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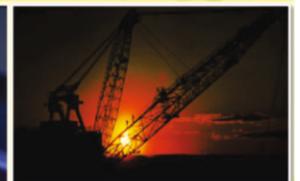
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Modelling of Thin-Layer Microwave Drying of Bitter Leaf Samples (*Vernonia Amygdalina*) For Preservation

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A B S T R A C T

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The thin-layer drying characteristics of bitter leaf (*Vernonia amygdalina*) was investigated over a microwave power settings range between 90 and 900 W. The effect of microwave power from the experiment affected the samples drying behaviours. The process of microwave drying of the samples occurred in the falling-rate period. The drying rate increased as the drying microwave power increased, and the drying process time decreased with the increase in the microwave power. The total drying time decreased from 3 minutes to 15 seconds with microwave power increase. Seven mathematical thin-layer drying models were applied to the experimental drying data The Midilli *et al.* model was adjudged the best as it adequately gave the best results and showed good consistency with the data obtained from the experiments over the microwave power range with result values of $0.9930 < R^2 < 1$, $0.000 \times 10^{-2} < RMSE < 4.80 \times 10^{-2}$, $0.000 \times 10^{-2} < SSE < 1.03 \times 10^{-2}$ and $0.000 \times 10^{-2} < NRMSE < 2.57 \times 10^{-2}$. The moisture ratio of the samples during the drying processes decreased with microwave power increase and effective moisture diffusivity coefficients values of the samples across the microwave output power using Fick's second law of diffusion varied from $2.30138 \times 10^{-8} m^2/s$ to $9.69307 \times 10^{-8} m^2/s$. The activation energy obtained from the Arrhenius type equation was found as 6.8545 kW/kg.

1. Introduction

Vernonia amygdalina is a well-known local average sized shrub plant characterised with relative bitter principle in all parts. It majorly finds its place as the main ingredient in 'bitter leaf soup' because of its therapeutic functions and nutritional values. The major constituents of its extracts include alkaloids, saponins, tannins, flavonoids, proteins, vitamins and minerals (Akah *et al.*, 2004). Malaria and stomach disorders remedy are few of its numerous uses. It is one of those plants or herbs whose nutraceuticals and natural plant foods consumption, and nutritional therapy and phytotherapy use bring about health improvement and diseases prevention and (Olaiya *et al.*, 2013). In traditional medicine, its leaves are prepared as one of the major ingredients in diabetes and impotency cure. Its safe use (liquid extracts, fresh, dried and powder forms) in medicine

is known, however, its preservation requires more attention (Akah *et al.*, 2002).

Drying is considered the oldest mean of preserving agricultural products. It retains crops' quality and quantity for a long period of time depending on the type of crops with reduced crops moisture content and increased shelf-life when compared to fresh fruits, vegetables and aquatic products. Moreover, to achieve effective drying of products, divers mechanisms through several drying methods such as solar drying, mechanical drying, oven drying and air drying are employed (Jiang *et al.*, 2015; Bennamoun *et al.*, 2016). Some of these drying techniques have the limitations of high-energy consumption, high time utilisation and direct heat penetration into food material, which destroys certain food properties.

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follows a diffusive pattern, and negligible sample shrinkage. Therefore, the analytical solution of the diffusion equation (4) for an infinite slab with constant diffusivity if appropriate initial and boundary conditions was applied can be used to determine the moisture ratio in equation (5) (Celma *et al.*, 2008 and Crank, 1975).

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (5)$$

where:

D_{eff} is the effective diffusivity (m^2/s),

L is the half-thickness of the slab (m) (if drying is from both sides and the thickness of slab if drying from one side), and

n is the number of terms of the series taken into consideration.

For long drying times, only the first term ($n=0$) in the series expansion of the above equation gave good estimate of the solution with equation (5) simplified to the first term of the series (Senadeera *et al.*, 2003). Taking natural logarithm of both sides, we have equation (6):

$$\ln(MR) = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (6)$$

The diffusion coefficient for each microwave drying power was calculated using equation (6). 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 (7):

$$\text{slope}(\phi) = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

Therefore;

$$D_{eff} = \frac{4L^2 \phi}{\pi^2} \quad (8)$$

The use of equation (8) was based on constant moisture diffusivity assumption for each microwave power which predicted a linear behaviour for the dependence of logarithmic dimensionless moisture ratio on drying time. Consequently, the slope was regarded as first useful approximation to the value of the diffusivity.

