

DRYING CHARACTERISTICS OF ERI SILKWORM SNACKS AS AFFECTED BY COMBINED MICROWAVE AND HOT AIR DRYING

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Abstract

Combined microwave and hot air drying was proposed as an alternative production method for eri silkworm snacks. Drying behaviors were investigated with variation of initial moisture content (30% and 75% wet basis), air temperature (60°C and 80°C) and microwave power (0-300 W). A suitable drying model was chosen based on the highest coefficient of determination, root mean square and chi square values. Color and hardness of dried eri silkworm were determined and compared with commercial varieties. Results showed that the Page model suitably described the drying characteristic of eri silkworm, and the power and Arrhenius functions correlated well with model parameters. Drying conditions affected product qualities such as color and texture. Optimal conditions for best drying characteristics and highest product quality were initial moisture content of 54%wb and microwave power of 300 W at temperatures of 78°C.

Keywords: Silkworm pupae, drying kinetics, quality aspect, microwave heating

Introduction

Due to an increase in global demand for protein, scientists are continuously seeking efficient, safe and low-impact resources. Insects have been suggested since they contain essential amino acids, fats, vitamins and minerals comparable to meat (Yates-Doerr, 2015). Insects are widely consumed in many countries due to their nutritive value and taste (De Foliart, 1997; van Huis *et al.*, 2013; Nowak *et al.*, 2016). In Thailand, insects have been consumed as food since ancient times, especially in northern and northeastern rural communities.

Recently, entomophagy has expanded from the rural areas and now occurs nationwide (Raksakantong *et al.*, 2010; van Huis *et al.*, 2013; Nowak *et al.*, 2016).

Besides mulberry silkworm pupae (*Bombyx mori*), eri silkworm (*Samia ricinii*) is increasingly consumed due to its high protein content (16%), fat (8%) and minerals (Longvah *et al.*, 2011). Raksakantong *et al.* (2010) reported that fried eri silkworm pupae were highly appreciated by consumers as a new snack food due to their pleasant taste and nutritional values. However, silkworm

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pupae have a short shelf life and quickly turn rancid caused by the reaction between oil and oxygen during storage (Paengkanya *et al.*, 2015; Wray and Ramaswamy, 2015). Consumption of high-oil products can also increase the risk of high blood pressure and heart disease. Therefore, silkworm pupae are not eaten by health-concerned consumers.

Microwave drying has been widely used as an alternative drying method that is faster than hot air drying due to improved energy efficiency (Paengkanya *et al.*, 2015; Wray and Ramaswamy, 2015). Electromagnetic microwaves accelerate the heating rate by direct penetration into moist materials, generating volumetric heat and resulting in rapid water evaporation (Paengkanya *et al.*, 2015; Wray and Ramaswamy, 2015). However, non-uniform electromagnetic waves inside the microwave drying chamber can result in uneven heating of the product (Serowik *et al.*, 2018). This problem can be solved by combining microwave drying with various techniques, including convective hot air, infrared and vacuum drying. The former seems to be most popular since it is flexible and versatile to enhance the drying rate and improve product qualities (Paengkanya *et al.*, 2015; Wray and Ramaswamy, 2015; Serowik *et al.*, 2018).



Figure 1. Drying equipment consisting of a system controller (1), a ½-hp blower (2), 8-kW heating box (3), and a drying chamber (4)

The kinetics of this complex phenomenon and the several factors involved were investigated using a mathematical model as an effective tool to design and optimize the drying processes. Copious research has attempted to mathematically formulate the drying kinetics of foods during microwave treatment such as garlic (Sharma and Prasad, 2006), wheat (Walde *et al.*, 2002), macadamia nut (Silva *et al.*, 2006), grape (Bingol *et al.*, 2008), cashew nut (Tirawanichakul *et al.*, 2011), papaya (Yousefi *et al.*, 2013) and instant rice (Jiao *et al.*, 2014). However, a dependable model is still required to predict drying behavior under convective hot air assisted with microwave energy treatments. To the best of our knowledge, investigations focusing on microwave-assisted hot air drying for eri silkworm pupae as a nutritive snack food have not been

previously published. Here, a mathematical drying model was developed for eri silkworm pupae by combining microwave and hot air drying methods. Drying characteristics and qualities of eri silkworm pupae as affected by initial moisture content, air temperature and microwave output were investigated. Optimal drying conditions were finally determined based on the physical and textural properties of commercial eri silkworm pupae.

