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ORIGINAL PAPER

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MATHEMATICAL MODELLING OF THIN LAYER FOAM MAT DRYING KINETICS OF *ARTEMIA* (*ARTEMIA FRANCISCANA*)

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ABSTRACT

Background. Foam mat drying can be considered a simple and economically effective way compared to modern drying methods to produce powdered foods. *Artemia* biomass contains high nutritional content but was previously only used as food for aquatic animals.

Materials and methods. This research aimed to use *Artemia* biomass as human food, with the foam drying technique implemented. *Artemia* foam was dried at different temperatures (65–80°C), with four common drying models applied.

Results. Among the applicable models, the Logarithmic model was chosen as the most suitable model to describe and explain the drying process of *Artemia* powder (the highest R^2, the lowest root mean square error and χ^2, respectively, are 91.7–97.59%, 0.0619–0.0861 and 0.0049–0.0111). The sample reached a moisture content of about 4% to 5% in 2, 2.5, 3 and 3.5 hours when drying at gradually decreasing temperatures from 80°C, 75°C, 70°C and 65°C, respectively. The drying rate was determined by temperature, and the effective moisture diffusivity values (D_{eff}) were calculated in the range of 9.285×10^{-12} m²/s to 1.065×10^{-11} m²/s, from Fick's diffusion model. The activation energy value E_a was determined to be 26.94 kJ/mol according to the Arrhenius relationship.

Conclusion. The sample was dried at 75°C for 2.5 hours and this temperature was chosen due to the short drying time, high nutrient content and bright colour. *Artemia* powder samples after drying had a low moisture content and an a_w value of 4.46% and 0.22, respectively. High protein content was determined (79.93%) in the foam-dried *Artemia* powder. In addition, lipid content, carbohydrate, ash and water absorption capacity were also analysed (1.75%, 6.31%, 6.17% and 298.81, respectively).

Keywords: foam-mat drying, Artemia, drying rate, mathematical modelling, quality

INTRODUCTION

In Vietnam, especially in the Mekong Delta, is where *Artemia* was discovered as a nutrient-rich animal and has been considered a quite popular cultured species for food in aquaculture. During the cultivation process of collecting cyst eggs, the amount of biomass discarded due to death during egg collection or after the end of the annual farming season reaches many thousands of tons and this problem has not yet been

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addressed (Hoa et al., 2007). Nevertheless, *Artemia* biomass has long been proven to be a good source of food and is widely used in rearing aquatic species around the world because it has a very high nutritional composition (Sorgeloos et al., 2001). However, most scientific research abroad also mainly focuses on researching the application of *Artemia* as food in aquaculture, but there has not been much research on using *Artemia* as food for humans.

Fresh *Artemia* biomass after collection is easily damaged by enzymes or chemical reactions, so drying is the most effective way to reduce its water activity and prevent this damage. Raw materials are dried using heat to evaporate the water in them. There are many different methods of drying raw materials, including sun drying, freeze drying, spray drying, vacuum drying and infrared drying. In some previous studies, the foam drying technique was quite suitable for foods that are sticky, viscous and sensitive to high temperatures. Foam mat drying is performed under moderate temperature conditions, causing no damage or slight changes in quality (Kadam et al., 2010; Thuy et al., 2022a; Thuy et al., 2023). Mounir et al. (2017) also suggested that foam mat drying can also be used to produce large quantities of food powder because of its suitability for all types of food ingredients, rapid drying at lower temperature, retention of nutritional value and bioactive compounds, good reconstitution and flowability properties and its cost-saving role during powder production. Foam drying techniques have been used for spirulina (Prasetyaningrum and Djaeni, 2012), extracts of magenta leaves and butterfly pea flowers (Thuy et al., 2022a; Thuy et al., 2023). The results of their study showed that foam drying increased the drying rate and minimised quality changes by reducing the water activity of the powder.

