Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2015; 3(8):693-700 **ISSN 2347-9523 (Print)**
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Research Article

Air Drying Characteristics of Aerial Yam (*Dioscorea bulbifera*)

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Abstract: The study investigated the air drying characteristics of aerial yam in a fabricated air dryer within a temperature range of 50 to 70°C. Prior to drying, the sample was divided into two portions; one part was boiled at 100°C for 20min and the other part left fresh. The drying data was fitted to twelve well-known thin layer drying models. Among the models used, the Midilli *et al.*,Verma *et al*., Diffusion Approach, Wang and Singh, Parabolic and Simplified Fick's Diffusion models were found to be the best models to predict the moisture ratio values during the drying process with high capability. The effective moisture diffusivity was found to vary between the range of 1.401 $\times 10^{-10}$ m^2/s to 6.720 x 10^{-10} m^2/s for the fresh yam slabs and 7.223 x 10^{-11} m^2/s and 2.306 x 10^{-10} m^2/s for the boiled yam slabs over the temperature range of 50 to 70°C. The values for activation energy were 28.42kJ/mol, 30.33kJ/mol for fresh yam samples of thicknesses of 0.5cm and 1cm respectively, whereas the values for boiled yam were 6.77kJ/mol and 15.37kJ/mol for slabs of 1cm and 0.5cm thicknesses respectively. Pre-treating the aerial yam by boiling will be beneficial in the optimisation of processing method for the *Dioscorea bulbifera*.

Keywords: Drying rate, thin-layer drying models, activation energy, diffusion mechanism, drying curve.

INTRODUCTION

Dioscorea bulbifera, which is also known as air potatoes or aerial yam, is a member of the yam species often considered as a wild species of yam native to Africa and Asia. It is among one of the most underutilized food crops in Ghana and other parts of the world where it grows and appears in both the wild and edible forms. Unlike the other yam species, *Dioscorea bulbifera* has a long vine and it produces tubers (bulbis) which grow at the base of its leaves. This species of yam is not popular among farmers or consumers and does not enjoy the patronage that some of the other edible yam species enjoy. Despite it underutilization, *Dioscorea bulbifera* has been shown to possess a myriad of compounds that have also been attributed to several health benefits [1, 2, 3].This species of yam has certain advantages that go beyond its health conferring abilities. It is very easy to grow under even harsh conditions and this presents an opportunity to have a reliable food source all year round.

Drying kinetics of food crops are generally affected by factors including drying temperature, pre-treatment method, relative humidity, and product sizes [4, 5] and are crop specific. Many authors studied the air drying characteristics and calculated the moisture diffusion and activation energy of agricultural produce [6, 7, 8]. However, there are no studies on the drying characteristics of *D.Bulbifera.* Therefore, this study investigated the air drying characteristics of the aerial yam to identify suitable conditions for optimisation of processing method for the aerial yam.

MATERIALS AND METHODS

Source of materials (Aerial yam)

Samples of the *D. bulbifera* were obtained from farmers in the Northern Region of Ghana.

The drying process

Yams were washed with four litres of distilled water, manually peeled and cut into slabs having dimensions of 0.5cm×1cm×2cm, 1cm×1cm×2cm using very sharp stainless steel knife. One part of the slabs was boiled at 100°C for 10mins, quickly cooled with cold water and the surface moisture dried off. 2 g of the boiled and fresh samples of different thickness were arranged in stainless steel mesh trays of dimensions of 10cm ×7cm and transferred into the drier designed and fabricated at the Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

The drier was started and allowed to run for approximately one hour before loading of samples to allow the heated air to stabilize at desired temperatures of 50, 60 and 70°C. The loaded pre-weighed yam samples were removed and weighed with an electronic balance (Sartorius model CPA 6235) with 0.01g precision at 30min intervals for three consecutive constant readings. The drying were conducted in triplicates and average values recorded. The average moisture ratio was used to plot the drying characteristics curves for the temperature range studied with dimensionless moisture ratio against drying time.