Materials and Methods

Samples of Eri Silkworm Pupae

Eri silkworm pupae were purchased from a local market in Kalasin Province, Northeastern Thailand. The samples were sorted based on size of 2.5-3.0 cm in length and approximately 1 cm in diameter. They were then blanched in boiled water for 5 min before storing in a freezer at -10°C. Before the drying experiment, the samples were stabilized at ambient temperature for one hour, and initial moisture content (MC, %wb) was determined following the standard method (AOAC, 1995).

Drying Procedure

The drying equipment (Figure 1) with two drying modes including convective hot air (HA) and combined microwave and hot air drying (MWhA) was employed in this work. Approximately 50 g of eri silkworm pupae (ESP) were spread on a drying tray as a monolayer so that they could absorb microwave energy uniformly. Variations of initial moisture content (30 and 75%wb), microwave power (150 and 300 W) and air temperature (60°C and 80°C) were employed to investigate the effects of operating factors on drying characteristics of ESP. Hot air was supplied through the system with constant velocity of 0.5 m s⁻¹. A 2-level full factorial design with 3 factors was established. Each experiment was conducted until moisture content reached the steady-state condition with triplication. Average values of moisture content were presented as wet basis (wb). Quality attributes in terms of color and texture of dried ESP for each condition were also evaluated.

Mathematical Analysis

Thin-layer Drying Models

Various drying models with different usage parameters are listed in Table 1. For more details concerning each model, refer to Usab *et al.* (2010).

MR in Table 1 is the moisture ratio calculated as $MR = (M_t - M_e)/(M_i - M_e)$, where M_t , M_i , and M_e represents moisture content at any time t , the onset and the equilibrium, respectively. Parameters a , b , c , k , and k_0 are equation constants, and n is a power

constant. All semi-empirical drying models summarized in Table 1 were fitted to the normalized moisture data obtained from all experiments. The following equations of the coefficient of determination (R^2), the root mean square error (RMSE) and the chi-square error (χ^2) were employed to evaluate the accuracy of fit.

Table 1. Summation of thin-layer drying models used in this work

No.	Model	Expression
1	Lewis	$MR = e^{-kt}$ (1)
2	Page	$MR = e^{-kt^n}$ (2)
3	Henderson and Pabis	$MR = ae^{(-kt)}$ (3)
4	Two-term exponential	$MR = ae^{(-kt)} + (1-a)e^{(-kat)}$ (4)
5	Wang and Singh	$MR = 1 + at + bt^2$ (5)
6	Logarithmic	$MR = ae^{(-kt)} + c$ (6)
7	Diffusion approximation	$MR = ae^{(-kt)} + (1-a)e^{(-kbt)}$ (7)
8	Verma <i>et al.</i>	$MR = ae^{(-kt)} + (1-a)e^{(-gt)}$ (8)
9	Two term with 4 parameters	$MR = ae^{(-k_0t)} + be^{(-k_1t)}$ (9)
10	Midilli-Kucuk	$MR = ae^{(-kt^n)} + bt$ (10)

$$\chi^2 = \frac{\sum_{i=1}^N (V_{obs,i} - V_{pre,i})^2}{N - z} \quad (11)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_{obs,i} - V_{pre,i})^2} \quad (12)$$

In Equations 11 and 12, V_{obs} and V_{pre} are the observed value at any experimental run and the corresponding predicted value according to the model being used, N is the number of observations, and z is the number of parameters used in each equation. Suitable drying models of ESP were chosen based on high R^2 and low RMSE and χ^2 values.

