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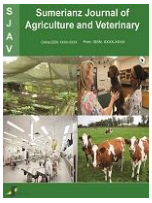

Original Article Open Access

Estimating the Drying Kinetics and Effective Moisture Diffusivity of Fresh Water Prawn (*Macrobrachium rosenbergii*)

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Abstract

Fresh-water prawn (*Macrobrachium rosenbergii*) once harvested, tends to deteriorate rapidly because of the high systemic moisture it constituent which has lead to post-harvest losses, drying as a method of preservation widely used for high moisture bio-products reduces moisture probably to bone-dry level and thereby increased the shelf-life of the fresh-water prawn. Therefore, Estimating the Drying Kinetics and Effective Moisture Diffusivity of Fresh Water Prawn (*Macrobrachium rosenbergii*) was investigated using a laboratory convective oven dryer and was arranged in a thin layer. 50-100°C temperatures were applied, varying on multiple of 10°C. It was observed that the drying rate increased with increasing drying temperatures. Drying data obtained were fitted into four empirical thin-layer drying models, and the best model was investigated after undergoing statistical parameters (of coefficient of determination, R2; root mean square error, RMSE and reduced chi-square, χ^2). The ANN and Henderson model was found to perform satisfactorily in describing the drying behaviour of the Fresh-water prawn samples at the chosen temperature levels. The initial moisture content of all the samples was 54% wb. The final effective moisture diffusivity of the samples during the drying experiments ranges from 1.26 x $10^{-7}m^2/s$ - 7.06 x $10^{-7}m^2/s$, and the temperature related activation energy of diffusion was found to be 12.82-kJ/mol. Drying occurred mainly in the falling rate period, and the characterizing drying curves were exponential with increase in drying temperatures.

Keywords: Fresh-water prawn; Thin-layer drying; Drying kinetics; Modelling, effective; Diffusivity; Activation energy.

1. Introduction

Fresh-water prawn *(Macrobrachium rosenbergii)* are highly nutritious in protein, lipids and has a unique taste, it is low in cholesterol and highly demanded in national and international market. Prawn and shrimps are relatively cheap and available for consumption; they are good sources of animal protein for low income earners [1]. Prawns are endowed with both organic and inorganic contents. The essential constituents are proteins, carbohydrates and lipids, it contains a reasonable and significant proportion of minerals such as Ca, Mg, P, Mn, and Cl and vitamins such as A, C, and D [2]. Many researchers have also reported on the growth and nutritional composition of Fresh-water prawn under different culture conditions [3-8].

Shell-fish generally contain reasonable sources of nutrient in the maintenance and growth of human body [9].

Crabs and Prawn are highly perishable because of high systemic moisture it constitutes with low convective cell and high amino acid content.

Bangladesh reflect one of the most appropriate countries in the world for giant fresh water crayfish *(Macrobrachium rosenbergii)* due to it favourable resources and agro-climatic situation, it has a unique opportunity for the production of prawn [10] and prawn is very important in Basgladesh because it boast their national economy.

Once harvested, Fresh-water prawn *(Macrobrachium rosenbergii)* tends to quickly degenerate into spoilage due to the presence of high level of constituent water, proteins and certain mucilaginous matter. Spoilage is generally undesirable as it results in severe post-harvest losses and withdrawal from human consumption. Drying is a widely used practice in post-harvest preservation of such high moisture agricultural products. It is used to decrease moisture content possibly to skin-dry level which goes to reduce or even halt physiological and other microbiological activities that cause food rancidity and decay, thus, enabling storability of the product under ambient temperatures. Well-dried agricultural products are also reported to have long shelf-life in food packaging, lower transportation, handling, and storage costs [11-13]. See Plate 1.1.

Diffusion is the major phenomena that defines the simultaneous heat and mass transfer concept that consequently results in drying. It is a complicated process causing transfer of moisture from inside the food material to the air-food interface, and from this interface to the surrounds by convection [14, 15]. Drying time and prediction of suitable drying conditions for a particular product can be deduced using the empirical and semi-empirical thin layer drying models. This would also create a good data base for obtaining generalized drying curves and improve equipment design in the drying processes. However technical literature is very silent in the drying kinetics of Fresh-