Mathematical modelling

Mathematical models for drying processes are used for designing new or improving existing drying systems and controlling of drying process [9].The moisture ratio (MR) of yam slabs were calculated using by the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e} \qquad (1)$$

Where, Mt is the moisture content at any time (kg water/kg dry solid), $M_0$is the initial moisture content (kg water/kg dry solid), and M_e is equilibrium moisture content of sample (kg water/kg dry solid).

To determine the drying model, the experimental moisture ratio data were fitted to 12 Thin – layer drying models widely used in scientific literature as represented in Table 1 to describe the drying rate of the yam slabs.

The non-linear regression analysis was performed with statistical package program QtiPlot 0.9.8.8 Svn 2255 and Curve Expert Professional. According to Erbay and Icier (2008), regression and correlation analysis are very useful tools in modelling the drying behaviour of biological materials. Determination of the best fit was done using higher values of coefficient of determination (R^2), and the lowest values of root mean square error (RMSE) and the reduced chi square (χ^2). The different statistical evaluation equation was used to describe the goodness of the fit of the dried yam samples are as follows:

$$R^2 = \frac{\sum_{i=0}^{n}\left(MR_i - MR_{pre,i}\right).\sum_{i=0}^{n}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\left[\sum_{i=0}^{n}\left(MR_i - MR_{pre,i}\right)^2\right].\left[\sum_{i=0}^{n}\left(MR_i - MR_{exp,i}\right)^2\right]}} \qquad (2)$$

$$\chi^2 = \frac{\sum_{i=0}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \qquad (3)$$

$$RMSE = \left[\frac{1}{z}\sum_{i=0}^{n}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \qquad (4)$$

Determination of effective moisture diffusivity and activation energy

The effective moisture diffusivity of the samples was estimated by using the simplified mathematical Fick's second diffusion model.

$$MR = \frac{8}{\pi^2} exp\left[-\frac{\pi^2 D_{eff}\, t}{4L^2}\right] \qquad (5)$$

The activation energy of the samples was determined from the slope of the natural logarithm of D^{eff} against the reciprocal of absolute temperature graph using the following equation.

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \qquad (6)$$

RESULTS AND DISCUSSION

Mathematical modelling of drying curve for aerial yam

The dimensionless moisture ratio against drying time for the experimental data at various air temperatures was fitted to the Page, Midilli *et al*, Wang and Singh, Henderson and Pabis, Verma *et al.*, Parabolic, Diffusion Approach, Logarithmic, Simplified Fick's Diffusion, Modified PageI, Modified PageII and Newton drying models available in literature. The criteria for selection of the best model depended on the highest coefficient of determination (R^2), the lowest residual mean square error (RMSE), and chi-square (χ^2).

The results of such fitting of the experimental data for the fresh yam slab of 0.5cm thickness dried at 50°C, 60°C and 70°C are displayed in Table 1 which showed the values of the estimated constants with their corresponding statistical R^2, χ^2 and RMSE values characterising each fitting. In all cases the value of R^2 was greater than 0.90 indicating a good fit [11, 12].

Table 1: Summary of values of the drying constants and coefficients of best fit models

Sample	Temperature	Model	χ^2	RSME	R²
Fresh 0.5cm	50°C	Diffusion approach	$1.185821x10^{-4}$	0.0136316	0.998631
	60°C	Wang and Singh	$3.231043x10^{-5}$	0.00568423	0.999759
	70°C	Diffusion approach	$1.426310x10^{-4}$	0.0119428	0.999149
Fresh 1cm	50°C	Simplified Fick's diffusion	$2.053277x10^{-5}$	0.00453131	0.999811
	60°C	Wang and Singh	$6.724053x10^{-5}$	0.00820003	0.999388
	60°C	Parabolic	$7.077015x10^{-5}$	0.0084125	0.999405
	70°C	Midilli *et al*	$2.401299x10^{-4}$	0.0154961	0.99816
Boiled 0.5cm	50°C	Midilli *et al*	$1.030250x10^{-4}$	0.0101501	0.999101
	60°C	Midilli *et al*	$3.467910x10^{-5}$	0.0058889	0.999725
	70°C	Verna *et al*	$1.307015x10^{-4}$	0.0114325	0.998845
	70°C	Diffusion approach	$1.307015x10^{-4}$	0.0114325	0.998845
Boiled 1cm	50°C	Midilli *et al*	$1.679551x10^{-5}$	0.00409823	0.999819
	60°C	Midilli *et al*	$9.948467x10^{-5}$	0.0099742	0.999031
	60°C	Modified page1	$8.585458x10^{-5}$	0.00926577	0.999011
	70°C	Midilli *et al*	$1.769201x10^{-4}$	0.0133011	0.998206
	70°C	Simplified Fick's diffusion	$1.707523x10^{-4}$	0.0130672	0.998052

