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Mathematical modelling and morphological properties of thin layer oven drying of *Vernonia amygdalina* leaves

O.R. Alara *, N.H. Abdurahman, O.A. Olalere

Faculty of Chemical Engineering & Natural Resources, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Pahang, Malaysia

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ABSTRACT

In this study, the oven drying behaviour, as well as changes in the morphological appearance of *Vernonia amygdalina* leaves before and after drying were investigated. The drying experiments were conducted using a universal oven. *Vernonia amygdalina* leaves were dried at 40, 50 and 60 °C air temperatures. During the drying processes, the air flow rate was held at 1 m/s^2 and the samples spread on the drying trays were placed parallel to the direction of air flow. The obtained data were fitted to eleven different mathematical drying models. Four statistical tools, viz, correlation coefficient, mean bias error, sum of the square error, and reduced chi-square were used to analyse the fittings. Amongst the considered drying models, Midilli-Kucuk drying model showed the best fitting in describing the drying behaviour of *Vernonia amygdalina* leaves. In addition, the effective diffusivities for the three air temperatures ranged from 4.55×10^{-12} to 5.48×10^{-12} m^2/s with the activation energy of 8.048 kJ/mol. Moreover, to evaluate the effect of drying conditions on the morphological changes of *Vernonia amygdalina* leaves, fresh and dried leaves under different conditions were compared. Thus, drying conditions had effects on microstructure of *Vernonia amygdalina* leaves.

1. Introduction

Bitter leaf, scientifically known as *Vernonia amygdalina* is a widely used aromatic and medicinal plant in Africa and Asia (Egharevba et al., 2014; Farombi and Owoeye, 2011; Iwalokun et al., 2006; Owen et al., 2011). The dried or fresh leaves, stems and roots of this plant are being used in food and pharmaceutical industries. In recent time, there have been increasing demands for vegetables and fruits due to their medicinal importance when compared with the synthetic medicines. *Vernonia amygdalina* leaves had been a promising plant because they possess appreciable amounts of minerals, vitamins, carbohydrates, sugar contents (glucose, sucrose, fructose, galactose, arabinose, raffinose and maltose), and proximate values (Alabi and Amusa, 2005; Toyang and Verpoorte, 2013). This plant contains a higher percentage of water and exhibit higher metabolic activity. This metabolic activity continues after harvesting, thus making most agricultural produce highly perishable (Gumus, 2015; Rosa et al., 2015; Sacilik and Elicin, 2006; Tunde-Akintunde, 2011).

Drying has been a method used in reducing the moisture content so as to increase the shelf life of vegetables and fruits. It prevents the growth of microorganism and molds. The basic importance of drying is to remove moisture from the agricultural produce to a minimum percentage that cannot allow the growth of microbes which affect the plants' bioactive compounds (Akpinar, 2006; Akpinar and Bicer, 2008). Different types of drying methods like solar, open sun, oven, cabinet, tray, freeze, spray, vacuum drying, and others are being used to elongate the shelf life of dried products. Importantly, oven drying of plant samples is being used because of the uniformity in the dried sample. Although, drying methods affect the morphology of the products being dried, whereas, studies have shown that oven air temperature below 80 °C caused no significant loss of plant nutrients (Alara et al., 2017; Mlambo et al., 2014).

Mathematical modelling of drying processes are the most important aspect of drying technology (Gunhan et al., 2005). The thin layer equations explain the drying process in a uniform way, regardless of the controlling mechanism. Several drying models including Page, Henderson and Pabis, logarithmic, Midilli and Kucuk, Newton, two-term and among others have been established

* Corresponding author.
E-mail address: ruthoalao@gmail.com (O.R. Alara).

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Nomenclature

a, b, c, g, h, n	dimensionless drying constant in drying models	MR	moisture ratio
D_{eff}	effective diffusivity (m^2/s)	N	number of terms taken into consideration
D_∞	diffusivity constant at an infinitely high temperature (m^2/s)	R	universal gas constant (8.314 J/mol K)
E_a	activation energy (kJ/mol)	R^2	correlation coefficient
k, k_o	drying velocity in drying models (1/h)	RMSE	root mean square error
L	half thickness of slab (m)	SSE	sum of the square error
M	moisture content	t	drying time (h)
M_e	equilibrium moisture content	T	absolute temperature (K)
M_o	initial moisture content	χ^2	reduced chi-square
M_t	moisture content of the sample at a particular drying time	W_1	weight of the sample before drying (g)
		W_2	weight of the sample after drying (g)