Studies using *Artemia* as food for human consumption are gradually gaining attention due to their outstanding nutritional properties (Thuy et al., 2022b). Until now, research on using *Artemia* biomass as a food source for humans has been limited and has not received much attention. Therefore, developing new products from *Artemia* is very necessary, helping to diversify food sources for humans and increase income for farmers. The obtained *Artemia* powder can be used effectively in the production of nutritious seasoning powder, in addition to the existing seasoning powder on the market. Our current research also addresses the drying of *Artemia* biomass powder using the foam mat drying technique, the effect of drying temperature on moisture loss and the drying rate of *Artemia* powder. Mathematical modelling in food drying is the use of mathematical equations to predict the behaviour of the operation (Wang et al., 2007). Computational modelling can be an effective alternative to experimental methods (Akter et al., 2022). The important parameters for the drying process are the effective moisture diffusion and the activation energy, which are also estimated along with the final product quality. Successful research will contribute to the effective use of locally available raw materials, diversify products from *Artemia* biomass and increase the income for local producers.

MATERIALS AND METHODS

Collection of *Artemia*

Artemia biomass was raised at the experimental farm of Can Tho University, located in Vinh Chau, Soc Trang province, Vietnam. Around 18 to 20 days after stocking, Artemia biomass can be harvested. After that, the *Artemia* biomass was cleaned and frozen at –10°C (for about 1 week, maximum) for use in drying experiments.

Development of *Artemia* foam

Frozen *Artemia* (100 gr) was mixed with warm water (temperature about 40°C) at a water/*Artemia* ratio of 4.6/1 (w/v) and pureed. The optimal ratios of albumin 13.5% (foaming agent) and xanthan gum 0.25% (foam stabilizer) were determined from previous research (Anh et al., 2024). All ingredients were put into a 1000 mL glass beaker and stirred for 5.8 minutes using a machine (Philips HR3705) at maximum speed according to the optimal conditions obtained in the previous study of Thuy et al. (2022a), to increase the surface area of the *Artemia* puree, creating a stable foam with the maximum amount of air in the foam system.

Drying process of *Artemia* biomass foam

After completing the foaming process, the mixture was put into stainless steel trays, with parchment paper placed on the surface. The foam was poured

(100 g) onto the tray (64 cm × 50 cm) to a thickness of about 5 mm. The drying process was carried out at four different temperatures (65°C, 70°C, 75°C and 80°C) in a hot air convection oven (MEMMERT, Germany), with a wind speed of 1.0 m/s. The weight change was recorded using a digital scale (Ohaus, USA) after every 15 minutes of drying. The sample was dried until equilibrium was reached (4–5%). At the end of the drying process, the dried foam sample was finely ground and sieved through a sieve size of about 50 µm to 70 µm.

Chemical compositions analysis

Moisture, ash, protein and lipid content were determined by AOAC (2000). Carbohydrate content was determined using the McCseady method (1970).

Physical properties analysis

The colour of the sample was measured by using a Colourimeter (CHN SPEC CS-10, China) with an L^* value. Water activity (a_w) was measured using an a_w meter (WA-60A, China). Water binding capacity was analysed according to Sosulski (1962).

Data statistical analysis

Statgraphics Centurion XVI software was applied for statistical analysis. The collected data were statistically analysed by ANOVA and LSD tests to determine any significant differences at the 5% level.

Calculate the drying rate (DR)

The drying rate was calculated according to formula 1.

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (1)$$

where

M_{t+dt} is the moisture content (g water/g dry matter) at time ($t + dt$)

M_t is the moisture content at time t.

Drying curve model

Experimental models are used to analyse the thin layer drying process. Some commonly used equations associated with these models and used in agricultural material drying research are presented in Table 1.

To find the best mathematical model, moisture data at different temperatures were converted into moisture content ratio (MR) and calculated according to formula 2.

$$MR = \frac{M_t - M_e}{M_o - M_e} \qquad (2)$$

in which

M_t is the humidity at each measurement time

M_o is the initial moisture content of the material

M_e is the equilibrium moisture content of the material.

However, the M_e value is relatively small and insignificant compared to M_t and M_o during long drying times. Therefore, formula 2 simplified to formula 3 (Toğrul and Pehlivan, 2004).

$$MR = \frac{M_t}{M_o} \qquad (3)$$

Regression analysis to determine the most suitable model for foam drying with different temperatures was performed using conventional statistical calculations, specifically the correlation coefficient of determination

Table 1. Thin layer drying models used in modelling of *Artemia*

Models	Equation	References
Logarithmic	MR = a.exp(–kt) + c	Akpinar and Bicer, 2008
Verma	MR = a.exp(–kt) + (1–a).exp(–gt)	Verma et al., 1985
Newton	MR = exp (–kt)	Sacilik et al., 2006
Henderson and Pabis	MR = a.exp(–kt)	Rosa et al., 2015

t is drying time (hrs); a, c, g, k are the model constants.