Computation of activation energy

In drying process via microwave oven since temperature is not the only measurable quantity, the activation energy could be obtained from modified Arrhenius equation as provided in Dadali *et al.* (2007), where the relationship between the effective moisture

diffusivity and the microwave power to sample weight was shown. The equation is given in equation (9)

$$D_{eff} = D_o \exp\left(\frac{-E_a m}{P}\right) \quad (9)$$

where:

D_o – pre-exponential factor of Arrhenius equation (m^2/s);

E_a – activation energy (W/kg);

P – microwave power (W);

m – sample weight (kg)

Statistical analysis

The behaviour of the samples during the processes was observed by plotting the moisture ratio against the drying time. The experimental data were fitted to seven of the most widely used thin-layer mathematical models (Table 1) to describe the kinetics of the drying process. Non-linear regression techniques of Statistica v. 12.5 (StatSoft Inc., Tulsa, USA) and Excel 2016 (Microsoft Inc.) were deployed in this study to adequately fit the thin-layer drying models used (as presented in Table 1).

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

Models	Analytical equation	Reference
Lewis	$MR = \exp(-at)$	McMinn (2006)
Page	$MR = \exp(-at^b)$	Kaleemullah and Kailappan, (2006)
HSP	$MR = b \exp(-at)$	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>	$MR = a \exp(-bt^d) + ct$	Sacilik <i>et al.</i> , (2006)

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

The best description of the variation in the moisture ratio values of dried bitter leaf was determined using the mathematical models in Table 1. Statistical parameters (coefficient of determination, R^2 ; normalized root mean square error, $NRMSE$; sum of square of residuals, SSE and root mean square error, $RMSE$) of the mathematical models were calculated and used to evaluate the fitting of each model to experimental data. The higher values of the coefficient of determination (R^2) and the lower values of the reduced normalized root mean square error ($NRMSE$), sum of square of residuals (SSE) and root mean square error ($RMSE$) were chosen for goodness of fit (Midilli *et al.*, 2007). These parameters were calculated using equations (10) to (13)

The introduction of microwave mechanism was such that electromagnetic radiation in the frequency range of 300 MHz to 300 GHz with a wavelength range of 1 m to 1 mm could enhance drying efficiency via creation of penetrating heating effect from the source into the materials. The wide range of application of this technique has found its place in the food, cosmetic, pharmaceutical, medical and wood industries (Feng *et al.*, 2012; Zhang *et al.*, 2007).

Microwave drying has been found an effective drying technique consequent upon several research inputs which in the recent past been directed into the drying of foods and other products. Some of the research works include the drying of apple (Wu *et al.*, 2014), cabbage (Duan *et al.*, 2013), instant mixed vegetable soup (Wang *et al.*, 2010), potato (Wang *et al.*, 2011; Wang *et al.*, 2013), stem lettuce slices (Wang *et al.*, 2013), potato chips (Su *et al.*, 2015), and sea cucumber (Duan *et al.*, 2007).

This study therefore investigates the microwave drying characteristics of bitter leaf using microwave-drying technique across power output range of 90 and 900 W; and model the drying characteristics using seven thin-layer mathematical drying models.

2. Materials and Methods

Materials

Fresh bitter leaf samples were obtained from a farm in Akure, South-West Nigeria. The samples were cleaned, washed and put into low-density plastic bags and kept in a refrigerator (Haier Thermocool; HR 177, Nigeria) at a temperature of 4 °C for a day. The samples were removed from the refrigerator before the drying experiments commenced to allow for equilibration with the ambient temperature. The sample's initial moisture content was 85.64 ± 1.27 (kg water/kg dry matter) using the AOAC moisture content determination method (AOAC 1990).