in predicting the drying behaviour of plants (Akpinar and Bicer, 2008). These equations had been used to determine the drying behaviour of different products and to generalize the drying curves (Akpinar, 2006). The models had been used in predicting the drying characteristics of different vegetables and fruits like long green pepper (Akpinar and Bicer, 2008), bay leaves (Gunhan et al., 2005), carrots (Doymaz, 2004; Zielinska and Markowski, 2007), chilli pepper (Tunde-Akintunde, 2011), black tea (Panchariya et al., 2002), barbunya bean (Kayisoglu and Ertekin, 2011), mint leaves (Doymaz, 2006), garlic (Madamba et al., 1996) and among others.

Several studies had been conducted on the drying of *Vernonia amygdalina* leaves using different drying techniques like an open sun, laboratory dryer, and air drying (Gumus, 2015; Panchariya et al., 2002; Sobukola et al., 2007). However, to the best of our knowledge, no published work seems to have been done on the drying behaviour of *Vernonia amygdalina* leaves using a universal oven (at different temperature with constant air velocity) and its effect on the morphological changes of the leaves. Thus, this study was carried out to investigate the thin layer drying behaviour of *Vernonia amygdalina* leaves using oven technique, to fit the drying data to the established mathematical drying models in literature, and to examine the effect of drying conditions on morphological changes of the leaves.

2. Materials and methods

2.1. Plant materials

Vernonia amygdalina fresh leaves were harvested from Gambang located at Latitude: 3°42′25.183″N and Longitude: 103°6′8.982″E in Pahang State, Malaysia. The leaves were manually removed from the stalks and matured leaves were selected randomly to ensure that the samples were homogenised.

2.2. Experimental procedures

The oven drying experiments were conducted using three drying temperatures (40, 50 and 60 °C) at a constant air velocity 1 m/s with 3 replicates for each treatment. The universal oven (Memmert UN55, Germany) shown in Fig. 1 was preheated to the desired temperature before loading the samples. 50 ± 1 g sample was weighed using a laboratory scale (Secura 513-1S, Brooklyn NY, readability 0.001 g). The leaves were cut into small pieces of approximately 1 cm in length. Then, the initial moisture content was determined using AOAC methods (AOAC, 1990). Briefly, the initial moisture content was determined by first weighed 5 g of the fresh sample and later weighed the sample after it has been dried for 3 h at 105 °C. Then, the initial moisture content was calculated using Eq. (1). Thereafter, the drying process kick-started by spreading the sample on a single layer of an aluminium tray, the tray was then placed in the drying chamber under selected drying conditions parallelled to air flow. The oven's door was opened at the time interval of 1 h and the sample's weight was recorded. The samples were dried until constant weight was attained. Then, water removed from the sample during the process was calculated by periodic weighing using an analytical balance. The experimental procedures were repeated thrice to obtain accurate results and thus average values were used for further analysis.

$$\textit{Initial moisture content}\ (\%) = \frac{(W_1 - W_2)}{W_1} * 100 \quad (1)$$

where W_1 is the weight of the sample before drying and W_2 is the weight of the sample after drying.

2.3. Mathematical models

The results recorded for moisture content in *Vernonia amygdalina* leaves were fitted to the 11 commonly used thin layer drying models shown in Table 1 using a non-linear regression. However, moisture ratio was calculated using Eq. (2) in place of $(M - M_e)/(M_o - M_e)$ due to the continuous fluctuation in the relative humidity during the drying processes (Akpinar, 2006; Doymaz, 2004; Doymaz, 2006; Gunhan et al., 2005; Toğrul and Pehlivan, 2003).

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

where M_t and M_o are the moisture contents of the sample at a particular drying time and initial moisture content, respectively (Akpinar, 2006; Akpinar and Bicer, 2008; Toğrul and Pehlivan, 2003). SOLVER in Microsoft Excel 2013® was used to fit the experimental data. The goodness of fit was determined using correlation coefficient (R^2), the sum of the square error (SSE), the root mean square error (RMSE), and the reduced chi-square (χ^2). Therefore, the best goodness of fit was selected based on the lowest values of SSE, RMSE and χ^2, and the higher value of R^2.