Correlations between model constants and operating variables were evaluated using various types of relationships as follows (Usub *et al.*, 2010):

Linear relationship:

$$\text{Constant} = a_1 + a_2MC + a_3T + a_4MW \quad (13)$$

Quadratic relationship:

$$\text{Constant} = a_1 + a_2MC + a_3T + a_4MW + a_5MC^2 + a_6T^2 + a_7MW^2 \quad (14)$$

Logarithmic relationship:

$$\text{Constant} = a_1 + a_2\ln(MC) + a_3\ln(T) + a_4\ln(MW) \quad (15)$$

Power relationship:

$$\text{Constant} = a_1(MC)^{a_2}(T)^{a_3}(MW)^{a_4} \quad (16)$$

Arrhenius relationship:

$$\text{Constant} = a_1(MC)^{a_2}(MW)^{a_3} \exp\left(\frac{-a_4}{T}\right) \quad (17)$$

where a_1 , a_2 , a_3 and a_4 are constant and MC, MW and T are initial moisture content (%wb), microwave power (W) and air temperature ($^{\circ}\text{C}$, but K for Equation 17), respectively. Drying rates (DR) of eri silkworm pupae under different drying conditions were calculated using the following equation:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (18)$$

where M_t is sample weight at a certain time t , and $M_{t+\Delta t}$ is sample weight at $t+\Delta t$.

Effective Diffusivity

In food materials, the falling-rate period plays an important role in drying as moisture transfer is dominated by internal diffusion (Tulek, 2011). Crank (1975) expressed diffusion according to Fick's second law for an unsteady state to describe the drying process during the falling-rate period as follows:

$$\frac{\partial M}{\partial t} = \nabla(D_{eff}(\nabla M)) \quad (19)$$

where D_{eff} is the effective moisture diffusivity (m^2/s) representing the conductive term of all moisture transfer mechanisms, M is the moisture content (dry basis), and t is time (s).

Assuming a uniform initial moisture content, constant effective diffusivity throughout a cylindrical sample, and negligible shrinkage, the analytical solution of Equation (19) given by Crank (1975) can be expressed by:

$$MR = \frac{M(t) - M_e}{M_i - M_e} = \frac{8r^2}{l^2} \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \frac{1}{\lambda_i^2 \beta_j^2} \exp\left(-(\lambda_i^2 + \beta_j^2) \frac{D_{eff}t}{r^2}\right) \quad (20)$$

where r is the radius and l is the length of a characteristic ESP (m), t is the drying time (min), λ_i is the i^{th} root of the Bessel function (2.405, 5.520, 8.654,...) of zero order, $i=1,2,3$ and

$$\beta_j = \frac{(2j-1)\pi}{2l}, j=1,2,3 \quad (21)$$

In practice, only the first term of Equation (20) is considered, yielding:

$$MR = \frac{32}{\lambda_1^2 \pi^2} \exp\left(-(\lambda_1^2 + \beta_1^2) \frac{D_{eff} t}{r^2}\right) \quad (22)$$

Taking the natural logarithm, Equation (22) becomes a straight line of the form $y = y_0 + ax$ as follows:

$$\ln MR = \ln \frac{32}{\lambda_1^2 \pi^2} - \left((\lambda_1^2 + \beta_1^2) \frac{D_{eff}}{r^2}\right) t \quad (23)$$

where

$$y_0 = \ln \frac{32}{\lambda_1^2 \pi^2} \quad (24)$$

and

$$a = -\left((\lambda_1^2 + \beta_1^2) \frac{D_{eff}}{r^2}\right) \quad (25)$$

Thus, the effective moisture diffusivity (D_{eff}) can be estimated for each operating condition from the slope (a) of the plot of $\ln(MR)$ as a function of time (t), Equation (23).

Quality Evaluation

Color Measurement

Color values of eri silkworm pupae dried under different conditions were evaluated using a Hunterlab Colorflex EZ Spectrophotometer in terms of lightness (L^*), redness (a^*) and yellowness (b^*). Hue angle ($^\circ\text{hue}$) was also calculated as $^\circ\text{hue} = \tan^{-1}(b^*/a^*)$.

Textural Property

ESP dried by both drying modes (HA and MWA) were subjected to texture evaluation in terms of hardness using a texture analyzer (Stable Micro System, TA-XT2i, Surrey, UK). A cylindrical probe with diameter of 2 mm steadily moved downward to penetrate a sample with a test speed of 1 mm s^{-1} was used to provide a force-time curve which was obtained using the Texture Expert software supplied with the instrument. The maximum penetration force from this curve was defined as the product hardness. All measurements were replicated ten times for each treatment and average hardness values were presented.