Microwave drying experiment

A domestic microwave oven (Sanyo EM-G4753 model) with drying chamber volume of 530 x 500 x 322 mm³ and a 300 mm diameter rotating glass plate was used for the drying experiment. The microwave output powers and operation time were controlled via an embedded digital control. The environmental conditions under which the experiments were conducted in the laboratory were 24 – 28 °C for ambient temperature and 76 – 83 % relative humidity.

A fresh sample of 10 ± 0.2 g of bitter leaf sample was placed into the microwave oven with sample thickness, 0.50 ± 0.06 mm

programmed at microwave drying powers of 90, 180, 360, 540, 720 and 900 W. The samples were evenly spread over the glass tray. The mass of the sample was intermittently recorded at 30 s interval until there was no significant decrease in the mass. The experiments were conducted in triplicate and the average values of the moisture content were utilised for further analyses.

$$M_t = \frac{m_w - m_d}{m_w} \quad (1)$$

where:

M_t is the moisture content (kg water/kg wet matter),

m_w is the wet mass of sample at any time, t (g), and

m_d is the corresponding dry mass of the sample (g)

The drying rate was defined by equation (2) as:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

where

$M_{t+\Delta t}$ is moisture content at time $t + \Delta t$ (kg water/kg wet matter),

t is the time (min) and

DR is the drying rate (kg water/kg wet matter.min).

The experimental data from the different drying runs were expressed in terms moisture ratio, drying time and drying rate.

Mathematical modelling of drying curves

The dimensionless moisture ratio, MR was estimated using equation (3) as suggested by Midilli *et al.*, (2007) for the drying microwave power settings of 90, 180, 360, 540, 720 and 900 W from the moisture content values obtained.

$$MR = \frac{M_t - M_{\infty}}{M_0 - M_{\infty}} \quad (3)$$

where:

M_t is the moisture content at any given time,

M_0 is the initial moisture content, and

M_{∞} is the equilibrium moisture content.

Determination of moisture diffusivity

Fick's second diffusion equation presented main a

mass-diffusive mechanism as expressed in equation (4):

$$\frac{\Delta M}{\Delta t} = D_{eff} \frac{\Delta^2 M}{\Delta r^2} \quad (4)$$

If the moisture movement by thermal gradient within the thin slab is neglected, the moisture transfer can be considered as a one-dimensional diffusion process in the upward direction from the bottom of the sample towards the top surface. The other assumptions involved for diffusion analysis are that the sample presents a uniform initial moisture content, the moisture movement

$$R^2 = \frac{\sum_{i=1}^N (\overline{MR}_{exp} - MR_{pre,i}) \sum_{i=1}^N (\overline{MR}_{exp} - MR_{exp,i})}{\sqrt{[\sum_{i=1}^N (MR_{exp} - MR_{pre,i})^2][\sum_{i=1}^N (MR_{exp} - MR_{exp,i})^2]}} \quad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (11)$$

$$NRMSE = \sqrt{\frac{1}{N} \left(\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{MR_{exp,max} - MR_{exp,min}} \right)} \quad (12)$$

$$SSE = \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \quad (13)$$

where;

- $MR_{exp,i}$ is the i th experimentally observed moisture ratio,
- $MR_{pre,i}$ is the i th predicted moisture ratio,
- N is the number of observations,
- $MR_{exp,max}$ is the maximum experimentally observed moisture ratio, and
- $MR_{exp,min}$ is the minimum experimentally observed moisture ratio.

3. Results and Discussion

The effect of microwave output powers on the moisture content, moisture ratio, drying rate and drying time of bitter leaf were studied. The plot of drying curves of bitter leaf samples at various microwave power settings is shown in Figure 1. The effect of microwave output power on the moisture ratio of bitter leaf from the moisture ratio versus drying time curves showed that the moisture ratio decreased with increased drying time with all the microwave powers. However, the drying process followed a falling rate pattern with rapid decrease in the moisture ratio at the higher microwave powers. The change in the moisture ratio became more rapid at higher microwave powers and steady at lower microwave powers. Also observed is the gradual change in the shape of the curves from inverted sigmoid shape at lower power settings to upward convex shape at lower power shape. This is similar to the trend observed by Miano and Augusto (2015) in the hydration study of adzuki beans.