2.4. Morphological characterization

The scanning electron microscopy (SEM) was used to observe changes in the morphology of *Vernonia amygdalina* leaves before and after drying at different conditions. The samples were mounted on a SEM stub and the morphologies were observed in a SEM (HITACHI TM3030Plus, Japan). The analyses were examined under the high vacuum condition at an accelerated voltage of 15 keV, 60× magnification and analytical working distance of 1 mm.

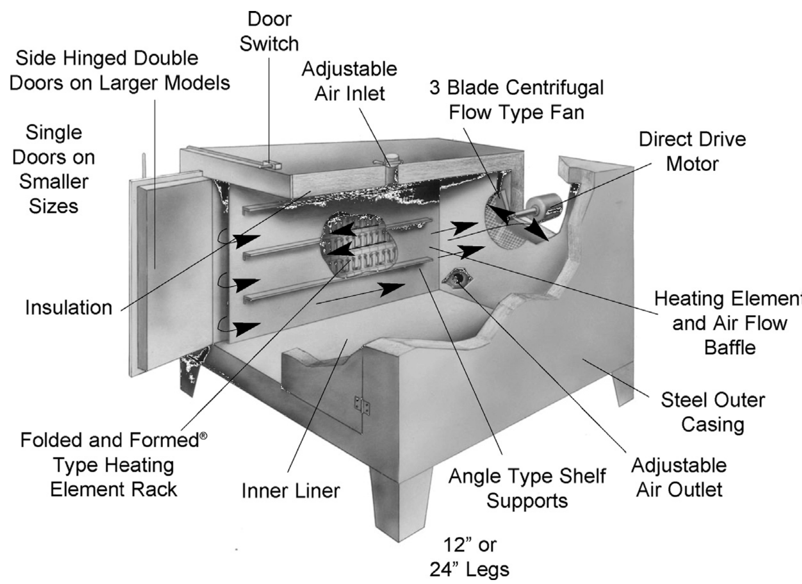

Fig. 1. Schematic diagram of a universal oven.

Table 1
Theoretical and semi-theoretical models for thin-layer drying.

Model number	Model name	Model equation	References
1	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Sobukola et al. (2007)
2	Henderson and Pabis	$MR = a\exp(-kt)$	Rosa et al. (2015)
3	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Akpinar and Bicer (2008)
4	Logarithmic	$MR = a\exp(-kt) + c$	Akpinar and Bicer (2008)
5	Midilli and Kucuk	$MR = a\exp(-kt^n) + bt$	Sobukola et al. (2007)
6	Newton	$MR = \exp(-kt)$	Sobukola et al. (2007)
7	Page	$MR = \exp(-kt^n)$	Akpinar and Bicer (2008)
8	Two-term	$MR = a\exp(-kt) + b\exp(-k_o t)$	Sobukola et al. (2007)
9	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Sobukola et al. (2007)
10	Simplified Fick's diffusion	$MR = a\exp(-c(t/L^2))$	Akpinar and Bicer (2008)
11	Verma, Bucklin, Endan, and Wratten	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Akpinar and Bicer (2008)

where a, b, c, g, h, n, k, k_o, L are the model constants.

3. Results and discussion

3.1. Effect of drying temperatures on the moisture content and drying rate of Vernonia amygdalina leaves

The *Vernonia amygdalina* leaves were dried in a single layer using oven drying temperatures of 40, 50 and 60 °C. The initial moisture content of about 1.89 ± 0.3 g water/g dry sample was dried to final moisture content of about 0.012 ± 0.15 g water/g dry sample until no significant reduction in the sample weight. Changes in the moisture contents and drying rates with time at different drying conditions are shown in Figs. 2a and b, respectively. From these drying curves, it can be seen that the moisture contents decrease as the drying time increases. In fact, drying air temperature has a noticeable effect on the moisture content whereby higher temperature resulted in higher loss of moisture content and consequently the drying time reduced. These may be due to the increase in heat transfer between the sample and air temperature which led to quick removal of moisture from the sample. Similar results had been reported from the drying of other agricultural products in the literature (Akpinar, 2006; Akpinar and Bicer, 2008; Ali et al., 2014; Hee and Chong, 2015; Sacilik and Elicin, 2006; Simal et al., 2000; Toğrul and Pehlivan, 2003; Tunde-Akintunde, 2011). The drying time required to reach the final moisture contents at drying air temperatures of 40, 50 and 60 °C were 10, 6 and 5 h, respectively. As seen from these curves, there was no constant rate period and all the drying processes occurred in the falling rate period. As reported that during the falling rate period, the sample surface will no longer be saturated with water and drying rate will only be controlled by diffusion of moisture from internal part to surface of the sample (Akpinar, 2006; Akpinar and Bicer, 2008; Doymaz, 2006).