Statistical Analysis and Process Optimization

With triplication, significant difference among the mean were analysed using one-way analysis of variance (ANOVA) with confidence level of 95% ($p < 0.05$). In addition, optimal drying operation was determined using desirability function of each

response. An overall desirability value ranging from 0 to 1 was calculated with regard to highest drying rate (DR), and effective diffusivity (D_{eff}), as well as the targeted qualities of the control, including L^* , a^* , b^* , $^\circ\text{Hue}$, and hardness. The operation with the highest overall desirability was consequently chosen as the optimal drying condition.

Results and Discussion

Drying Characteristics

Thin-layer drying experiments were conducted using two modes, HA and MWA to produce ESP snacks. Figure 2(a) and 2(b) show drying curves under varied air temperatures and microwave outputs with initial MC of 75%wb and 30%wb, respectively.

As seen in Figure 2(a), it took approximately 600 and 270 min to reduce MC of ESP from 75%wb to the desired level of about 7%wb under HA at 60°C and 80°C , respectively. As commonly observed in drying treatment of biological materials, shorter drying time was employed with higher air temperature. When microwave outputs of 150 and 300 W were incorporated with hot air at each

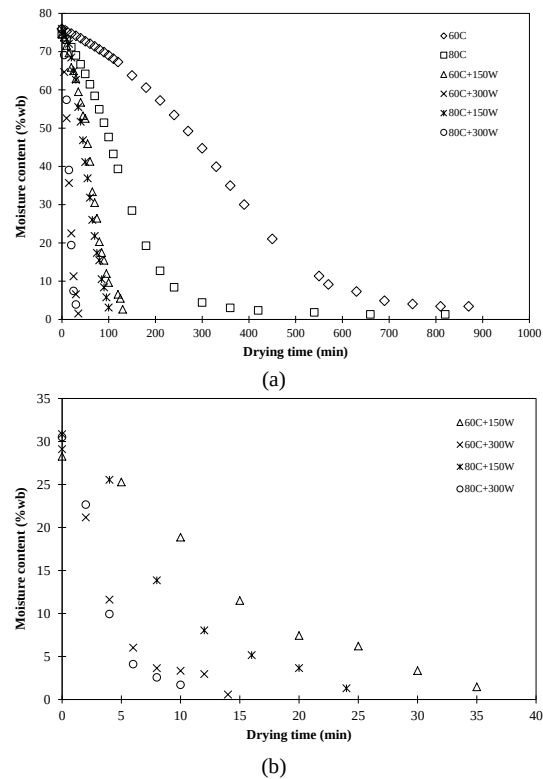


Figure 2. Drying curves at different temperatures and microwave power for (a) 75%wb and (b) 30%wb

temperature, MWAH gave faster drying time for drying ESP to the final MC. It took 110 and 28 min for drying under 60°C with 150 W and 300 W, respectively, while ESP samples were dried to the desired MC in 92 and 25 min under 80°C combined with microwave power of 150 W and 300 W, respectively. It was clear that microwave energy incorporated with convective hot air at a given power reduced drying time at more than 60% compared to drying with HA alone since the incorporation of microwaves improved the moisture diffusion rate. In MWAH operation, water molecules in ESP absorbed microwave energy during the early drying period. This resulted in rapid volumetric heating generated within the material, and consequently moisture from the inner layers moved quickly to the surface (Sharma and Prasad, 2006). However, increase in drying temperature had less effect on drying time at high microwave power (300 W).

To investigate the effect of initial MC on drying characteristics and final product qualities, the MC of fresh samples (~75%wb) were air dried at 60°C and 80°C until reaching 30%wb, before subjection to combined microwave and hot air drying. Figure 2(b) shows the drying curves obtained using microwave power of 150 W and 300 W for each hot-air temperature. Likewise, drying times used to reduce the sample MC from 30%wb to the desired MC of ~7%wb decreased with increasing air temperature and microwave power. Results in Figure 2(b) show that microwave power dominantly affected drying characteristics of ESP, while air temperature had less effect, especially at 300 W when drying times for both air temperatures were insignificant (5 min). However, differences in drying time affected by air temperature were observed at low microwave intensity of 150 W; 23 and 13 min under 60°C and 80°C, respectively.