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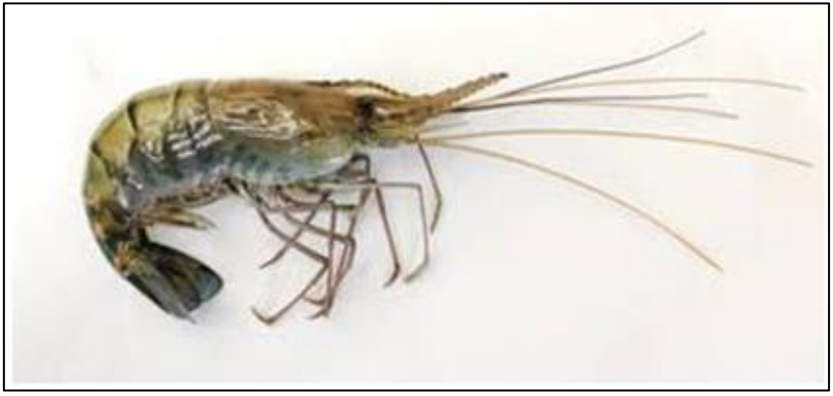
water prawn *(Macrobrachium rosenbergii)*. Objectives of this work therefore, are to estimate the drying kinetics and effective moisture diffusivity of Fresh Water Prawn *(Macrobrachium rosenbergii)* and to fit experimental data obtained at each of the chosen drying temperatures to some thin-layer models as to select the suitable drying model for the Fresh-water prawn (Macrobrachium rosenbergii).

Plate-1.1. A Fresh-water prawn (Macrobrachium rosenbergii)



2. Materials and Method

A large quantity of freshly Fresh-water prawn *(Macrobrachium rosenbergii)* was obtained from a local market at Ondewari community in Bayelsa State, Nigeria. The bulk was thoroughly washed to remove debris and stored in a refrigerator in the Processing Laboratory of the Department of Agricultural and Environmental Engineering, Niger Delta University, Bayelsa State, Nigeria. Samples were then taken from the bulk for the drying experiments. Initial moisture content of each set of five replicate samples (45-g each) was determine using (Plate.2.1) the oven-drying method with the temperature of the oven (WTC binder oven Model WTCB 1718). Equal thickness of the sample was 0.010-m using vanier claiper see Plate 2.2. All weight measurements were done using a laboratory–type digital balance with 0.01-g precision see Plate 2.3. An initial moisture content of about 54%wb was obtained by averaging the five replications. Thin-layer drying experiments were conducted at five levels of temperature (60, 70, 80, 90 and 100^{o}C) and on five replications and average values of the final moisture content fixed at about 12-% db was reached. Weighing of the samples was continued, monitored at time intervals of 10-munites until no discernable change of weight was observed between the five replicates as described in Zibokere and Egbe [16] on red head palm weevil larvae, and Sankat and Mujaffar [17] on catfish. The drying data obtained at the falling rate period of drying were then worked into dimensionless moisture ratios (MR) based on Sahey and Singh [18].

Plate-2.1. WTC binder oven Model WTCB 1718)

Plate-2.2. A picture of Venier caliper

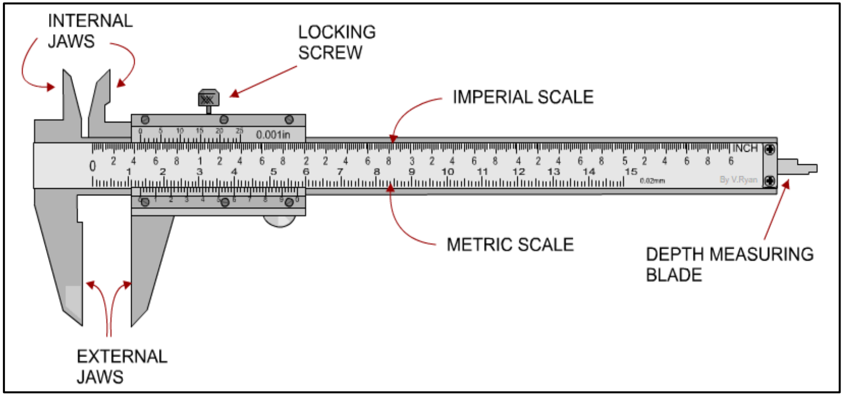


Plate-2.3. Laboratory–type digital balance with 0.01-g precision

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} \qquad 1$$

where

M_e = equilibrium moisture content (emc), $\mathrm{kg_{H_2O}/kg_{solid}}$

M_o = initial moisture content, $\mathrm{kg_{H_2O}/kg_{solid}}$.