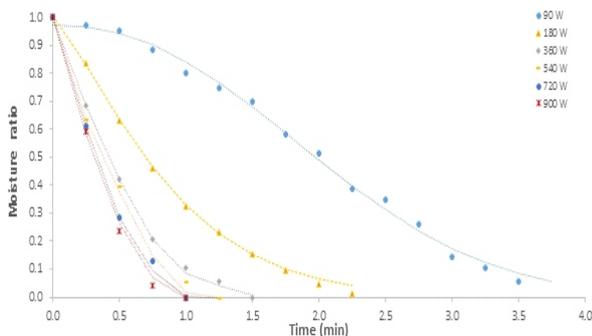


Figure 1 Drying curves of bitter leaf samples at various microwave power settings

The times required to dry bitter leaf samples from initial moisture content of 87.76 ± 1.25 (kg water/kg wet matter) to the final moisture content of 6.67 ± 0.98 (kg water/kg wet matter) were 3.75, 2.50, 2.50, 1.25, 1.00 and 0.75 minutes at 90, 180, 360, 540, 720 and 900 W respectively. The drying microwave power produced a significant effect on the drying time. Because of microwave volumetric heating characteristics, the samples created a significantly high vapour pressure difference between the centre and the surface of the samples, thus the mass transfer of samples was more rapidly at higher microwave power heating because more heat was generated

The drying time of samples decreased as the microwave output power increased and the microwave-drying processes took 0.75 minutes to 3.75 minutes to dry the samples. The drying time was reduced by 75 % at 900 W. From the experimental plot it was revealed that during microwave drying of bitter leaves, there was no constant rate period observed and the drying only took place in the falling period as internal liquid diffusion controls all through. It was obvious that the drying time was governed by the internal opposition to mass transfer as it occurred through falling rate period.

The drying rate (DR) was expressed as the amount of the evaporated moisture ratio over time. Figure 2 presented the change in the DR against the drying time of bitter leaf samples at different drying microwave powers. Drying rate periods were observed for all the microwave powers as the DR decreased with time with decreasing moisture content. The drying process followed a falling rate pattern. The DR was also observed to increase as microwave power increased thus the total drying time also reduction as the microwave power increased.

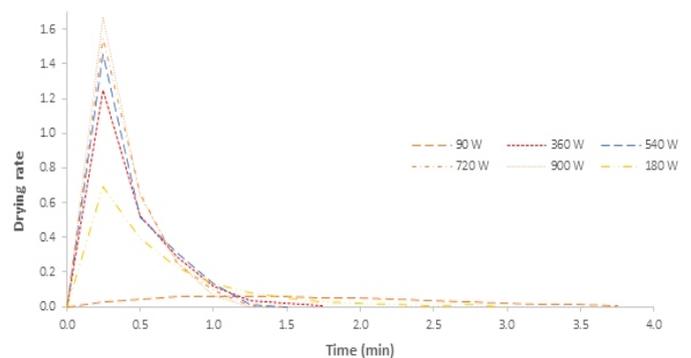


Figure 2 Microwave power effect on the drying rate of the bitter leaf sample

In Figure 2, the drying rate of bitter leaf samples changed with increased drying time across various microwave power drying conditions. As the microwave power levels increased, the drying rates also increased with maximum DR drying rates 0.0605, 0.6891, 1.2534, 1.4534, 1.5456 and 1.6680 kg water/kg dry matter. min, at the applied microwave powers of 90, 180, 360, 540, 720 and 900 W respectively. The initial phase of the drying revealed that the DR and absorption of microwave power was consequent upon high moisture diffusion, which leave high drying effect. Moisture loss with respect to time presented a decrease in microwave power absorption during the process, which consequently led to a fall in the DR.