(R^2) (Equation 4), Chi square (χ^2) (Equation 5) and root mean square error (RMSE) (Equation 6). The highest value of R^2 and the lowest values of χ^2 and RMSE represent the best model (Akpinar, 2010).

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)\cdot\sum_{i=1}^{N}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)^2\cdot\sum_{i=1}^{N}\left(MR_i - MR_{exp,i}\right)^2}} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (5)$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \quad (6)$$

in which

- $MR_{exp,i}$ is the i[th] experimentally observed moisture ratio
- $MR_{pre,i}$ is the i[th] predicted moisture ratio,
- N is the number of observations
- z is a constant.

Calculation of the diffusion coefficients (D_{eff}) and activation energy (E_a)

The drying properties of different foods are well described using Fick's diffusion equation (John et al., 2014). In the case of thin-layer drying, it is possible to construct an equation form according to Crank (1979) (Equation 7).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{4L^2}\right) \quad (7)$$

in which

- D_{eff} is diffusion coefficients (m^2/s)
- t (s) is drying time; n is a positive integer
- L is ½ the material thickness (m).

When taking the natural logarithm of both sides (Akgun and Doymaz, 2005) (Equation 8) and plotting ln(MR) corresponding to the time for each temperature studied, a straight line is obtained. D_{eff} was calculated using Equation 9 (Zarein et al., 2015).

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

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

The activation energy is calculated using the Arrhenius equation (Equation 10) (Sanjuán et al., 2003).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (10)$$

in which:

- D_o is the diffusion coefficient corresponding to infinite temperature (m^2/s)
- E_a is the activation energy (kJ/mol)
- R is the ideal gas constant (8.314 J/mol K)
- T is the absolute drying air temperature (°K).

RESULTS AND DISCUSSION

Effect of drying temperature on moisture ratio and drying rate

The curve of moisture ratio versus drying time, for different drying air temperatures, was illustrated in Figure 1. The moisture percentage of the foam decreased as the drying time increased. Similar results have been reported for shrimp foam drying (Azizpour et al., 2013). At higher temperatures, due to rapid moisture loss, drying time was shorter. The time required to dry *Artemia* foam to its final moisture content (4–5%) was 3.5; 3; 2.5 and 2 hours, respectively, at drying air temperatures of 65°C, 70°C, 75°C and 80°C. This time was slightly longer than the shrimp foam drying time conducted by Azizpour et al. (2013). They obtained drying times of 135, 105 and 80 minutes, respectively, at drying air temperatures of 50°C, 60°C and 70°C,

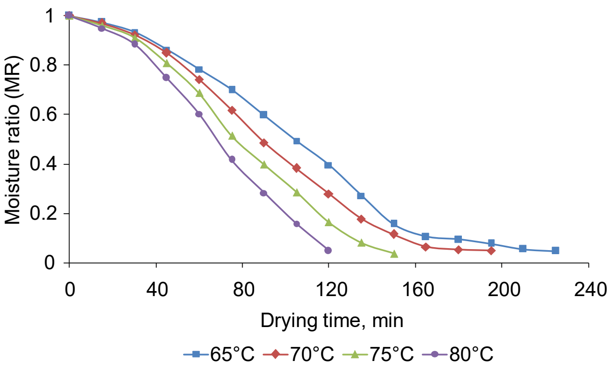

Fig. 1. Change in moisture ratio (M/M_o) of *Artemia* foam according to drying time at different temperatures

to a final moisture content of 7.25 ±1% (dry basic). The continuous decrease in moisture ratio showed that moisture diffusion had dominated the mass transfer inside the foam. High drying temperatures increased the supply rate of hot air to the material, and the movement speed of water molecules in the food also increased, thus shortening the drying time (Demir et al., 2004).