Figure 3 shows drying rate profile during different operations. All runs showed quite long constant rate periods which lasted down to a critical mean moisture content of about 0.5 g water g⁻¹ dry

matter, and 0.2 g water g⁻¹ dry matter for initial MC of 75% and 30% (wb), respectively. This difference in critical MC was attributed to dependency of drying condition, micro-structure, bond moisture and diffusivity of moisture inside materials (Srikiatden and Roberts, 2007). All operations were followed by a falling rate period in which moisture content decreased to 0.1 g water g⁻¹ dry matter, which was consistent with the results obtained by Usub *et al.* (2010) reporting that moisture content of silkworm reduced from 4.37 g water g⁻¹ dry matter to 0.15 g water g⁻¹ dry matter under solar drying. In addition, this figure shows an obviously different drying manners for varied initial MC; the higher the longer constant rate period. This was due to more water saturated on ESP surface which was enough to be evaporated with a constant rate. This mechanism is commonly found in moist materials (Mujumdar and Devahastin, 2000; Mujumdar, 2007). Moreover, at the fixed initial MC of 75%, microwave power seemed to be more dominant effect as a drying rate fluctuated around 0.15-0.2 g water g⁻¹ dry matter min⁻¹ and about 0.05 g water g⁻¹ dry matter min⁻¹ for 300 W and 150 W, respectively. The same manner was found for initial MC of 30% with lower drying rate.

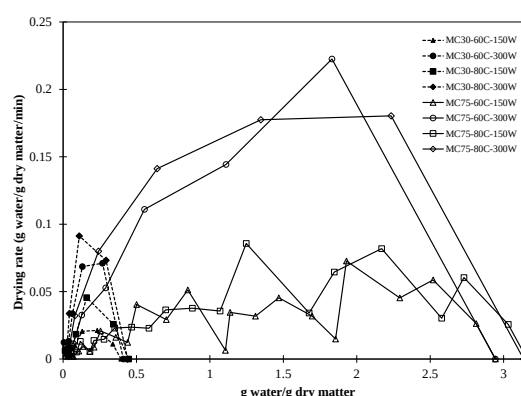


Figure 3. Drying rate as a function of moisture content (g water/g dry matter)

Table 2. The goodness-of-fit parameters

Model	Statistical parameter		
	R ²	RMSE	χ ²
Lewis	0.865 - 0.983	0.0422 - 0.1258	0.0020 - 0.0185
Page	0.976 - 0.998	0.0141 - 0.0493	0.0003 - 0.0033
Henderson and Pabis	0.897 - 0.985	0.0404 - 0.1139	0.0022 - 0.0182
Two-term exponential	0.864 - 0.996	0.0212 - 0.1242	0.0006 - 0.0216
Wang and Singh	0.957 - 0.997	0.0182 - 0.0788	0.0005 - 0.0093
Logarithmic	0.956 - 0.996	0.0204 - 0.0799	0.0007 - 0.0128
Diffusion approximation	0.939 - 0.998	0.0142 - 0.0871	0.0004 - 0.0121
Verma <i>et al.</i>	0.865 - 0.996	0.0209 - 0.1258	0.0008 - 0.0277
Two term	0.897 - 0.985	0.0404 - 0.1139	0.0033 - 0.0332
Midilli-Kucuk	0.968 - 0.999	0.0106 - 0.0584	0.0002 - 0.0066

Drying Models

Table 2 shows the goodness-of-fit parameters for various thin-layer drying models proposed elsewhere (Equations 1-10). As a criterion for model selection, high R^2 and low RMSE and χ^2 values were given by the Page and Midilli-Kucuk models. The Page model gave R^2 values ranging from 0.976 to 0.998, while the RMSE and χ^2 values ranged 0.0141-0.0493 and 0.0003-0.0033, respectively. Compared to the Page model, the Midilli-Kucuk model also showed high values of R^2 and low RMSE and χ^2 ranging 0.968-0.999, 0.0106-0.0584 and 0.0002-0.0066, respectively. Therefore, both the Page and Midilli-Kucuk models gave high consistency with the experimental data for describing the drying behavior of ESP under the combined microwave and hot air drying method.