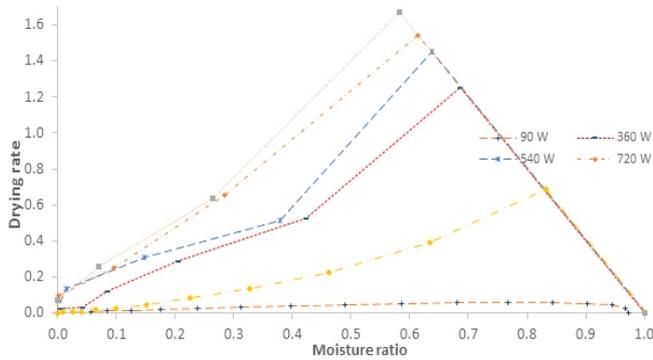


Figure 3. Drying rate curves of bitter leaf at various microwave powers

Figure 3 shows the drying rate curves of bitter leaf at various microwave powers. From Figure 3, the drying rates increased as microwave power increased, implying that at higher power heat and mass transfer is high and excessive water loss. At the beginning of the drying process in the samples the drying rates were higher, and afterward they decreased with moisture content decrease. This is because of reduced porosity and increased shrinkage in the samples and that account for increased resistance to water movement which consequently resulted in further fall in drying rates (Doymaz *et al.*, 2015).

Figure 4 shows the samples drying dependence on MR logarithmic scale at various microwave powers. The experimental drying dependence though is not strictly linear on a logarithmic scale as shown in the figure.

The effective moisture diffusivity

The values of D_{eff} increased with increasing microwave power as shown in Figure 5. The increased heating energy increased the water molecules activity thus leading to higher moisture diffusivity. The determined values of D_{eff} were 2.30138×10^{-8} , 4.87917×10^{-8} , 8.148×10^{-8} , 6.9883×10^{-8} , 8.6694×10^{-8} and $9.69307 \times 10^{-8} m^2/s$ for microwave drying powers of 90, 180, 360, 540, 720 and 900 W respectively.

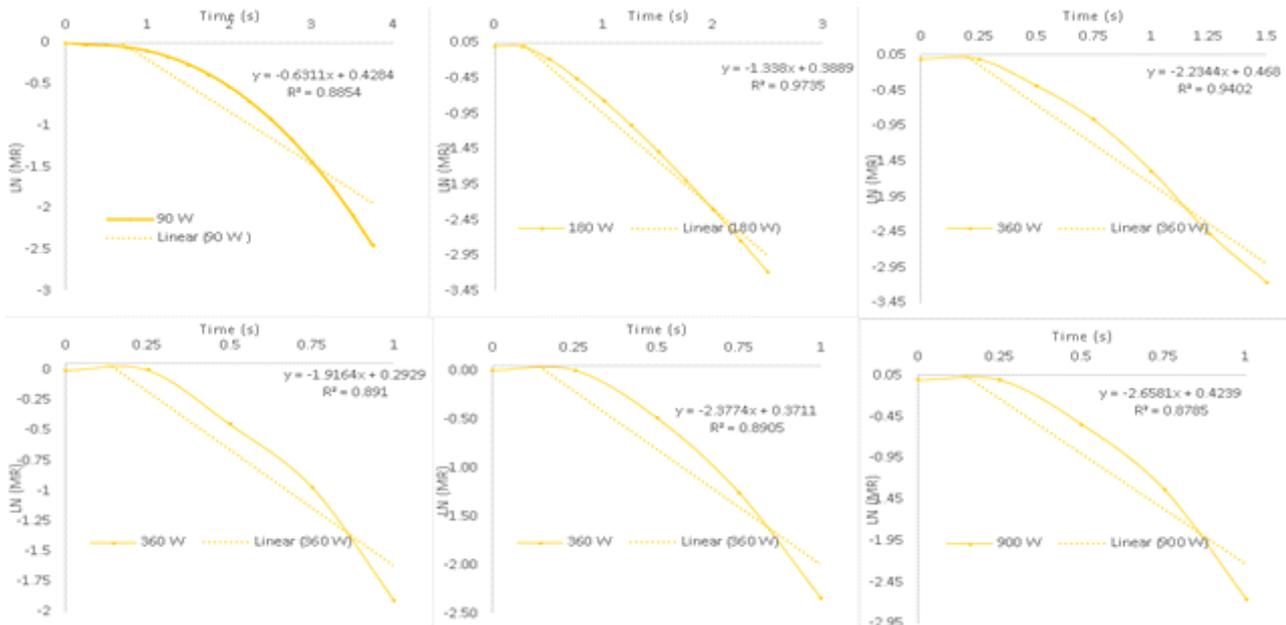


Figure 4 Microwave power effect on samples drying dependence on MR logarithmic scale