The DR of *Artemia* puree at temperatures of 65°C, 70°C, 75°C and 80°C, was shown by the drying curve (Fig. 2). For all the temperatures studied, the DR was higher in the early stages of the process, where *Artemia* puree has a very high water content, and the fast

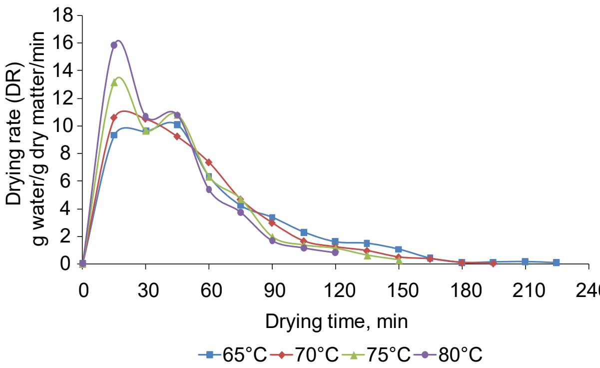

Fig. 2. Effect of drying temperature on drying rate of foam-mat dried *Artemia* puree over time

drying time is evidenced by the initial increase in DR reaching the maximum treatment value. The period in which the DR decreased with drying time was also clearly observed. The sample drying process mainly takes place at a stage where the speed gradually decreases over time. This is because over drying time, the water content gradually decreases and it is difficult to remove moisture from the sample, so the DR gradually decreases. The highest DR was shown at a drying temperature of 80°C and the lowest at a drying temperature 65°C. Fantinel et al. (2017) reported that when the surface of the product dries quickly and the diffusivity of water molecules becomes smaller than its external convection, the drying surface will move inside the product. Then, the internal resistance to the movement of water molecules became the main transport mechanism, so the drying rate decreased (Babalis and Belessiotis, 2004).

Mathematical model of *Artemia* foam drying curve

Moisture data from the experiments were converted into a more useful moisture ratio (MR) expression, and time-matched calculations of drying curves were performed with four drying models (presented in the methods section). A summary of the statistical evaluation of each model was presented in Table 2. Models were evaluated based on root mean square error(RMSE), correlation coefficient of determination (R^2), and Chi square (χ^2). The analysis results showed that all four equations gave high correlation coefficients, in the range of 85.88% to 97.59%, so all equations can be used to describe the DR of *Artemia* foam. RMSE ranged from 0.0619 to 0.135 and χ^2 ranged from 0.0049 to 0.0274. Among the four applied models, the Logarithmic model (2008) showed higher compatibility (at all drying temperatures performed) than the other models. With the Logarithmic model chosen in the case of drying *Artemia* foam, the change in MR of foam dried at different temperatures over time could be established with quite high R^2 ($R^2 \geq 0.92$). Similarly, the lowest RSME (0.0619 to 0.0861) and χ^2 values (0.0049 to 0.0111) were obtained in the Logarithmic model at the defined temperature. The logarithmic model was found to be a better model to describe strawberry properties at both 50°C and 55°C (Doymaz, 2008). Ajala and Ajala (2014) also chose the Logarithmic model for dried shrimp, at temperatures of 60°C, 70°C and 80°C.

Artemia foam can be dried well at temperatures of 65°C to 80°C. The experimental and predicted MR curves for the Logarithmic model are shown in Figure 3.

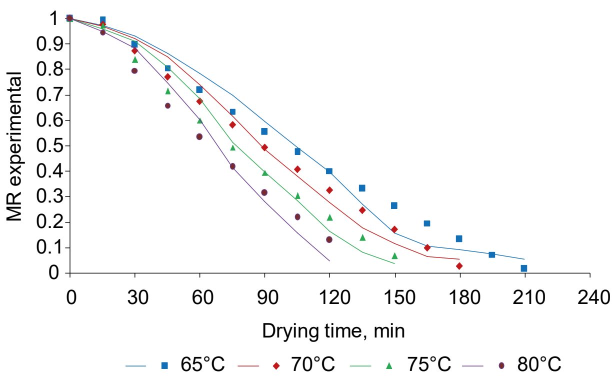

Fig. 3. Experimental MR and Logarithmic model for *Artemia* foam-mat drying

Table 2. Estimated coefficients and statistical analysis of the applied models for Artemia foam mat drying at different temperatures