From the obtained results, it is evident that the experimental data fitted to all the models used as correlation coefficients in this study were in the range of 0.972154 to 0.998631. The values for R² for all the models were above 0.97 but the diffusion approach model gave a comparatively higherR² and lower $\chi^2(1.185821x10^{-4})$ and RMSE (0.0136316), therefore the diffusion best described the thin layer drying behaviour of the 0.5cm fresh *D. bulbifera* yam slabs dried at 50°C.

The correlation coefficients for 0.5cm fresh *D. Bulbifera* slab dried at 60°C is within the range of 0.972154 to 0.998631.All the R² values were higher than 0.97 also indicating a good fit, however, the Wang and Sing model gave a comparatively higher R² value (0.999759) and lower $\chi^2(3.231043x10^{-5)}$ and RMSE (0.00568423) values. The Wang and Singh model may assume to represent the thin layer drying behaviour of the fresh 0.5cm *D. bulbifera* slabs dried at 60°C.

For the fresh 0.5cm yam slabs dried at 70°C, the correlation coefficients were in the range of 0.972154 to 0.998631. The diffusion approach and Wang and Singh best predict the thin layer drying behaviour of the fresh 0.5cm slabs dried at 70°C.Further evidence of the fitness of the selected models (Diffusion approach and Wang and Sing) is giving in Fig. 1.

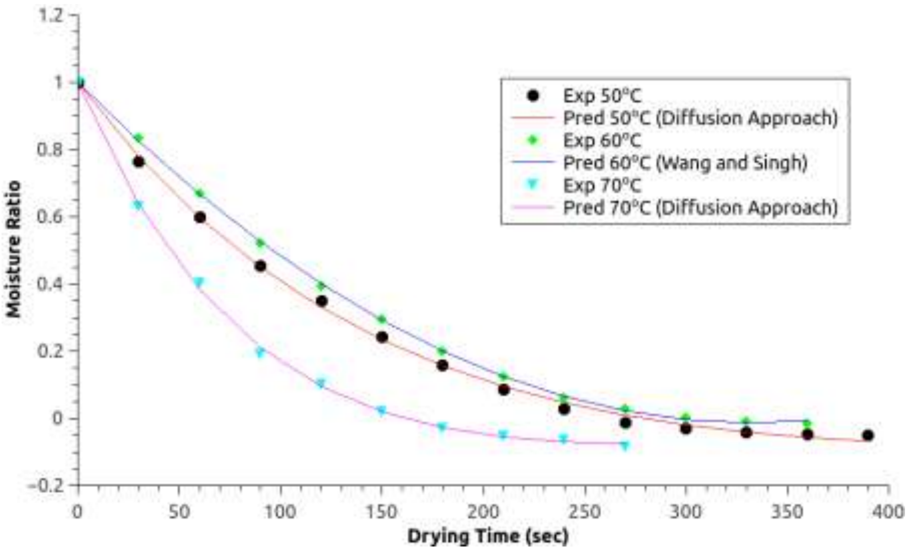


Fig. 1: Variation of experimental and predicted moisture ratio with drying time by the Diffusion approach and Wang and Singh

The results of statistical analysis for the fresh samples of 1cm thickness dried at 50°C, 60°C and 70°C showed in all instances that, the values of R^2 were greater than 0.97 signifying a good fit. The values of R², χ^2 and RMSE for models ranged from 0.992463 to 0.999811, 2.053277x10^{-5} to 9.374781x10^{-4} and 0.00453131 to 0.02863 respectively. The (Simplified Fick's Diffusion), (Wang and Singh and Parabolic), and (Midilli *et al*) models were found to be better models for describing the drying characteristics of 1cm fresh *D. bulbifera* dried at 50°C, 60°C and70°C respectively. The curve in Fig .2 further confirms the fitness of the selected models for fresh yam slab at 1.0cm thickness (Simplified Fick's diffusion, Wang and Sing, Parabolic and Midilli *et al*).

