141m}{P}\right) \quad (17)$$

From the above equations, the estimated values of the pre-exponential factor (D_0) and activation energy (E_a) are $2.63 \times 10^{-9} \text{ m}^2/\text{s}$ and 31.801 W/g for scent leaf, and $2.10 \times 10^{-9} \text{ m}^2/\text{s}$ and 28.141 W/g for bitter leaf, respectively.

The specific energy consumption and drying efficiency values for both leaf types under varying microwave power conditions are reported in Table 5. For bitter leaf, specific energy consumption increased from 2.89 to 24.82 MJ/kg as microwave power increased from 90 to 900 W. For scent leaf, values ranged from 4.09 to 13.23 MJ/kg over the same power range. In contrast, drying efficiency improved with increasing microwave power: from 75.00% to 98.10% for bitter leaf, and from 81.82% to 97.14% for scent leaf. However, at excessively high-power levels, reduced microwave absorption likely contributed to slightly lower efficiencies, as shown in Table 5.

Conclusions

Microwave thin-layer drying significantly accelerated the dehydration of *Ocimum gratissimum* and *Vernonia amygdalina*, reducing processing time from approximately 19 minutes at 90 W to as low as 4 minutes at 720–900 W. At the highest power levels, energy efficiency exceeded 97%. Drying proceeded entirely within the falling-rate period, and the Midilli model most accurately represented the experimental moisture ratio data, with a mean

coefficient of determination (R^2) of approximately 0.995.

Effective moisture diffusivity increased by an order of magnitude across the tested microwave power range. The estimated apparent activation energies were 32 W/g for scent leaf and 28 W/g for bitter leaf, values that fall within the established range for leafy herbal materials. Specific energy consumption was reduced to as low as 4 MJ/kg of water removed, resulting in operational energy costs approximately one-third of those associated with conventional hot-air drying systems.

The optimal microwave power range was 540–720 W for scent leaf, which prevented case hardening, and 720–900 W for bitter leaf. The drying kinetics and energy parameters established in this study provide a practical framework for designing efficient, industrial-scale microwave dryers aimed at the rapid and cost-effective preservation of nutraceutical herbs.

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