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Kinetics Modelling of Moringa Oleifera Leaves using Microwave Drying

Nabilah Abdul Samad[1], Dayang Norulfairuz Abang Zaidel[2,3,*], Nor Alafiza Yunus[1], Ida Idayu Muhamad[1], Yanti Maslina Mohd Jusoh[1], Daniel Joe Dailin[4], Joko Sulistyo[5]

[1] Department of Bioprocess and Polymer Engineering, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[2] Department of Chemical & Environmental Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia
[3] Innovation Centre in Agritechnology for Advanced Bioprocessing, Universiti Teknologi Malaysia, Pagoh Campus, 84600 Pagoh, Johor, Malaysia
[4] Institute of Bioproduct Development, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[5] Universitas Ciputra, Surabaya, Jawa Timur 60219, Indonesia

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ABSTRACT

The drying kinetics of (*Moringa Oleifera*) leaves were studied at various microwave power levels (300, 500, 800, and 1000 W) using an existing drying mathematical model. The best-fitted mathematical models of the drying curves were determined by considering the coefficient of determination (R^2), SSE, and RMSE based on the experimental drying data of moringa leaves. For drying *M. oleifera* leaves, three out of six models exhibited the optimum drying behaviour with the highest R^2 and lowest SSE and RMSE values, with R^2, SSE, and RMSE values ranging from 0.92-0.98, 0.09-0.3, and 0.06-0.10, respectively. Besides, the effective moisture diffusivity of moringa oleifera leaves during microwave drying varied from 1.56×10^{-8} to 5.49 × 10-8 m^2/s. The values of D_0 and Ea from microwave drying of Moringa oleifera leaves were estimated as 9.0 x 10-8 m^2/s and 17.53 W/g.

1. Introduction

Moringa Oleifera Lam., a fast-growing tree, is well-adapted to drought conditions and can be found in South, East, and West Africa, tropical Asia and Latin American nations. It is commonly known as moringa, ben oil tree or benzoil tree, kelor tree, drumstick and horseradish tree. *M. oleifera* is a medicinal plant found widely in tropical countries and is renowned for its versatility as a multipurpose tree. Moringa leaves have gained extensive recognition among healthcare professionals and nutrition specialists for their significant protein content utilised in addressing malnutrition and various ailments [1]. However, the nutritional contents of M. *oleifera* differ based on the cultivation location [2]. Thus, it is advisable to assess the nutritional composition of *M. oleifera* beforehand for optimal utilisation in medicinal or food applications.

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[*] *Corresponding author.*
E-mail address: dnorulfairuz@utm.my

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Mathematical modelling of the drying process under various drying conditions is critical for better operation control and overall product quality improvement. There are plenty of models related to drying kinetic. According to research by Karathanos and Belessiotis [3], the model was often employed to gather additional information about the process components because optimising the operational parameters would enhance the drying kinetics of the product. These are the kinetic models widely used in agricultural drying methods, such as the Newton, Page, Midilli *et al.*, Weibull Distribution, Logistics, and Demir *et al.,* models. Furthermore, the models mimic moisture transport and mass transfer throughout the drying process of various agricultural samples.

This work aimed to study the effect of microwave power (300 - 1000 W) on the drying properties of *M. oleifera* leaves to determine the best-fitted mathematical model with reference to the experimental drying data. Furthermore, the effective moisture diffusivity (D_{eff}) and activation energy (Ea) values were calculated.

2. Methodology

2.1 Preparation of Sample

As in the previous study [4], *M. Oleifera* Lam's leaves were acquired from Hadham Enterprise in Johor, Malaysia.

2.2 Analysis of Moisture Content and Drying of Moringa Oleifera Leaves

Earlier research [5] was used to carry out the drying treatment steps. Four distinct microwave power levels (300, 500, 800 and 1,000 W) were studied in triplicates. The leaves were dried until their moisture content (MC) fell below 5% [6]. The dried leaves were then crushed with an electric grinder (Waring Commercial Blender 8011S, Model HGB2WTS3, USA) and sieved through a 355 m aperture stainless-steel sieve. The dried leaves powder (MOLP) was stored in a sealed container in a dry and dark cabinet.