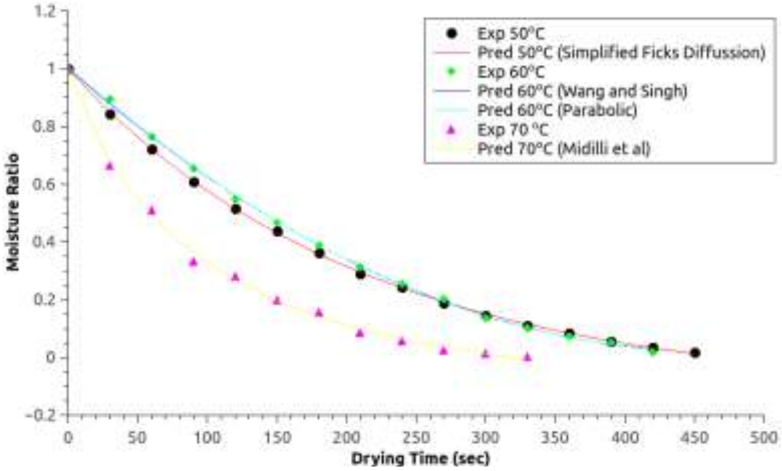


Fig. 2: Variation of experimental and predicted moisture ratio with drying time by the Simplified Ficks Diffusion, Wang and Singh, Parabolic and Midilli *et al* models for the fresh yam slab thickness of 1cm

The results showed correlation coefficients in the range of 0.995455 to 0.999101, for sample dried at 50°C while the best fit model was found to be Midilli *et al* with the highest R² (0.999101) and lowest χ^2 (1.030250×10^4) and RMSE (0.0101501). All the models used in this study fitted reasonably well with the drying data.

The results for sample dried at 60°C had correlation coefficients in the range of 0.986457 to 0.999725 indicating Midilli *et al.* to be the best suited model in describing the drying data of the 0.5cm boiled yam slabs dried at 60°C air temperature with the highest R^2 of 0.999225 and lowest RMSE, 0.0058889 and χ^2 of 3.467910x10^{-5}**.** Midilli *et al* was found to fit both boiled samples dried at 50°C and 60°C with the exception of the sample dried at 70°C air temperature which was best fitted to both Midilli *et al* and Diffusion approach models with the same highest R² (0.998845), lowest χ^2 (1.307015x10^{-4}) and RMSE (0.0114325).The result for the boiled yam slabs of 1cm thickness dried at 50°C, 60°C and 70°C are presented in table 1. The correlation coefficients are in the range of 0.988938 to 0.999819, 0.992217 to 0.999031and 0.993517-0.998052 for 50°C, 60°C and 70°C dried samples respectively. Midilli *et al*model was found to fit all the samples except for the 60°C and 70°C samples that was good fit for Modified Page I and Simplified Fick's diffusion respectively. Fig.3 below confirms the fitness of the selected thin layer drying models was confirmed as shown in Fig. 3.

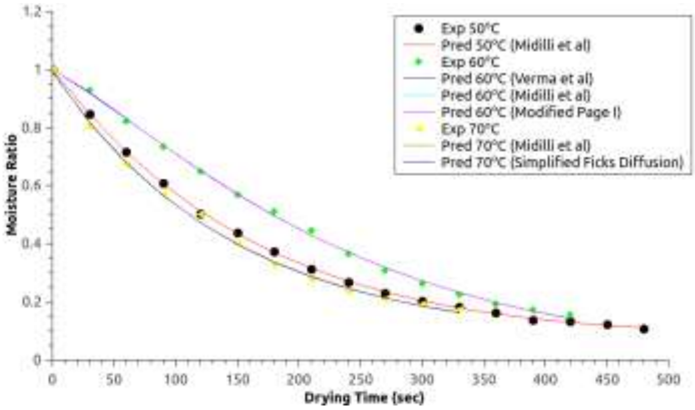


Fig. 3: Variation of experimental and predicted moisture ratio with drying time by the Simplified Fick's Diffusion, Verma *et al.*, Modified Page I and Midilli *et al* models for the boiled slab thickness of 1cm

Validation of Established Models

The experimental and predicted moisture ratio values were compared in Fig. 4.Validation of the established models was made by comparing experimental moisture ratio with the predicted ones. The established models provided satisfactorily a good conformity between the experimental and predicted moisture ratios. The predicted data generally banded around the straight line indicating the suitability of the selected models in describing the drying behaviour of different thicknesses of *D. bulbifera* at varying temperatures.