In most instances, the modified Page and logarithmic models were determined as optimal (Falade and Solademi, 2010; Doymaz, 2011), while the Midilli-Kucuk model (Midilli *et al.*, 2002) was useful for practical proposes. This finding concurred with results reported for solar drying of silkworm (*Bombyx mori*) (Usub *et al.*, 2010), microwave drying of Jerusalem artichoke tubers (Karacabey *et al.*, 2011) and other products such as apricot reported by Mirzaee *et al.* (2010).

However, when the complexity of model parameters was addressed, the Page model appeared to be more suitable as it contained fewer parameters compared to the Midilli-Kucuk model that contained four parameters. Therefore, the more simple Page model was selected to describe the drying characteristics of eri silkworm pupae under combined microwave and hot air drying in the range of 30%-75%, 150-300 W and 60°C-80°C as initial moisture content, microwave power and hot temperature, respectively.

Model parameters of the Page model for all drying conditions were correlated with initial MC, microwave power and air temperature using linear, quadratic, logarithmic, power and Arrhenius type, as expressed in Equations 13-17. Table 3 shows variations of constants and coefficients obtained

from different correlation types. Based on the highest coefficient of determination (R^2), 0.98 for k and 0.81 for n , the power and Arrhenius equations suitably correlated with the Page model parameters for initial MC, microwave power, and air temperature. Consequently, the Page model associated with suitable constant correlations was expressed as follows:

$$MR = \frac{M(t)}{M_0} = e^{-kt^n} \quad (16)$$

where

$$k = 1.8593(MC)^{-3.7565}(T)^{-1.1907}(W)^{2.6671} \quad (17)$$

$$n = 0.0657(MC)^{0.3170}(T)^{0.4194}(W)^{0.0421}$$

represent the power correlation type, and

$$k = 22.3105(MC)^{-6.2988}(W)^{2.6536}e^{\left(\frac{81.7773}{T}\right)} \quad (18)$$

$$n = 0.5928(MC)^{-0.3170}(W)^{0.0421}e^{\left(\frac{28.9583}{T}\right)}$$

represent the Arrhenius correlation type.

However, these correlations were not consistent with the results reported by Usub *et al.* (2010) in which the linear equation was more suitable for describing the relationship between operating parameters and model constants. This could be due to different operating parameters being used.

In food materials, the falling-rate period plays an important role in drying as moisture transfer is dominated by internal diffusion (Tulek, 2011). Effective diffusivity values, D_{eff} , obtained from different drying conditions are presented in Table 4. At initial MC of 75%, the D_{eff} values obtained from hot air drying (6.6083×10^{-8} and $1.0108 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ for 60°C and 80°C, respectively) were approximately 10-fold lower than those obtained from microwave-

Table 3. Correlation of model parameters using the Page model

Type	Constant	Model constants							R^2
		a ₁	a ₂	a ₃	a ₄	a ₅	a ₆	a ₇	
Linear	k	0.074849	-0.001756	-0.000415	0.000392	-	-	-	0.722
	n	0.398243	0.010684	0.009790	0.000140	-	-	-	0.794
Quadratic	k	-64.9742	-1274.96	-2083.01	988.0303	12.14246	14.87863	-2.19562	0.722
	n	-65.3583	-1282.49	-2095.31	993.874	12.21428	14.96656	-2.20861	0.794
Logarithmic	k	0.042462	-0.086258	-0.028822	0.084820	-	-	-	0.729
	n	-3.39590	0.524683	0.680642	0.030282	-	-	-	0.794
Power	k	1.859349	-3.75653	-1.19073	2.667057	-	-	-	0.981
	n	0.065696	0.316972	0.419419	0.042115	-	-	-	0.806
Arrhenius	k	22.31052	-6.29881	2.653563	-81.7773	-	-	-	0.980
	n	0.592837	0.316972	0.042114	28.95835	-	-	-	0.806