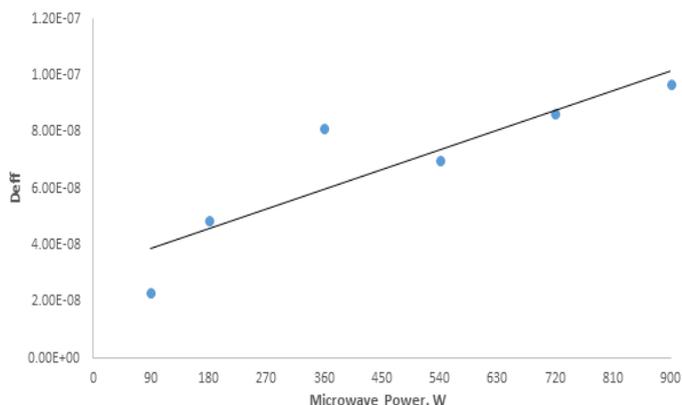


Figure 5 The effective diffusivity values for microwave drying of bitter leaf

This agreed with the findings of Bakal *et al.* (2011), Lin *et al.* (2005), Aghbashlo *et al.* (2011), McMinn *et al.* (2003) and Khraishah *et al.* (1997) who obtained 5.612×10^{-9} to $1.317 \times 10^{-8} \text{ m}^2/\text{s}$, 4.606×10^{-6} to $7.065 \times 10^{-6} \text{ m}^2/\text{s}$, 3.17×10^{-7} to $15.45 \times 10^{-7} \text{ m}^2/\text{s}$ and 2.90×10^{-8} to $4.88 \times 10^{-8} \text{ m}^2/\text{s}$, 7.04×10^{-8} to $24.22 \times 10^{-8} \text{ m}^2/\text{s}$, and 3.15×10^{-8} to $5.36 \times 10^{-8} \text{ m}^2/\text{s}$ for fluidized bed dried potatoes, far-infrared freeze-dried sweet potato cubes, continuous band thin-layer dried carrot cubes and convective, microwave and combined dried potato cylinders, respectively. The general range values of D_{eff} for food materials is from 10^{-9} to $10^{-11} \text{ m}^2/\text{s}$.

The microwave power effect on the effective moisture diffusivity is defined by equation (14)

$$D_{eff} = 8 \times 10^{-11}(P) + 3 \times 10^{-9} \quad (R^2 = 0.7959) \quad (14)$$

This result is in agreement with Doymaz *et al.* (2015) findings on microwave drying of green bean slices.

The activation energy

Figure 6 shows the samples $\ln(D_{eff}) - \text{amount/power}$ Arrhenius relationship. From Figure 6, the estimated activation energy, E_a was obtained from the plot of natural logarithm

of D_{eff} against sample $\frac{\text{amount}}{\text{power}} \left(\frac{\text{m}}{\text{p}} \right)$.

A straight line relationship between the two variables was observed in the studied microwave power range, which indicated Arrhenius - type dependence. The $(-E_a)$ equals to the slope of the line and $\ln(D_0)$ equals to the intercept.

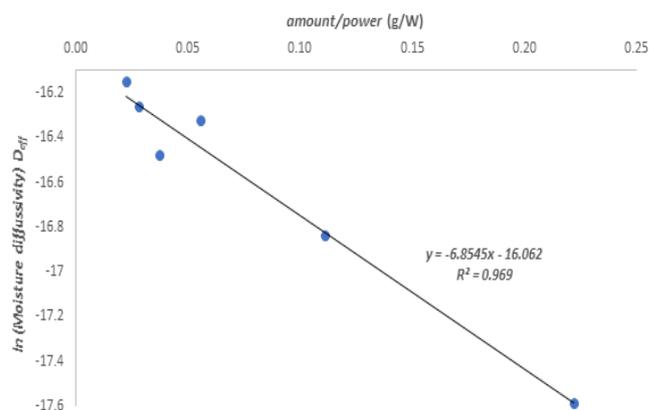


Figure 6 Samples $\ln(D_{eff}) - \frac{\text{amount}}{\text{power}}$ arrhenius relationship

Equation 15 presents the samples' $\frac{\text{weight}}{\text{microwave power}}$

effect on the D_{eff} of samples with the following coefficients:

$$D_{eff} = 1.0577 \times 10^{-7} \exp\left(\frac{6854.5m}{P}\right) \quad (R^2 = 0.969) \quad (15)$$

From the modified Arrhenius type exponential equation (14), the estimated values of D_0 and E_a are $1.0577 \times 10^{-7} \text{ m}^2/\text{s}$ and 6.8545 kW/kg , respectively.