However, for a rather cylindrical geometry of the crayfish samples, it was desired to obtain the equivalent moisture ratios by transformation using the Fick's second law diffusion equation as Guine, *et al.* [19] Chen, *et al.* [20].

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} = \frac{8}{\pi^2}\int_{n=1}^{\infty}\frac{1}{n^2}e^{-(n)^2\frac{\pi^2 D_e t}{L^2}} \qquad 2$$

where MR is dimensionless

n denotes the number of terms in the series (0, 1, 2, 3,…),

t is drying time,

D_e is effective moisture diffusivity ($m^2\ s^{-1}$)

L relates to the geometric diameter, d_c of the samples [21].

$$d_c = (L \times W \times T)^{\frac{1}{3}}$$

The factor, d_c is the dimensional estimator for L (length), W (width) and T (thickness) being the major, intermediate and minor diameters of the crayfish sample. Then Equation 2 will now give as Guine, *et al.* [19].

$$\mathrm{MR} = 0.8106\int_{n=1}^{\infty}\varepsilon_n^{-2}\, e^{-9.87\varepsilon_n\left(\frac{D_e t}{r_c^2}\right)} \qquad 3$$

where $\varepsilon_n = n^2$ seen as the root of a related Bessel function in terms of n

r_c = geometric radius of the crayfish, and

$\left(\frac{D_e t}{r_c^2}\right)$ can be recognized as a Fourier factor.

For a long period of drying time ($t \approx \infty$), Equation 3 will tend to converge on the integration operation. The first term seems dominating for high drying time as required in thin-layer drying of products of cylindrical dimensions; thus rendering other terms in the series small enough to be ignored to give Equation 4 [22-24],

$$\mathrm{MR} = 0.8106e^{-9.87\left(\frac{D_e t}{r_c^2}\right)} \qquad 4$$

Taking natural log on both sides, equation 4 will linearize to

$$\ln(\mathrm{MR}) = -\left(47D_e\left(\frac{1}{R_c}\right)^2 t + 1\right) \qquad 5$$

2.1. The Effective Moisture Diffusivity, D_e

Drying parameter can be estimated from the slope of the plot when Equation 5 is plotted on a logarithmic scale (known as the slope method), as follows [19].

$$D_e = -\,slope\,\frac{[r_c^2]}{47} \qquad 6$$

2.2. Fitting to Thin-layer Drying Models

Data obtained from the drying experiments were fitted to seven thin-layer drying models as detailed below –

Lewis model

$$\mathrm{MR} = e^{-kt} \quad [25] \qquad 7$$

Henderson-Parbis model

$$\mathrm{MR} = ae^{-kt} \quad [26] \qquad 8$$

Page model

$$MR = e^{-kt^n} \quad [27] \qquad 9$$

where

k is the kinetic (drying) rate constant and a, b, n are model constants.

The fitted models were each regressed using the nonlinear least squares regression method [28]. And by using SPSS 17.0 Microsoft Excel software, the experimental data used in the fitting were processed to statistical indicators such as coefficient of determination, R^2, the reduced chi-square, χ^2 , mean bias errror MBE, and the root mean square error, RMSE. These were used as indicators in selecting the best drying model. Following the procedure in Ndukwu, *et al.* [29] and Burubai [22] the statistical indicators were evaluated as follows

$$R^2 = 1 - \left[\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right] \qquad 10$$

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

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{n - k} \qquad 12$$

$$MBE = \left[\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right] \qquad 13$$

where

$MR_{pre.}$ = predicted moisture ratio

$MR_{exp.}$ = experimental moisture ratio

n = number of observations

k is as previously defined.

The set decision rule was that the model with the highest R^2 value, and the least χ^2 and RMSE values was selected as the best fit in describing the drying characteristics of the Fresh-water prawn *(Macrobrachium rosenbergii)* samples [30-32].

2.3. Activation Energy, E_a

The energy that is required to initiate molecular diffusion to cause drying in biomaterials is referred to as activation energy. Since in this work temperature, t is a measurable parameter, an Arrhenius type function was used to estimate the activation energy as Saxena and Dash [33] Da Silva, *et al.* [34].

$$D_e = D_o(e^{-E_a/Rt}) \qquad 14$$

where

E_a = activation energy, kJ/mol

D_e = effective diffusivity at t°K, m^2/s.