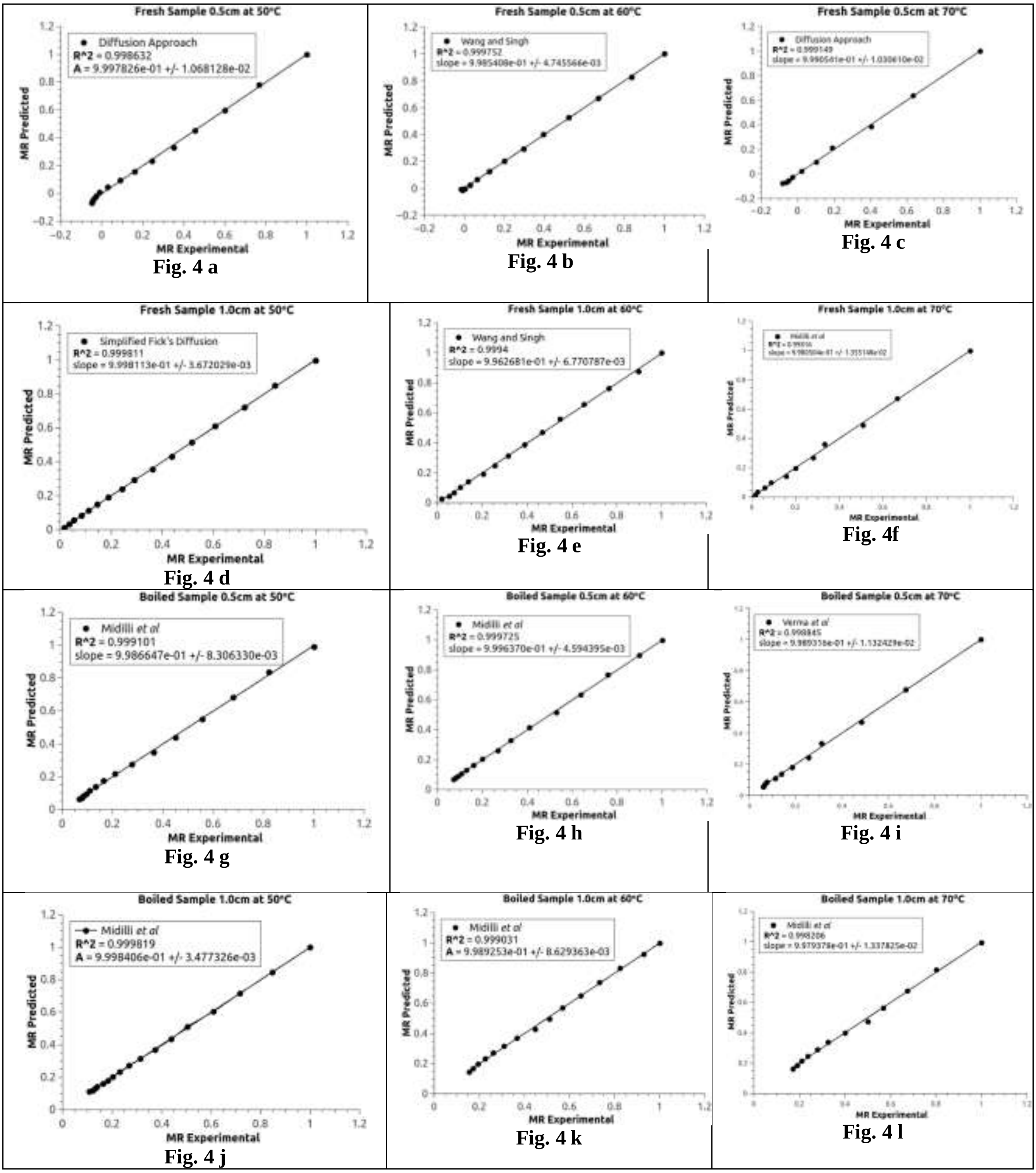


Fig. 4 a **Fig. 4 b** **Fig. 4 c**

Fig. 4 d **Fig. 4 e** **Fig. 4f**

Fig. 4 g **Fig. 4 h** **Fig. 4 i**

Fig. 4 j **Fig. 4 k** **Fig. 4 l**

Fig. 4: Experimental versus predicted moisture ratio values

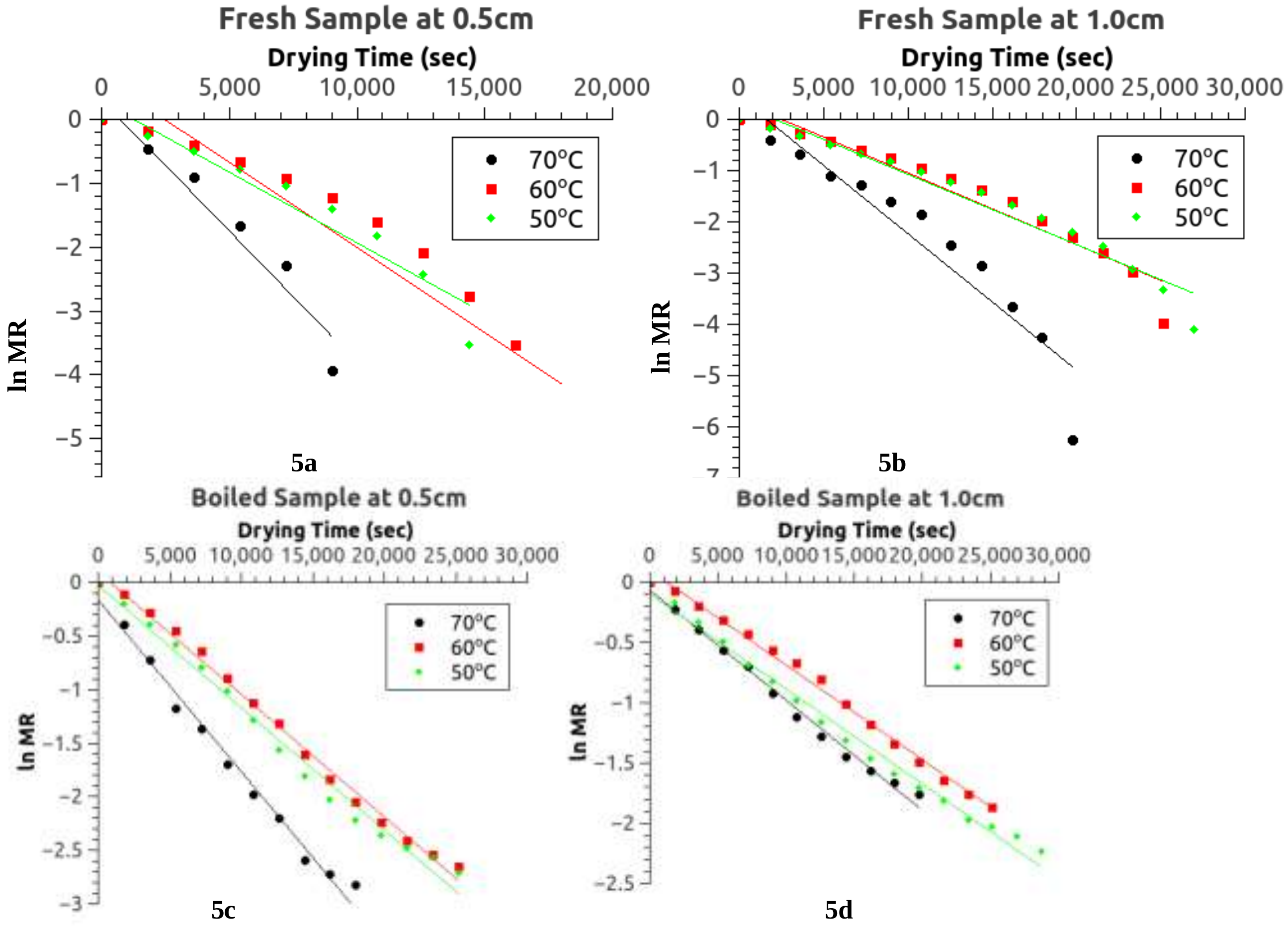
Determination of Effective Diffusivity

The values of the effective diffusivity are given in Table 2. These values were obtained from plots of ln*MR* against *t* for the samples as shown in Fig. 5(a-d).

Table 2: Moisture Diffusivity for Fresh and Boiled Samples

Pre-treatment	Temperature (^{o}C)	Moisture diffusivity (m^2/s)	
		0.5 cm	1.0 cm
Fresh	50	1.401 x 10^{-10}	3.456 x 10^{-10}
Fresh	60	1.689 x 10^{-10}	3.533 x 10^{-10}
Fresh	70	2.603 x 10^{-10}	6.720 x 10^{-10}
Boiled	50	7.223 x 10^{-11}	1.987 x 10^{-10}
Boiled	60	7.223 x 10^{-11}	1.981 x 10^{-10}
Boiled	70	1.012 x 10^{-10}	2.306 x 10^{-10}

The effective moisture diffusivity ranged from 1.401 x 10^{-10} m^2/s to 6.720 x 10^{-10} m^2/s for the fresh samples and 7.223 x 10^{-11} m^2/s to 2.306 x 10^{-10} m^2/s for the boiled samples. It was observed that at any temperature, the fresh samples had higher diffusivity than the boiled samples. The effective moisture diffusivity values obtained from the experimental data fell within 10^{-11} – 10^{-6} m^2/s