2.3 Mathematical Modelling of Drying

The investigation of drying kinetics and its mathematical modelling is required to build an appropriate drier for the researched leaves [7]. 6 distinct thin-layer drying models from the literature were utilised to calculate the moisture ratio as a function of drying time, as shown in Table 1. The moisture ratio and drying rate of moringa oleifera leaves were calculated using the formula below.:

$$MR = \frac{M_t - M_e}{M_0 - M_t} \tag{1}$$

where MR is the moisture ratio, M_t is the moisture content at a specific time (g water g Dry Matter^{-1}), M_e is the equilibrium moisture content (g water g Dry Matter $^{-1}$), M_0 is the initial moisture content (g water g Dry Matter^{-1}). The equilibrium moisture content (M_e) was assumed to be zero for microwave drying.

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

where DR (Drying Rate (g water g Dry Matter $^{-1}$ min $^{-1}$), M_{t+dt} (moisture content at t + dt (kg moisture kg dry matter $^{-1}$)), M_t (moisture content at t (g water g Dry Matter $^{-1}$), and dt (drying time (min)).

Table 1
Thin-layer drying models used for drying of *Moringa oleifera* leaves

No	Model Name	Equation	Reference
1	Newton	MR = exp(-k*t)	[6]
2	Page	MR = exp(-k*t^n)	[7]
3	Midilli *et al.,*	MR = (a*exp(-k*t^n)) + (b*t)	[8]
4	Weibull Distribution	MR = a-(b*exp(-k*(t^n)))	[9]
5	Logistics	MR = (a)/(1+(b*exp(k*t)))	[10]
6	Demir *et al.,*	MR = (a*exp(-k*t^n)) + c	[10]

MR, Moisture Ratio (dimensionless); *a, b, c,* dimensionless coefficients and *n,* microwave drying exponent specific to each equation; *k* drying coefficient specific to each equation; *t*, time in the drying model.

Various mathematical models were developed from the previous literature to calculate the moisture ratio as a function of time. To identify which model gives the best-fit curves, the non-linear regression was used to evaluate the fit of the mathematical models to the experimental data. The parameters used for the evaluation comprise the coefficient of determination (R^2) and the reduced chi-square (X^2). The best-fit model shall show a higher value for R^2 and lower values for X^2, Root Mean Square Error analysis (RMSE) and Standard Error Estimate (SEE). These parameters can be calculated as follows:

$$X^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n} \tag{3}$$

$$RMSE = [\frac{1}{N}\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre,i})^2]^{1/2} \tag{4}$$

$$SEE = [\frac{1}{N-z}\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre,i})^2]^{1/2} \tag{5}$$

2.4 Effective Moisture Diffusivity

Effective moisture diffusion could indicate the moisture transfer mechanism inside a food or agricultural product. Using drying curves, Fick's second law of diffusion may be used to compute effective moisture diffusivity (D_{eff}). Manzoor *et al.,* [11] provided the following equation for one-dimensional slab geometry:

$$\frac{\partial M}{\partial t} = D_{eff}(\frac{\partial^2 M}{\partial^2} + \frac{\eta}{r}\frac{\partial M}{\partial r}) \tag{6}$$

where M is the moisture content at any time of drying (kg water/kg dry basis) is the time (s), η is a constant, D_{eff} is the moisture-dependent diffusivity (m^2 s^{-1}), r is the diffusion path (m) which will be 0 for planar geometry.

Moringa oleifera leaves were modelled as an infinite slab geometry with a thickness of L. Hence, from Fick's diffusion equation, and by considering all the assumptions and modifications, D_{eff} can be determined by plotting drying data in the form of ln (MR) against drying time, t.

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

where MR is moisture ratio, D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is drying time (s), and L is the half thickness (drying from both sides) of Moringa oleifera leaves (L = 0.0005 m).

2.5 Activation Energy

The least energy necessary to activate moisture diffusion from a product’s interior regions is called activation energy (Ea). In the microwave mechanism, the temperature is not a directly measured quantity for drying in this study.