3.2. Fitting of the oven drying curves

Data from moisture content versus time were converted to dimensionless moisture ratio so as to normalise the drying curves (Fig. 3). The moisture ratio calculated using Eq. (2) at various drying conditions were fitted to 11 selected thin layer drying models reported by previous studies. These models were evaluated based on statistical tools: R^2, SSE, RMSE and χ^2 (Akpinar, 2006; Akpinar and Bicer, 2008; Doymaz, 2006; Gumus, 2015; Gunhan et al., 2005). The obtained results at different drying air temperatures of 40, 50 and 60 °C are shown in Table 2. In general, the R^2, SSE, RMSE and χ^2 values for the models ranged between 0.9743 and 0.9999, 0.0086 and 0.0722, 0.0276 and 0.0802, 0.0011 and 0.0104, respectively for oven drying at 40 °C; 0.9764 and 0.9999, 0.0023 and 0.0665, 0.0438 and 0.0711, 0.0019 and 0.0065, respectively for oven drying at 50 °C; 0.9721 and 0.9999, 0.0028 and

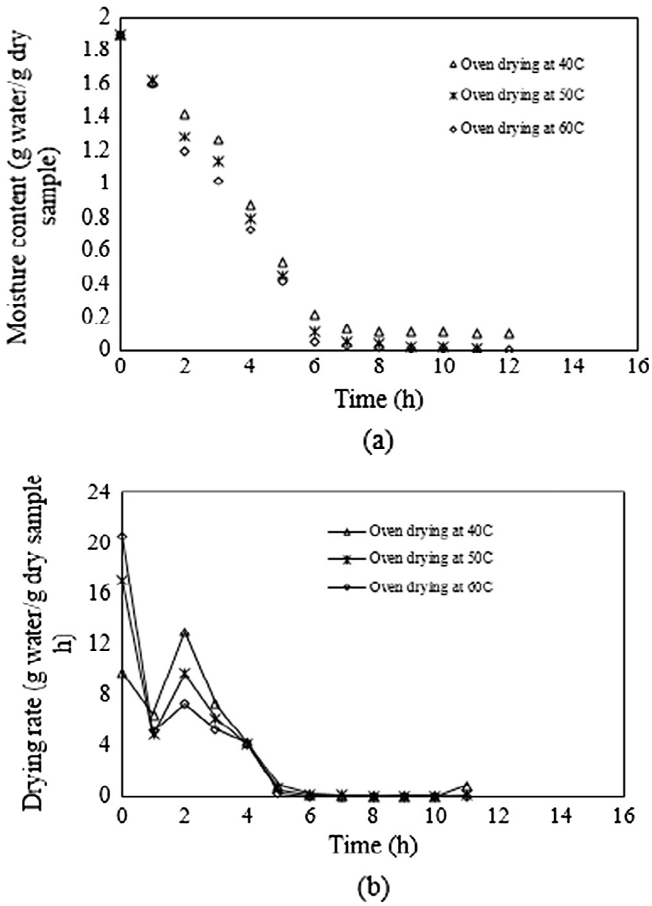

Fig. 2. Changes in moisture content (a) and drying rate (b) with time at different oven drying conditions of *Vernonia amygdalina* leaves.

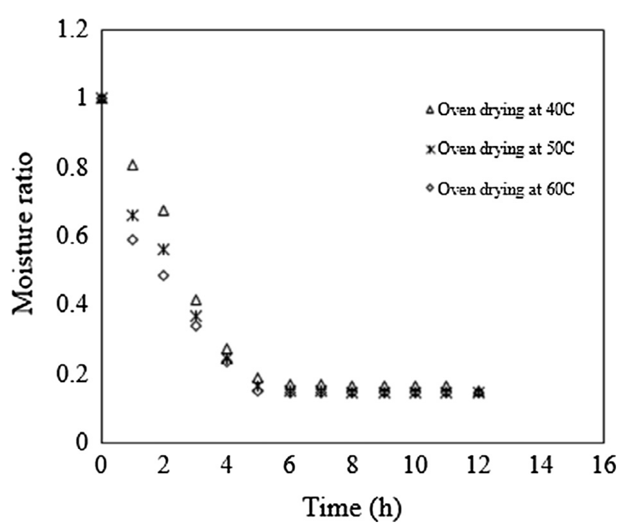

Fig. 3. Changes in moisture ratio with time at different oven drying conditions of *Vernonia amygdalina* leaves.