Modelling of drying kinetics

The degree of accuracy between the observed data and predicted data was examined using the selected models. The regression analyses results are presented in Table 2. The Midilli *et al* model was adjudged the best as it described the process with the highest R^2 range value, $0.9930 < R^2 < 1$ and lowest $RMSE$, SSE and $NRMSE$ range values, $0.000 \times 10^{-2} < RMSE < 4.80 \times 10^{-2}$, $0.000 \times 10^{-2} < SSE < 1.03 \times 10^{-2}$ and $0.000 \times 10^{-2} < NRMSE < 2.57 \times 10^{-2}$ respectively.

Figure 7 shows a good agreement between the predicted and observed moisture ratio data with the coefficient of correlation, $R^2 = 0.9984$.

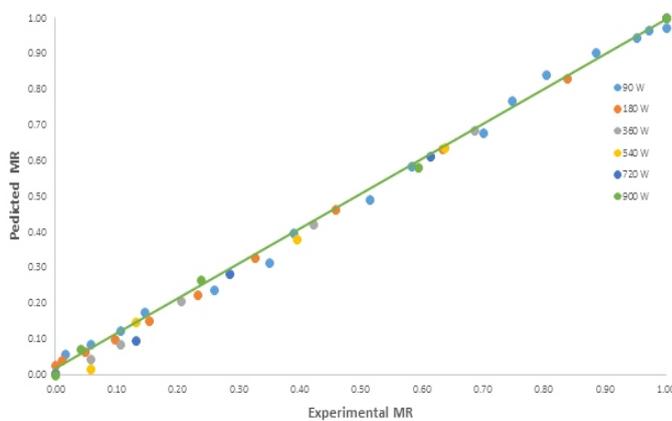


Figure 7. Experimental and predicted moisture ratio values comparison using Midilli *et al* model

Table 2 Thin-layer drying kinetics parameters of the seven models for bitter leaf samples

Microwave power	Thin-layer models	Statistical parameters				Model constants			
		SSE	R ²	RMSE	NRMSE	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	
	Midilli <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	
	Midilli <i>et al</i>	0.0038	0.9948	0.0217	0.0257	1.0034	0.1927	0.0093	1.3461
450	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	
	Midilli <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	
	Midilli <i>et al</i>	0.0024	0.9963	0.0220	0.0240	1.0016	0.5277	-0.0079	1.2678
750	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	
	Midilli <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	
	Midilli <i>et al</i>	0.0000	1.0000	0.0000	0.0000	1.0000	0.2746	-0.1463	0.9998

4. Conclusions

The thin-layer drying characteristics of bitter leaf samples were investigated in a microwave oven at various microwave powers. The process of microwave drying of the samples occurred in the falling-rate period. The drying rate increased as the drying microwave power increased, and the drying process time decreased with the increase in the microwave power. The mathematical modelling of thin-layer microwave drying of bitter leaf was investigated, using a non-linear regression. The Midilli *et al.* model was adjudged the best as it adequately gave the best results and showed good consistency with the data obtained from the experiments over the microwave power range with result values of $0.9930 < R^2 < 1$, 0.000

$\times 10^{-2} < RMSE < 4.80 \times 10^{-2}$, $0.000 \times 10^{-2} < SSE < 1.03 \times 10^{-2}$ and $0.000 \times 10^{-2} < NRMSE < 2.57 \times 10^{-2}$. The effective moisture diffusivity value of bitter leaf samples varied between 2.30138×10^{-8} and $9.69307 \times 10^{-8} m^2/s$ for the microwave power range. The activation energy was found to be 6.8545 kW/kg.

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