D_o = pre-exponential factor of the Arrhenius equation at 0°K, m^2/s.

R = universal gas constant (8.314×10^{-3}, kJ/mol.K).

t = air temperature expressed in °K

Simplification of Equation 14 gives

$$\ln D_e = \ln D_o - \frac{E_a}{R}t^{-1} \qquad 15$$

$$\text{or } -\frac{E_a}{R}t^{-1} = \ln D_e - \ln D_o \qquad 16$$

$$\frac{E_a}{Rt} = \ln\left(\frac{D_o}{D_e}\right) \qquad 17$$

$$\frac{E_a}{R}t^{-1} = \ln\left(\frac{D_o}{D_e}\right) \qquad 18$$

Plotting of $\ln D_e$ as a function of t^{-1} with regression line of slope, z (Fig. 1) that can be given as;

$$z = -\frac{E_a}{R} \text{ (as in Equation 19)} \qquad 19$$

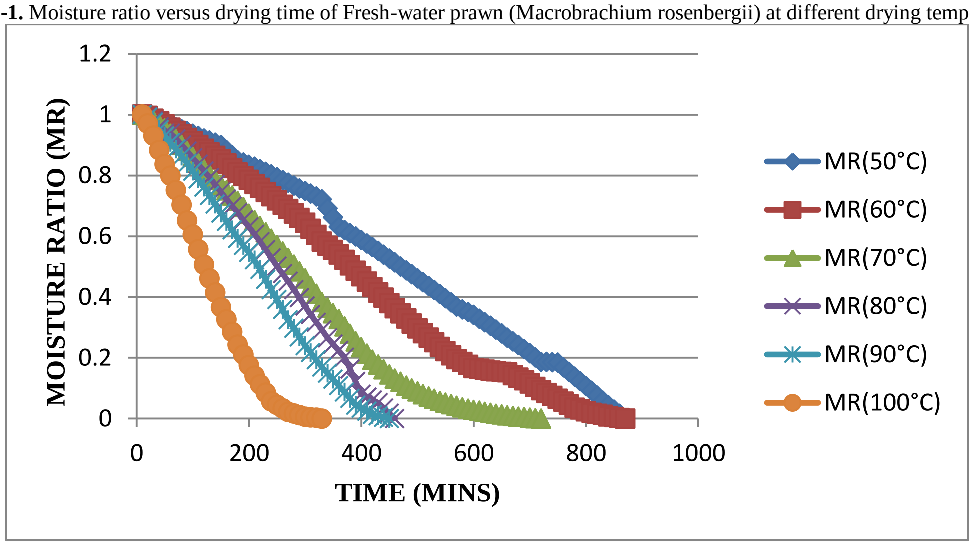
whence, the activation energy can be estimated as Taheri-Garavanda, *et al.* [35], Navneet, *et al.* [36].

$$E_a = -zR \qquad 20$$

3. Results and Discussion

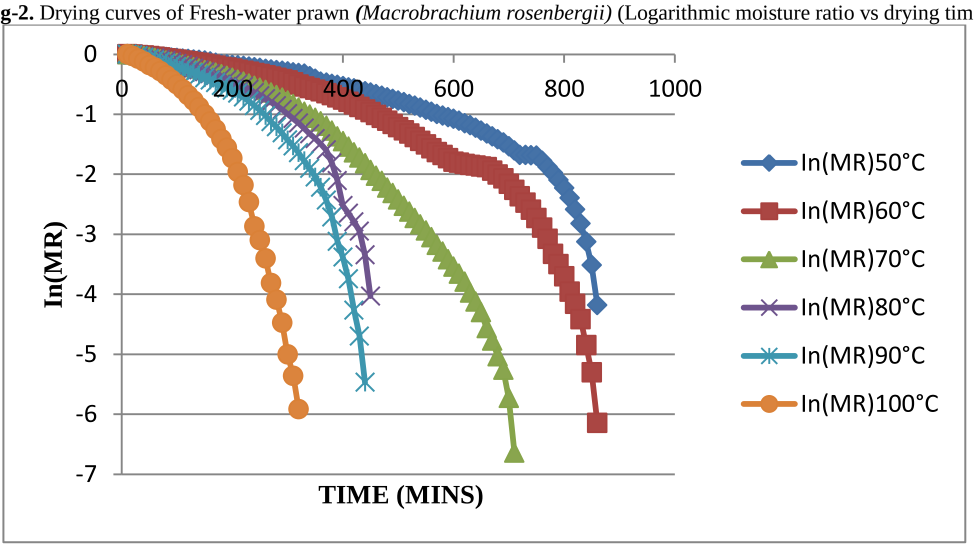
Figure 1 presents changes in moisture ratio with drying time of the Fresh-water prawn (Macrobrachium rosenbergii). As with literature report on drying of visco-elastic materials (such as the sea foods) the drying environment had significant effect on the moisture migration from the interior to the exterior in the drying of the Fresh-water prawn samples as expected [22, 32, 37, 38]. The figure 1 shows that on the same state of drying indicated by the moisture ratio, drying time increased greatly with drying temperature. This indicates that rate of moisture depletion during drying is significantly a function of drying time.