0.0728, 0.0216 and 0.0752, 0.0016 and 0.0228, respectively for oven drying at 60 °C. It can be seen from Table 2 that the highest values of R^2 as well as lowest values of SSE, RMSE and χ^2 for the various drying conditions were obtained from the Midilli and Kucuk drying model. Thus, this model was selected as suitable to predict the thin layer oven drying behaviour of *Vernonia amygdalina* leaves.

The correlation between the experimental and predicted moisture ratio at different drying conditions are shown in Fig. 4. The selected model showed a good agreement between the experimental and predicted moisture ratio, which is banded around 45° straight line. The obtained results are in agreement with the past studies conducted on *Vernonia amygdalina* leaves under an open sun and *Citrus aurantium* leaves under forced convection (Mohamed et al., 2005; Sobukola et al., 2007). Eq. (3) shows the predicted model for the thin layer oven drying of *Vernonia amygdalina* leaves. The four drying parameters of Midilli and Kucuk model were correlated for the *Vernonia amygdalina* leaves by the Eqs. (4)–(7). The correlations between the coefficients of Midilli and Kucuk drying model and oven temperature were significant with R^2 of 1 and S_T of 0.

$$MR(a,k,n,b,t) = a\exp(-kt^n) + bt \tag{3}$$

where

$$a = -16.736 + 1.084 * 10^4 T - 2 * 10^6 T^2 \tag{4}$$

$$b = -176.77 + 1.049 * 10^5 T - 2 * 10^7 T^2 \tag{5}$$

$$k = 147.33 - 9.08 * 10^4 T + 1 * 10^7 T^2 \tag{6}$$

$$n = -130.49 + 8.127 * 10^4 T - 1 * 10^7 T^2 \tag{7}$$

3.3. Determination of effective diffusivity coefficients

The mechanism of mass transfer in vegetables and fruits are complex to explain. Therefore, the Fick's second law are mostly used to describe their drying behaviour with an assumption that the main mechanism has diffusion nature, negligible shrinkage, constant temperature and diffusional coefficients (Akpinar, 2006; Sacilik and Elicin, 2006). Eq. (8) expresses the Fick's second law.

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

where D_{eff} is the effective diffusivity (m^2/s), L is the half thickness of slab (m) of drying from both sides, and n = 1, 2, ... the number of terms taken into consideration.

For a longer period of drying, MR < 0.6, Eq. (8) can be simplified to its first term only (Akpinar and Bicer, 2008). Then, the diffusion coefficients are calculated from the plots of lnMR against drying time and D_{eff} was determined from the slope of the linear regression. The values of D_{eff} for various drying air temperatures are shown in Table 3. The values ranged from 4.55×10^{-12} to 5.48×10^{-12} m^2/s. It can be seen from Table 3 that the effective diffusivity increased with increasing temperature. An increase in temperature causes a reduction in water viscosity and enhances the activity of water molecules. This may be attributed to the fact that at a higher temperature, water molecules are loosely bound to food matrix, therefore require a lesser energy to remove than at lower temperature (Touil et al., 2014). The calculated values fall within the general range of 10^{-9} to 10^{-12} m^2/s for food samples and agricultural crops (Akpinar, 2006; Hee and Chong, 2015; Rosa et al., 2015; Sobukola et al., 2007; Toğrul and Pehlivan, 2003). In relation with other reported studies on agricultural products: 48.72×10^{-10} m^2/s for *Vernonia amygdalina* leaves under open sun (Sobukola et al., 2007); 7.04×10^{-12}, 4.53×10^{-12} and 6.44×10^{-12} m^2/s for mint, parsley and basil leaves, respectively under open sun drying (Akpinar, 2006); 0.776×10^{-9}–1.371×10^{-9} m^2/s for carrot under convective air drying (Doymaz, 2004); 1.14×10^{-11}–2.98×10^{-11} m^2/s for black tea (Panchariya et al., 2002); 2.27×10^{-10}–4.97×10^{-10} m^2/s for

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Table 2
Model results from statistical analyses of *Vernonia amygdalina* leaves at 40, 50 and 60 °C.