assisted hot air drying, ranging from 3.8988×10^{-7} to $1.7065 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. This could be explained by the higher drying rate under combined microwave and hot air drying as $0.0529\text{-}0.1947 \text{ kg water kg}^{-1} \text{ dry matter h}^{-1}$, with $0.0076\text{-}0.0180 \text{ kg water kg}^{-1} \text{ dry matter h}^{-1}$ for hot air drying (Table 4). The D_{eff} obtained from this work seemed to be higher than the normally expected range of 10^{-11} to $10^{-9} \text{ m}^2 \text{ s}^{-1}$ for food materials (Babalís and Belessiotis, 2004). This was due to the fact that the applied microwave power sped up water diffusion rate even in the falling rate period (Chandrasekaran *et al.*, 2013). Çelen (2019) also found that incorporation of microwave energy contributed to higher D_{eff} ($2.97 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ at 120 W to $4.67 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ at 600 W), compared to heated air alone ranging in $7.05 \times 10^{-11}\text{-}2.34 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at $50^\circ\text{C}\text{-}70^\circ\text{C}$ (Doymaz, 2012). For both initial MCs, D_{eff} values increased with higher temperature combined with microwave power of 150 W but air temperature was less effective on moisture migration at 300 W microwave-assisted hot air drying. When considering variation of initial MC with constant air temperature and microwave power, the D_{eff} value increased with lower initial MC, possibly because

moisture diffusion plays a more important role during the falling-rate period, while water evaporation at moist surface depends only on external heat and mass transfer resistance (Chandrasekaran *et al.*, 2013). A similar trend was found for average drying rate that increased with increasing air temperature and microwave power. A slight change in drying time was also observed when using microwave power of 300 W.

Quality Aspects

Color and texture are important quality attributes when making consumption choices. Table 5 presents these values for dried eri silkworm pupae together with the control (commercial ESP product).

As shown in Table 5, color of ESP dried at different drying conditions was represented in terms of L^* (22.84-27.35), a^* (9.05-10.29), b^* (11.34-12.72). For initial MC of 75%wb, the drying method slightly affected the product lightness, especially at microwave power of 300 W, with ESP lighter than dried by conventional hot air. This trend was not found for lower initial MC of 30%. This could be explained by a similar condition for the first drying step when the fresh sample MC was reduced to the

Table 4. Estimated effective diffusivity and averaged drying rate

MC _i (%wb)	Temperature (°C)	MW (W)	D _{eff} (m ² s ⁻¹)	Averaged DR (kg water h ⁻¹)
75	60	0	$6.6083 \pm 0.7101^b \times 10^{-8}$	0.0076 ± 0.0004^f
		150	$3.8988 \pm 0.43123^f \times 10^{-7}$	0.0444 ± 0.0041^c
		300	$1.7165 \pm 0.1175^d \times 10^{-6}$	0.1751 ± 0.0115^a
	80	0	$1.0108 \pm 0.0984^g \times 10^{-7}$	0.0180 ± 0.0023^g
		150	$4.6753 \pm 0.5008^f \times 10^{-7}$	0.0529 ± 0.0048^c
		300	$1.7065 \pm 0.1763^d \times 10^{-6}$	0.1947 ± 0.0227^a
30	60	150	$1.3596 \pm 0.0848^g \times 10^{-6}$	0.0253 ± 0.0019^d
		300	$4.0938 \pm 0.3522^b \times 10^{-6}$	0.1216 ± 0.0155^b
	80	150	$2.1212 \pm 0.1984^c \times 10^{-6}$	0.0453 ± 0.0044^c
		300	$5.1594 \pm 0.4861^a \times 10^{-6}$	0.1212 ± 0.0106^b

Different superscripts denote significance ($p < 0.05$).

MC_i, MW and DR stand for initial moisture content, microwave power, and drying rate, respectively.