Figure-1. Moisture ratio versus drying time of Fresh-water prawn (Macrobrachium rosenbergii) at different drying temperatures



The drying curves in Fig. 2 depict the general trend of characteristic drying curves as reported for many bio-materials. The curves present initial steeper slope, and become asymptotic to the axis of drying time even with changing drying temperatures. This form adequately describes a more rapid initial moisture loss, and as moisture available for evaporation at the surface of the samples become lesser in drying [16, 17, 22, 38, 39].

Fig-2. Drying curves of Fresh-water prawn *(Macrobrachium rosenbergii)* (Logarithmic moisture ratio vs drying time)



3.1. Fitting Experimental Data into Thin-Layer Drying Models

Table 1 and 2 summarizes the statistical results from the thin-layer drying models for the different drying temperatures chosen in this work. The model with the highest R^2 value, and the least $\chi^2$and RMSE values was the criteria applied in selecting the best model describing the thin-layer drying characteristics of Fresh-water prawn (Macrobrachium rosenbergii). The fitting statistical results in the Tables showed that the coefficient of determination, R^2 values were consistently high in all the models. The shows that the R^2 in Henderson-pabis model ranging from 0.9986-.9326, RMSE values ranging from 0.004015-0.03035, χ^2 0.0000163-0.000228 while Page model R^2 has 0.7515-0.9965, RMSE 0.1741-0.006403 and χ^2 ranges from0.01054-0.000041 and Lewis model R^2 ranges from 0.9833-0.9439, RMSE 0.0139-0.03608 and χ^2 0.00033-0.014316, Artificial Neural Network ANN, has R^2 is 0.9999 and χ^2 0.00000000000043 -0.000000003, RMSE has 0.000000367-0.0000548 as shown in table 1 and 2. This simply indicates the suitability of these empirical models in describing drying behavior Fresh-water prawn. However, when further tuned alongside the other statistical parameters, the model expression of ANN followed by that of the Henderson-pabis model gave the highest R^2 values and the lowest χ^2 and RMSE values in the temperature range of the work. However, Fig. 3 and 4 compared experimental data with data predicted with the ANN and Henderson-pabis model respectively at the chosen drying temperatures. It was observed that the value of k (kinetic rate constant with coefficient of determination, R^2 = 0.9999) increased with decrease in the drying temperatures indicating a steady drying rate suitable for good drying stability of the product without case-hardening. And the clustering of the moisture ratio values along the straight line, further indicated the suitability of ANN and Henderson-pabis model in describing drying characteristics of Fresh-water prawn (Macrobrachium rosenbergii) samples, similar in trend as observed by Darvishi, *et al.* [32] for shrimp.

Figure-3. Showing graph experimented moisture ratio against prediction moisture ratio for Fresh-water prawn (*Macrobrachium rosenbergii*) at 50°C