Drying method	Model number	Model constants	R	SSE	RMSE	χ^2
Oven at 40 °C	1	a = 0.8906, b = 0.0000, k = 0.3456	0.9970	0.0350	0.0540	0.0039
	2	a = 1.0007, k = 0.2538	0.9775	0.0652	0.0780	0.0062
	3	a = 0.3336, b = 0.3336, c = 0.3336, g = 0.2539, h = 0.2539, k = 0.2539	0.9743	0.0722	0.0802	0.0104
	4	a = 0.9360, k = 0.3700, c = 0.1155	0.9953	0.0496	0.0653	0.0053
	5	a = 0.9920, b = 0.0155, k = 0.1856, n = 1.4858	0.9999	0.0086	0.0276	0.0011
	6	k = 0.2536	0.9886	0.0622	0.0720	0.0057
	7	k = 0.5036, n = 0.5036	0.9821	0.0622	0.0720	0.0062
	8	a = 0.1155, k = 0.0000, b = 0.9360, k_o = 0.3700	0.9994	0.0316	0.0513	0.0037
	9	a = 0.7391, k = 0.3404	0.9968	0.0472	0.0627	0.0047
	10	a = 1.0007, c = 0.5620, L = 1.4879	0.9784	0.0678	0.0792	0.0069
	11	a = 0.1094, k = 0.0000, g = 0.3152	0.9970	0.0350	0.0540	0.0039
Oven at 50 °C	1	a = 0.9281, b = 0.0000, k = 0.3610	0.9990	0.0104	0.0503	0.0034
	2	a = 1.0065, k = 0.2956	0.9883	0.0439	0.0605	0.0049
	3	a = 0.0774, b = 0.0848, c = 0.8793, g = 0.3820, h = 0.3820, k = 0.000	0.9923	0.0382	0.0595	0.0047
	4	a = 0.9641, k = 0.3820, c = 0.0774	0.9993	0.0085	0.0493	0.0031
	5	a = 1.0117, b = 0.0097, k = 0.2716, n = 1.2303	0.9999	0.0023	0.0438	0.0019
	6	k = 0.9011	0.9764	0.0665	0.0711	0.0065
	7	k = 0.9959, n = 0.2973	0.9832	0.0505	0.0663	0.0053
	8	a = 0.0179, k = 0.0000, b = 4.0642, k_o = 0.0925	0.9984	0.0225	0.0520	0.0041
	9	a = 0.8626, k = 0.2697	0.9968	0.0326	0.0576	0.0043
	10	a = 1.0065, c = 0.1783, L = 0.7767	0.9784	0.0439	0.0605	0.0049
	11	a = 0.0719, k = 0.0000, g = 0.3610	0.9990	0.0104	0.0503	0.0034
Oven at 60 °C	1	a = 0.7358, b = 0.1519, k = 0.6146	0.9968	0.0209	0.0418	0.0023
	2	a = 0.9190, k = 0.3050	0.9883	0.0549	0.0676	0.0055
	3	a = 0.3063, b = 0.3063, c = 0.3063, g = 0.3050, h = 0.3050, k = 0.3050	0.9734	0.0649	0.0776	0.0091
	4	a = 0.8771, k = 0.4690, c = 0.1027	0.9964	0.0228	0.0436	0.0025
	5	a = 0.9988, b = 0.0047, k = 0.4971, n = 0.7670	0.9999	0.0028	0.0216	0.0016
	6	k = 0.3370	0.9864	0.0620	0.0724	0.0057
	7	k = 0.5252, n = 0.6607	0.9721	0.0728	0.0752	0.0228
	8	a = 0.4595, k = 0.3050, b = 0.4595, k_o = 0.3050	0.9814	0.0633	0.0752	0.0069
	9	a = 0.2632, k = 0.9763	0.9948	0.0379	0.0592	0.0039
	10	a = 0.9190, c = 0.1319, L = 0.6576	0.9823	0.0639	0.0736	0.0061
	11	a = 0.2642, k = 0.0934, g = 0.6146	0.9968	0.0209	0.0418	0.0023