as reported for most food products [13, 14, 15]. Moisture diffusivity is related to the quantity of heat passing normally through a unit area per unit time. Moisture diffusivity is therefore affected by drying temperatures. It was observed that to reach sample, the moisture diffusivity increased considerably with increase in the drying temperature. Thus, energy consumption is expected to decrease as temperature increases. This result is similar to the results of other workers [16, 17, 18].



5a 5b 5c 5d

Fig. 5(a-d): Change in*ln* MR over time in seconds

Determination of Activation Energy

Activation energy determined from the plots of lnD_{eff} against T is shown in Table 3. It was observed that the fresh yam had higher activation energies than the boiled yam, for samples of the same thickness.

Table 3: Activation Energy for Boiled and Fresh Samples

Pre-treatment	Activation energy (kJ/mol)	
	0.5cm	1.0 cm
Fresh	28.42	30.33
Boiled	15.37	6.77

This indicates that it is easier to induce the water release process in the boiled samples than in the fresh samples. Lower Activation Energy (E_a)indicates greater (higher) temperature sensitivity of diffusion coefficient and less energy to remove moisture from the product. According to Falade *et al.*, [14], boiling and blanching does cause gelatinization of yam starches which results in decreased rate of moisture transport from within the material to the surface during air drying. The values of activation energy obtained lies within the general range of 12.7 – 110 kJ/mol for food materials [19, 20] except for the 1.0 cm boiled sample which had activation energy of 6.77kJ/mol.

CONCLUSION

Among the twelve drying models the data was fitted to, Midilli *et al.*,Verma *et al*., Diffusion Approach, Wang and Singh, Parabolic and Simplified Fick’s Diffusion models were found to be the best models to predict the moisture ratio values during the drying process with high capability. Values of the effective moisture diffusivity of *D. bulbifera* varied between 1.401 $\times 10^{-10}$ m^2/s to 6.720 x 10^{-10} m^2/s for the fresh yam slabs and 7.223 x 10^{-11} m^2/s to 2.306 x 10^{-10} m^2/s for the boiled yam slabs over the temperature range of 50 – 70°C. The moisture diffusivity increased with increasing drying temperature. The low activation energy of the boiled yam indicates the ease in inducing water release process in boiled yam. Based on the above results, pre-treating the aerial yam by boiling will be beneficial in the optimisation of processing method for the *D. bulbifera.*

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