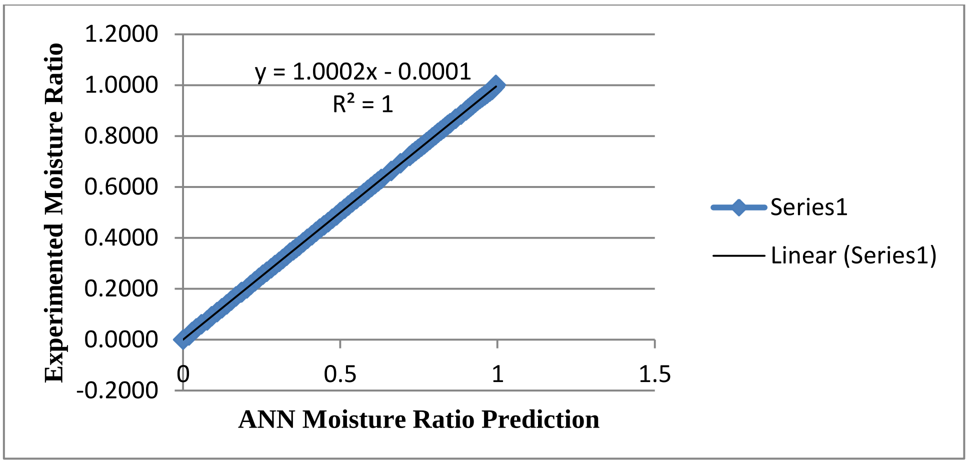


Figure-4. Showing graph experimented moisture ratio against prediction moisture ratio for Fresh-water prawn (*Macrobrachium rosenbergii*) at 50°C

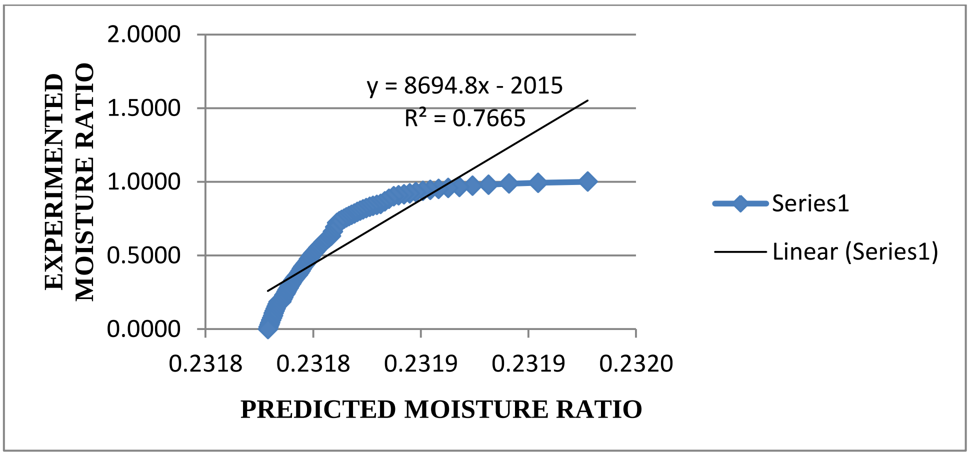


Table-1. Statistical Measures of Fresh-water prawn (Macrobrachium rosenbergii) *on* Thin-layer Drying Models Using Hendeson-pabis, Lewis and Page Model

	Model	**TEMP°C**	**R^2**	**X^2**	**RMSE**	**MBE**	**A**	**N**	**K**
		50	**0.9986**	**0.0000163**	**0.004015**	**0.0014**	**1.6307**		**0.0029**
		60	0.9743	0.000303	0.017199	0.025735	2.1924		0.0049
		70	0.9329	0.000946	0.030535	0.067132	2.6886		0.0075
HENDERSON MODEL		80	0.9895	0.000228	0.002205	0.010509	1.8683		0.0065
		90	0.9892	0.00046	0.002337	0.010811	2.3941		0.0095
		100	0.9849	0.000471	0.003779	0.0151	2.9359		0.017
PAGE MODEL		50	0.9063	0.01054	0.011006	0.09374		1.461	0.0000982
		60	0.9965	0.000041	0.006403	0.0035		1.575	0.00007401
		70	0.9645	0.0005	0.022206	0.036		1.629	0.0000953
		80	0.8491	0.003281	0.056667	0.1509		1.592	0.000133
		90	0.8023	0.004493	0.09992	0.1977		1.636	0.000145
		100	0.7515	0.00776	0.1741	0.2485		1.56	0.000543
LEWIS MODEL		50	0.9833	0.000195	0.01387	0.0167			0.001
		60	0.97163	0.00033	0.018057	0.02837			0.004
		70	0.9616	0.00054	0.02309	0.03839			0.007
		80	0.9645	0.000773	0.0275	0.03556			0.006
		90	0.9489	0.001161	0.033697	0.05109			0.009
		100	0.957	0.014316	0.036076	0.04295			0.017