Temperature, °C	Model constants	RSME	R^2, %	χ^2
Logarithmic (2008): MR = a.exp(–kt) + c				
65	a = 2.4491; k= –0.1660; c= –1.3557	0.0668	91.70	0.0055
70	a = 2.7606; k= –0.1615; c= –1.6734	0.0619	97.59	0.0049
75	a =1.9846; k= –0.3024; c= –0.8659	0.0733	96.72	0.0074
80	a =1.9001; k= –0.3646; c= –0.7868	0.0861	95.59	0.0111
Verma: MR = a.exp(–kt)+(1 –a).exp(–gt)				
65	k = –0.5886; a =0.8292; g = –0.5544	0.1146	91.47	0.0162
70	k = –0.6638; a =0.8348; g = –0.6192	0.1145	91.76	0.0167
75	k = –0.7320; a =0.8488; g = –0.6869	0.1274	90.08	0.0223
80	k = –0.8143; a =0.8661; g = –0.7479	0.1350	89.16	0.0274
Newton: MR = exp(–kt)				
65	k = –0.4974	0.1274	87.83	0.0173
70	k = –0.5634	0.1259	88.22	0.0171
75	k = –0.6223	0.1329	86.52	0.0194
80	k = –0.6982	0.1335	85.88	0.0200
Henderson and Pabis (2008): MR = a.exp(–kt)				
65	a = 1.1740; k = –0.5852	0.1104	91.47	0.0139
70	a = 1.1683; k = –0.6600	0.1095	91.77	0.0140
75	a = 1.1538; k = –0.7285	0.1201	90.09	0.0176
80	a = 1.1365; k = –0.8109	0.1250	89.17	0.0201

High compatibility between model and experimental data (R^2 = 0.98) was also found (Fig. 4).

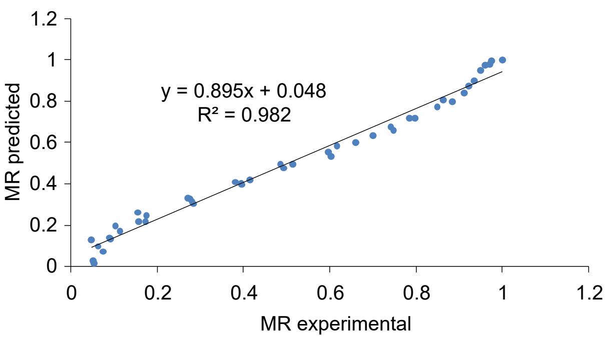

Fig. 4. Compatibility between MR experimental and Logarithmic model of *Artemia* foam (65–80°C)

Effective moisture diffusion and activation energy

The effective moisture diffusion coefficient values of *Artemia* foam ranged from 9.285×10^{-12} to 1.065×10^{-11} m^2/s, at drying temperatures from 65°C to 80°C. D_{eff} values increased significantly as temperature increased, and drying at 80°C gave the highest D_{eff} value. These acquisition values are quite consistent with the estimated D_{eff} values for *Vernonia amygdalina* leaves (Alara et al., 2019). The effective diffusivity for three air temperatures of 40°C, 50°C and 60°C were from 4.55×10^{-12} to 5.48×10^{-12} m^2/s. These results were quite similar to the publication of Taheri-Garavand and Meda (2018) on the study of the drying kinetics of savoury leaves at drying temperatures from 40°C to 80°C. Here, the moisture diffusion coefficient fluctuated between

6.76×10^{-12} and 1.57×10^{-10} m^2/s. However, our results were lower than those of Azizpour et al. (2016), with the average values of the effective diffusivity of samples, at a temperature range of 50°C to 70°C, estimated to be in the range of 3.24–6.49×10^{-9} m^2/s.