As a result, Dadali *et al.,* [12] computed the activation energy using a modified version of the Arrhenius equation. In contrast to the drying temperature in the original equation, Ea was related to D_{eff} and m/P, which stand for effective moisture diffusivity and the microwave output power to sample mass ratio, respectively. In the case of microwave drying, Ea was calculated from the slope of ln (Deff) versus m/P, Eq. (8) can be written as follows:

$$ln(D_{eff}) = \ln{(D_0)} - \mathrm{E}_a \frac{m}{\mathrm{P}} \tag{8}$$

where D_0 denotes Arrhenius or pre-exponential factor (m^2 s^{-1}), P denotes microwave output power (W), m represents sample mass (g), Ea signifies activation energy (W g^{-1}), and m denotes sample mass (g).

2.6 Computational Work

The numerical computations were carried out with the help of the software application MATLAB R2021a. The parameters were assessed using the Marquardt-Levenberg process’s non-linear least squares approach. The important criteria for determining the best equation to account for variance in dried sample drying curves were the coefficient of determination (R^2), standard error estimate (SEE), root mean square error analysis (RMSE), and reduced chi-square (X^2). The model with the greatest R^2 and the least reduced chi-square (X^2) and RMSE would be the best-fit model in the drying properties of Moringa oleifera leaves. These statistical characteristics can be used to forecast moisture ratio values, with unity being more accurate.

3. Results

3.1 Drying Kinetic Model

The thin layer drying properties of Moringa oleifera leaves were tested at four microwave power levels of 300, 500, 800, and 1000 W, and the experimental data was used as the benchmark of drying models. The model parameters were determined using non-linear regression analysis, and the best-fitted model was determined using the coefficient of determination (R^2) and standard error of estimate (SEE).

The mathematical modelling results are shown in Table 2. The coefficient of determination (R^2), SSE, and RMSE were employed to identify the best-fitted mathematical model for the drying curves. Doymaz [13] defined R^2 as the primary parameter for selecting the best-fit agricultural product drying kinetics model. Demir *et al.,* Weibull Distribution, and Midili model were identified as the best drying behaviour as they have the highest values of R^2 and lowest values of SSE and RMSE. The results for R^2, SSE and RMSE values are in the range between 0.92-0.98, 0.09-0.3 and 0.06-0.10, respectively.

Another study found the Demir *et al.,* model as the best model in the literature for describing drying curves of green olives by Demir *et al.,* [10]. Demir *et al.,* [10]model is a modification from Page, Logarithmic and Midilli *et al.,* models. However, in the case of drying celery leaves [9] and quince slices [14], the Weibull Distribution model was found to be a more accurate fit. Several other authors have found the Midilli *et al.,* model to be well fitted to the drying of Lime slices [15], Mint leaves [8], Black mulberry [16], Green pepper [17] and mango ginger [18].

3.2 Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity means the impact of all input factors on mass transfer throughout the drying process. The effective moisture diffusivity of moringa oleifera leaves during microwave drying ranged from 1.56×10^{-8} to 5.49×10^{-8} m^2/s, as shown in Table 3. As the power of the microwave increased, the time required for drying decreased, and the diffusion of moisture increased due to the rise in temperature and higher energy input. The values reported in this study were within the range of 10^{-6} to 10^{-12} m^2/s for drying food materials, which agreed well with the previous studies [19,20].

The maximum diffusivity value was achieved after microwave drying at 1000 W, whereas the lowest was obtained at 300 W. The increased heating energy can explain the increase in moisture diffusivity with increasing microwave power. Higher heating energy enhanced water molecule activity as the samples were dried at increasing microwave power, resulting in greater moisture diffusivity [21]. This result has a similar trend reported by previous studies in drying *Adathoda vasica* leaves and *Cymbopogon citratus* leaves [7], celery leaves [9], mint leaves [8] and black mulberry [16].

The minimum energy necessary to activate moisture diffusion from a product’s interior regions is called activation energy (Ea). Figure 1 depicts the Ea generated from the logarithmic of moisture diffusivity versus sample weight/power level (m/P) plot. The outputs indicate a linear connection because of the modified Arrhenius-type exponential equation dependency.