Table-2. Statistical Measures of Fresh-water Prawn *on* Thin-layer Drying Models Using Artificial Neural Network, ANN

TEMP°C	MBE	R^2	X^2	RMSE
50	2.076E-09	0.9999	2.38E-11	0.00000488
60	8.207E-10	0.9999	4.3E-13	0.000000971
70	3.323E-09	0.9999	4.62E-11	0.00000679
80	6.33E-12	0.9999	1.35E-12	0.000000367
90	3.83E-08	0.9999	8.52E-10	0.00002919
100	9.92E-08	0.9999	3.0E-09	0.0000548

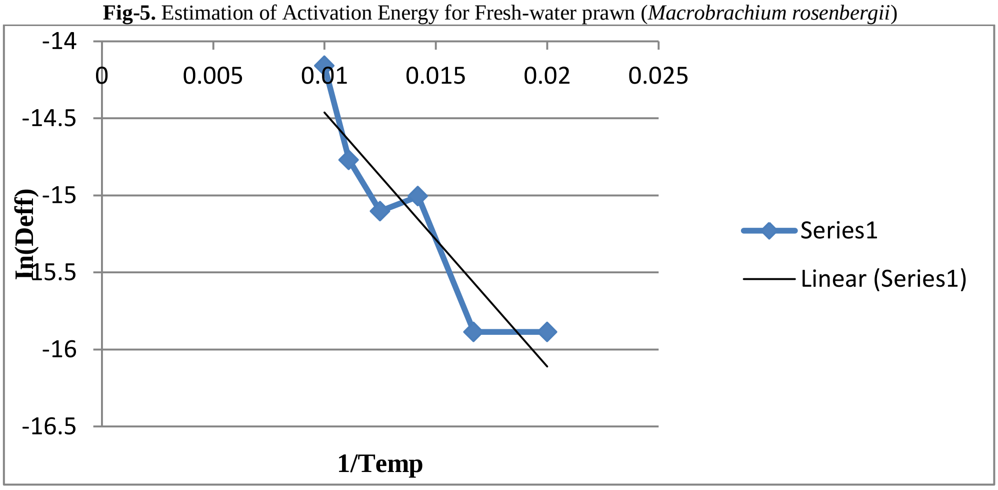
3.2. Estimation of Effective Moisture Diffusivity and Activation Energy

The logarithmic moisture ratio values, ln (MR) plotted as a function of inverse of drying time, t^{-1} at the various drying temperatures (as in Fig. 5), was used in the estimation of effective moisture diffusivity in table 3. The almost flattened regression line showed that less energy was required to remove moisture at the higher drying temperature as the water molecules within the body matrix tend to become free moisture at the surface of the samples. Effective moisture diffusivity, D_e thus, increased with drying time and temperature. In this work the D_e values ranged from 1.26 x $10^{-7}m^2/s$ - 7.06 x $10^{-7}m^2/s$ with the related activation energy, E_a value of 12.82-kJ/mol, similar in trend as observed by Xiong, *et al.* [40] for porous foods; in the work of Zogzas, *et al.* [24]; Guochen, *et al.* [41] for shrimp and for fruits and vegetables [42].

Table-3. Mosisture diffusivity values of African Giant Snail (*Achatina Achatina*)

Temperature °C	Average effective moisture diffusivity
50	0.000000126
60	0.000000126
70	0.000000304
80	0.000000276
90	0.000000385
100	0.000000709

Fig-5. Estimation of Activation Energy for Fresh-water prawn (*Macrobrachium rosenbergii*)



4. Conclusion

Drying kinetics was investigated for Fresh-water prawn (*Macrobrachium rosenbergii*) dried on thin layers at drying temperatures of 50 60, 70, 80, 90 and 100°C. As with other biological materials drying was observed to follow the falling rate period. The ANN followed by Henderson-pabis model was considered adequate and was selected as good estimator of the drying behaviour of the Fresh-water prawn (*Macrobrachium rosenbergii*) at the drying temperatures applied. In this work, the D_e values ranges from 1.26 x $10^{-7}m^2/s$ - 7.06 x $10^{-7}m^2/s$ with the related activation energy, E_a value of 12.82-kJ/mol following an Arrhenius relationship reduces to the slope method and fall within the values in technical literature over same temperature range of this work. The effective moisture diffusivity also increased in value with increased drying temperatures.

Conflict of Interest

There is no potential conflict of interest on this work.

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