To obtain the effect of temperature on effective moisture diffusivity, the values of ln(D_{eff}) versus 1/T (1/K) are recorded. The plot was found to be a straight line over the investigated temperature range, showing an Arrhenius dependence. The activation energy was calculated from the slope of the line and was found to be 26.94 kJ/mol. This value is slightly lower than the value obtained from the shrimp foam drying process (Azizpour et al., 2013; Taheri-Garavand and Meda, 2018), with E_a determined to be 32.16 kJ/mol and 42.07 to 44.74 kJ/mol under different air drying conditions, respectively. The value of activation energy for most agricultural and food products ranges from 12.7 to 110 kJ/mol (John et al., 2014). Lower activation energy indicates less sensitivity to drying temperature.

Effect of temperature and drying time on colour, moisture, a_w and water binding capacity of foam mat *Artemia* powder

Colour is one of the most important quality attributes of food ingredients after drying. This property can be affected by drying temperature and drying time, enzymatic/non-enzymatic browning effects, and humidity (Dehghannya et al., 2018). The *L** value of *Artemia* powder dried in foam under different drying conditions showed a significant difference (from 78.99 to 84.32) (Table 3), when increasing the drying temperature from 65°C to 75°C. However, when increasing the drying temperature from 75°C to 80°C, the *L** value did not show any significant difference. The reason is probably because high temperature reduces drying time, leading to a decline in the double decomposition effect of the Maillard reaction. The addition of albumin as a foaming agent, which is rich in amino acids in its protein, induces the Maillard reaction during high temperature processing (Djaeni et al., 2018).

Moisture content represents the water content in the food system, while a_w measures the free water activity in the food system. This water content is responsible for any biochemical reactions, and is an indicator that determines the shelf life of the produced powder. The moisture and a_w of *Artemia* powder at different temperatures and drying times did not show significant differences, ranging from 4.46 to 4.74 and 0.22 to 0.23, respectively (also presented in Table 3). Salahi et al. (2017) suggested that at higher drying temperatures, the heat transfer rate in the foam system increased, creating a greater driving force for moisture evaporation. The food structure will be more porous at higher DR, leading to dry foam, while the moisture content and a_w also decreased. With an a_w in the product <0.6, it is possible to limit the activity of most microorganisms (Rahman and Labuza, 2007).

Water binding capacity is the amount of water a dry powder is capable of absorbing and represents its hydrating ability. Analytical results showed that the water binding capacity of *Artemia* sponge drying powder ranges from 278.55 ±3.43 to 318.85 ±2.55. The results showed that the rehydration of Artemia powder is quite good (also indicated in Table 3).

Different temperatures and drying times did not significantly affect the nutrients in *Artemia* powder. The contents of protein, lipid, carbohydrate and ash

Table 3. Colour, moisture content, a_w and water binding capacity of foam-mat dried *Artemia* powder at different temperatures

Temperature, °C – Drying time, hrs	*L** value	a_w	Moisture content %	Water binding capacity
65 – 3.5	78.99 ±0.14^a	0.23 ±0.004^a	4.72 ±0.16^a	318.85 ±2.55^d
70 – 3.0	81.75 ±0.33^b	0.22 ±0.005^a	4.74 ±0.12^a	305.25 ±3.20^c
75 – 2.5	84.32 ±0.23^c	0.22 ±0.003^a	4.46 ±0.20^a	298.81 ±1.85^b
80 – 2.0	84.45 ±0.29^c	0.22 ±0.006^a	4.49 ±0.16^a	278.55 ±3.43^a

Mean ±STD; different letters accompanying the mean in the same column represent significant differences ($p < 0.05$).

measured between 79.93 ±0.47 and 80.50 ±1.52%; 1.72 ±0.06 to 1.75 ±0.13%; 6.26 ±0.04 to 6.32 ±0.13% and 6.15 ±0.09 to 6.2 ±0.03%, respectively.

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DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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CONCLUSION

Based on the values obtained, the logarithmic models were adequate in describing the drying process of *Artemia* biomass. It also showed that the best fit with the highest correlation coefficient (R^2), the smallest Chi-square (χ^2), and RMSE were obtained. The diffusion coefficients for *Artemia* and activation energy were determined. With the foam mat drying method, the final product can be produced in a short drying time (2.5 hours) at 75°C, with minimal quality change. Although there have been good applications for the foam drying technique, further research also needs improvements to apply the foam carpet drying process in order to create the highest product quality and an ease of use. It is also possible to combine other drying methods to create significant innovations in the food industry.

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