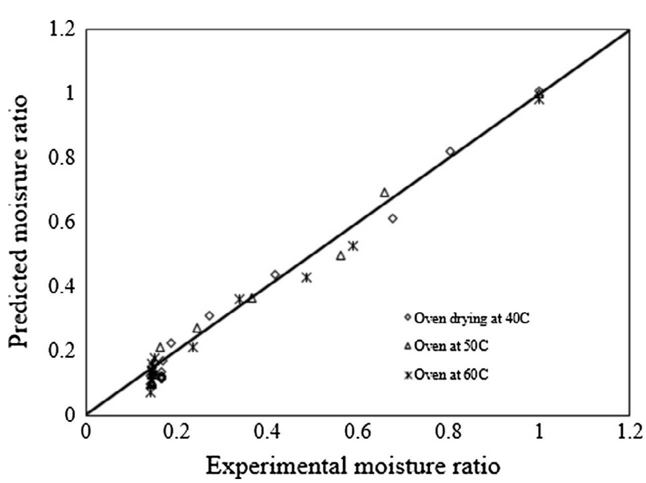

Fig. 4. Correlation between experimental and predicted moisture ratio of the established model for *Vernonia amygdalina* leaves at various drying conditions.

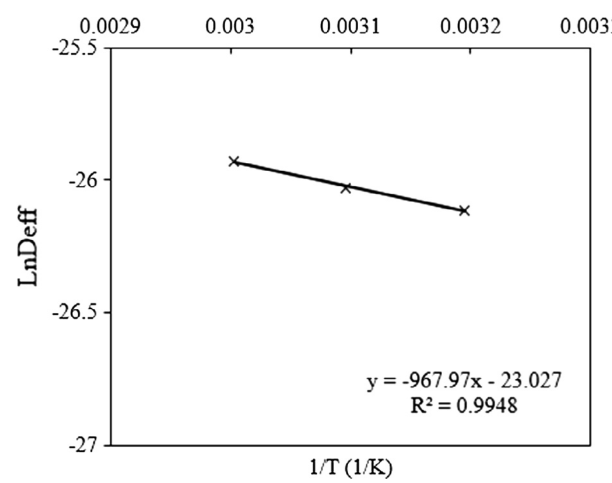

Fig. 5. Relationship between effective diffusivity and temperature based on Arrhenius' model.

Table 3
Values of effective diffusivities obtained for *Vernonia amygdalina* leaves at different oven air temperatures.

Drying condition	Effective diffusivity (D_{eff}) (m^2/s)
Oven at 40 °C	4.55×10^{-12}
Oven at 50 °C	4.95×10^{-12}
Oven at 60 °C	5.48×10^{-12}

orange apple slices (Sacilik and Elicin, 2006); and 2.0×10^{-10}–4.2×10^{-10} m^2/s for garlic (Madamba et al., 1996). However, variation in the values of the effective diffusivities may be due to the drying conditions which implies that effective diffusivity D_{eff} depends on temperature.

3.4. Determination of activation energy

The effect of drying air temperature on the effective diffusivity is generally explained using Arrhenius' equation (Eq. (9)) to obtain a better agreement of the experimental and predicted data (Hee and Chong, 2015; Madamba et al., 1996).