Based on Figure 1, the values of D_0 and Ea were estimated as 9.0×10^{-8} m^2/s and 17.53 W/g, respectively. Ea obtained in this study were higher than those reported for drying celery leaves (13.51 W/g) [9], Mint leaves (12.28 and 11.049 W/g) [8] but lower than the values found in the study in Adathoda vasica leaves (31.88 W/g) [7] and Mango ginger (21.6 W/g) [19]. Table 3 shows the fitness of different models at different microwave power.

Table 2
The fitness of different models at different microwave power

Model Name	Equation	MW (W)	SSE	R^2	adj R^2	RMSE	a	b	c	k	g	h	n
Newton	MR = exp(-k*t)	300	0.5670	0.8836	0.8836	0.1273				0.0974			
		500	0.6326	0.8529	0.8529	0.1406				0.1877			
		800	0.3309	0.9249	0.9249	0.1068				0.3123			
		1000	0.2392	0.9309	0.9309	0.1020				0.3430			
Page	MR = exp(-k*t^n)	300	0.2158	0.9557	0.9544	0.0797				0.0115			1.901
		500	0.3462	0.9195	0.9169	0.1057				0.0454			1.851
		800	0.1087	0.9753	0.9745	0.0623				0.1000			1.904
		1000	0.0904	0.9739	0.9727	0.0641				0.1401			1.756
Midilli *et al.,*	MR = (a*exp(-k*t^n))+(b*t)	300	0.2129	0.9563	0.9522	0.0816	0.9865	0.0013		0.0088			2.033
		500	0.3444	0.9233	0.9156	0.1071	0.9828	-0.0014		0.0415			1.874
		800	0.0971	0.97798	0.9754	0.0611	1.0010	0.0054		0.0913			2.049
		1000	0.0904	0.9739	0.9700	0.0672	1.0000	0.0003		0.1397			1.763
Weibul Distribution	MR = a-(b*exp(-k*(t^n)))	300	0.2131	0.9563	0.9522	0.0816	0.0287	-0.9577		0.0084			2.057
		500	0.3444	0.9233	0.9156	0.1071	-0.0163	-0.9993		0.0421			1.861
		800	0.0966	0.9781	0.9755	0.0610	0.0425	-0.9578		0.0884			2.104
		1000	0.0904	0.9739	0.9700	0.0672	0.0025	-0.9975		0.1397			1.764
Logistics	MR = (a)/(1+(b*exp(k*t)))	300	0.2090	0.9571	0.9545	0.0796	1.0830	0.0888		0.2938			
		500	0.3338	0.9256	0.9208	0.1038	1.0750	0.0928		0.5655			
		800	0.1058	0.9760	0.9742	0.0626	1.1030	0.1002		0.8921			
		1000	0.0905	0.9739	0.9714	0.0656	1.1500	0.1505		0.8625			
Demir *et al.,*	MR = (a*exp(-k*t^n))+c	300	0.2131	0.9563	0.9522	0.0816	0.9577		0.0288	0.0084			2.058
		500	0.3456	0.9287	0.9221	0.1039	0.9837		-0.0017	0.0412			1.890
		800	0.0966	0.9781	0.9755	0.0610	0.9578		0.0425	0.0884			2.104
		1000	0.0904	0.9739	0.9700	0.0672	0.9975		0.0025	0.1397			1.764

MR, Moisture Ratio (dimensionless); *a, b, c,* dimensionless coefficients and *n,* microwave drying exponent specific to each equation; *k* drying coefficient specific to each equation; *t*, time in the drying model; r^2, coefficient of determination; RMSE, Root Mean Square Error analysis; SSE, Standard Error Estimate.