$$D_{eff} = D_{\infty} e^{\left(\frac{-E_a}{RT}\right)} \qquad (9)$$

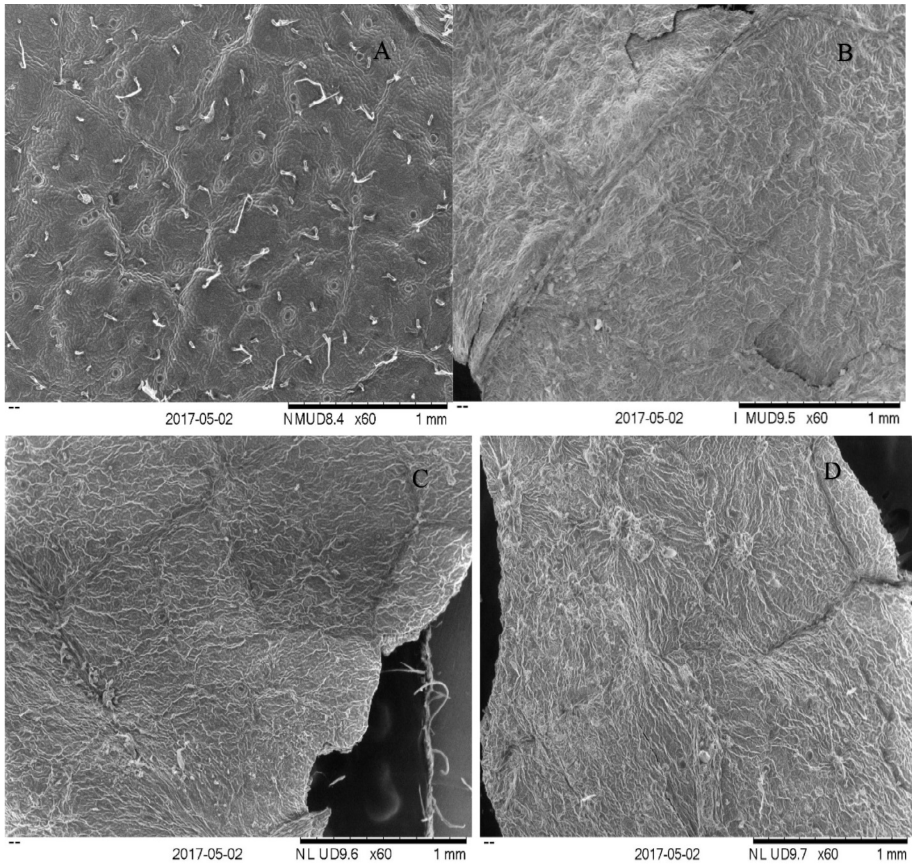

Fig. 6. Scanning electron microscopy (SEM) micrographs of *Vernonia amygdalina* leaf for fresh leaf (A), oven-dried leaf at 40 °C (B), oven-dried at 50 °C (C), and oven-dried at 60 °C (D).

where D_∞ is the diffusivity constant at an infinitely high temperature (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol K), and T is the absolute temperature (K).

The plot of ln D_{eff} against 1/T in Fig. 5 shows a linear regression. The values of activation energy and diffusivity constant were calculated from the slope and intercept as 8.048 kJ/mol and 9.989×10^{-11} m^2/s, respectively. The obtained activation energy falls within the general range (1.27–110 kJ/mol) reported for food materials (Aghbashlo et al., 2008). Lower E_a of this process may be due to the presence of lesser water in the sample which may require lesser energy if a proper dryer was used. The activation energy is lower than that of *Andrographis paniculata* drying (33.4 kJ/mol) (Hee and Chong, 2015), black tea drying (406.028 kJ/mol) (Panchariya et al., 2002), and mint leaves drying (57.12 kJ/mol) (Kane et al., 2009).

3.5. Morphological changes in the Vernonia amygdalina leaves

The scanning electron microscopy images of fresh and dried *Vernonia amygdalina* leaves under different oven drying conditions are shown in Fig. 6. The fresh leaf (Fig. 6A) present glandular and non-glandular trichomes on the epidermal surface. The drying processes damaged the epidermal surfaces and caused the shrinkage of the glandular trichomes. These may be attributed to the increased in the drying temperature and intense heating. The severe damage was in the order: oven drying at 40 °C < oven drying at 50 °C < oven drying at 60 °C (Figs. 6B–D). For all the drying conditions, high temperature caused a more violent evaporation of moisture as well as a melting of starch granules (İzli, 2016). In addition, this phenomenon suggests that drying affects the physical structure of plant cell wall which might lead to breakage of vegetal tissue. Likewise, it had been reported that higher drying temperature tends to reduce the yields and phytochemicals present in plants (Antal et al., 2011; Vyankatrao, 2014). Thus, it is important to select appropriate drying temperature so as to preserve the plant phytochemical nutrients.

4. Conclusion

In this study, the drying conditions have an effect on the drying behaviour and morphological properties of *Vernonia amygdalina* leaves. The drying processes occurred in falling rate period. The drying time was shorter at higher drying air temperature but resulted in an imbalance of the leaf microstructure. Amongst the non-linear regression drying model equations examined, the Midilli and Kucuk model exhibited the best fit in predicting the drying behaviour of *Vernonia amygdalina* leaves using oven drying. More so, Arrhenius' equation was used to evaluate temperature dependence of the effective diffusivity for calculating activation energy. In addition, the results from the scanning electron microscopy suggested that the degree of deformity in the morphology of *Vernonia amygdalina* leaves depends on drying conditions whereby an increase in drying air temperature resulted in higher deformity of the cell wall. Therefore, this study suggested the use of lower temperature in the drying of *Vernonia. amygdalina* leaf in order to preserve its phytochemical nutrients.

Conflict of interest

The authors report no conflicts of interest.

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