Table 3
Effective moisture diffusivity of Moringa oleifera leave at various microwave power

Microwave Power Level (W)	Time required for drying (min)	MASS/POWER (g/W)	Effective Diffusivity, Deff (m^2/s)
300	20	0.100	1.56 x 10^{-8}
500	10	0.060	3.11 x 10^{-8}
800	8	0.038	4.45 x 10^{-8}
1000	6	0.030	5.49 x 10^{-8}

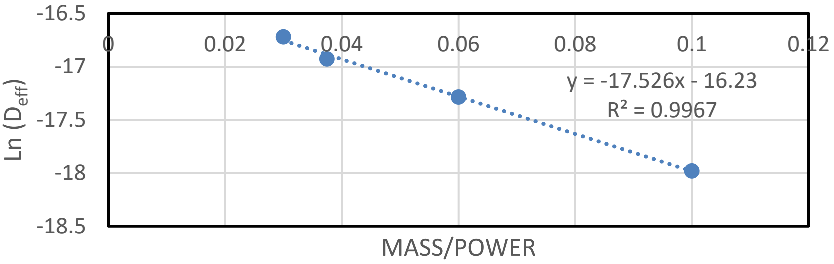

Fig. 1. The plot of ln (D_{eff}) against m/P (kg/W)

3.3 Validation Modelling Results

Figure 2 illustrates the relations between the predicted and experimental values with fitted data for M*oringa oleifera* leaves samples at different microwave power. Considering the gradient of each of the best-fit models was close to 1, the predicted values were in excellent agreement with the experimental drying values.

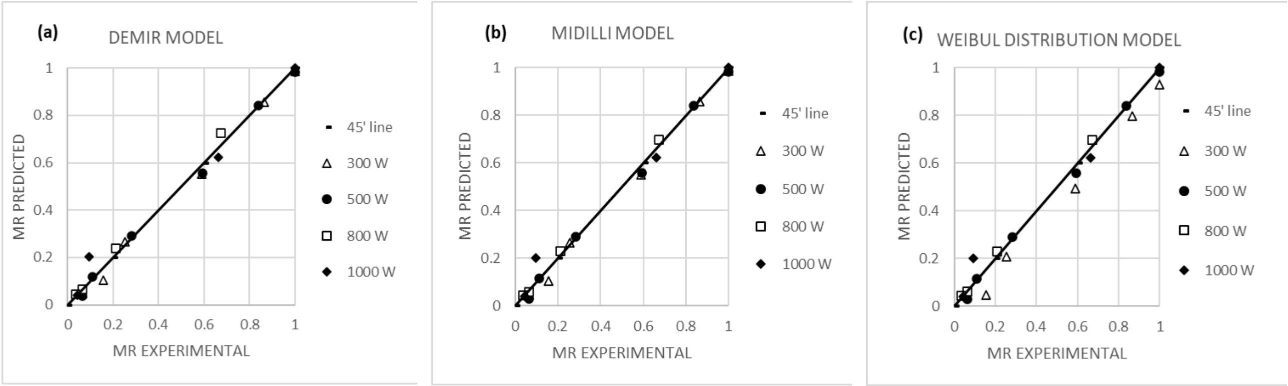

Fig. 2. Comparison of predicted versus experimental moisture ratio values *Moringa oleifera leaves* dried in microwave method using different mathematical models

4. Conclusions

In conclusion, the drying kinetics of (*Moringa Oleifera*) leaves were evaluated at different microwave power levels (300, 500, 800, and 1000 W) by altering the drying properties of *Moringa oleifera* leaves to determine which mathematical model best fits the experimental drying data. From the results obtained, Demir *et al.*, Weibull Distribution, and Midili model show the best drying behaviour with the highest R^2 and lowest SSE and RMSE values for drying *M. oleifera* leaves, with R^2, SSE, and RMSE values ranging from 0.92-0.98, 0.09-0.3, and 0.06-0.10, respectively. Besides, the effective moisture diffusivity of moringa oleifera leaves during microwave drying varied from 1.56 ×

10^{-8} to 5.49×10^{-8} m^2/s. As microwave power increased, moisture diffusivity increased due to higher heating energy from the microwave output from the drying process. The values of D0 and Ea from microwave drying of Moringa oleifera leaves were estimated as 9.0×10^{-8} m^2/s and 17.53 W/g, respectively.

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