Table 5. Color and hardness values of dried Eri silkworm pupae

MC _i (%wb)	T (°C)	MW (W)	Color values				Hardness (N)
			L*	a*	b* ^(ns)	°Hue	
75	60	0	23.18 ± 1.32^b	10.27 ± 0.63^{ab}	12.72 ± 1.52	50.98 ± 1.65^{abc}	7.44 ± 0.85^a
		150	24.28 ± 1.28^b	9.14 ± 0.78^b	11.54 ± 1.96	51.40 ± 2.41^{abc}	6.90 ± 0.71^a
		300	27.35 ± 1.13^a	9.15 ± 0.86^{ab}	11.98 ± 1.42	52.58 ± 0.69^a	5.67 ± 0.47^b
	80	0	22.84 ± 1.02^b	10.33 ± 0.39^a	11.60 ± 0.99	48.26 ± 1.36^{bc}	7.31 ± 1.24^{ab}
		150	23.07 ± 0.82^b	9.05 ± 0.35^b	11.42 ± 1.07	51.53 ± 1.54^{ab}	6.00 ± 0.79^{ab}
		300	24.96 ± 1.55^{ab}	9.22 ± 0.67^b	12.16 ± 1.69	52.69 ± 1.86^{ab}	4.97 ± 0.41^{bc}
30	60	150	23.89 ± 1.25^b	10.29 ± 0.90^b	11.55 ± 1.84	48.12 ± 2.08^{bc}	6.52 ± 1.85^{abc}
		300	23.72 ± 1.06^b	9.67 ± 0.93^{ab}	11.34 ± 1.66	49.42 ± 1.45^{bc}	4.70 ± 0.47^c
	80	150	23.49 ± 0.67^b	9.90 ± 0.36^{ab}	12.12 ± 0.98	50.70 ± 1.25^{abc}	5.80 ± 0.32^b
		300	23.52 ± 1.05^b	9.59 ± 0.60^{ab}	11.93 ± 1.33	51.12 ± 1.38^{ab}	4.50 ± 0.93^{bc}
	control		24.39 ± 0.85^b	10.37 ± 0.63^{ab}	13.69 ± 2.67	52.49 ± 3.79^{abc}	4.73 ± 0.30^c

MC_i, T and MW stand for initial moisture content, hot air temperature and microwave power, respectively.

desired level of 30%wb. Results mainly showed insignificant difference in lightness of ESP dried by the MWA method when compared to the commercial product. The redness of ESP dried under different conditions was presented in terms of a^* value. Results in Table 5 show a slight decrease when using the MWA method compared with conventional drying but with no significant difference from the control sample. The b^* value indicating yellowness of ESP showed insignificant differences for all cases. Varied drying parameters were used to investigate the color of ESP as presented by hue angle ($^\circ\text{hue}$) in Table 5. Hue angles ranged 48.12° - 52.58° in the reddish-yellow range (0 - 60°). For both initial MCs, $^\circ\text{hue}$ value tended to increase with increasing microwave power at a given air temperature, while it had an insignificant effect on this value at the same initial MC and microwave power. Compared with the commercial product, ESP dried by MWA at all conditions gave the same color, except for the sample with initial MC of 30%wb under 60°C assisted with 150 and 300 W at which appeared to show less yellowness.

Hardness also plays an important role in consumer acceptability. Table 5 shows the hardness of ESP as affected by drying variables. Hardness varied with the different drying parameters, ranging from 4.50 to 7.44 N. For initial MC of 75%wb, ESP hardness decreased with increasing microwave power. At this initial MC level, the drying method using microwave power of 150 W for both air temperatures did not affect the hardness compared to hot air drying. A possible explanation for this was

that reduced drying rate in HA and MWA at low microwave power led to product shrinkage and resulted in a tough surface, which is not preferred by consumers for crispy products. For initial MC of 30%wb, ESP was softer and more easily penetrated by a needle probe, inferring higher crispiness at increased microwave power. This trend was not observed when considering the effect of temperature at constant microwave power. ESP dried by the MWA drying method with initial MC of 30%wb showed texture hardness similar to the fried commercial product, while the conventional drying methods and MWA with high initial MC provided the hardest surface.

It could be observed from Table 5 that all operating factors influenced on not only drying characteristics but also the product qualities. Hence, optimal microwave assisted with hot air drying operation was dependent on initial MC, air temperature and microwave power. Based on the highest drying rate (DR) and effective diffusivity (D_{eff}), as well as the targeted qualities of the control, including L^* , a^* , b^* , $^\circ\text{Hue}$, and hardness, the optimal operations with overall desirability value higher than 0.7 are summarized in Table 6. These corresponded to initial MC in a range of 49%-60% (wb), air temperature of 69°C - 80°C and microwave power of 300 W. However, considering the feasibility of operation, initial MC of 54%wb, air temperature of 78°C and microwave power of 300 W was considered as the globally suitable drying operation.

Table 6. Optimal drying conditions with high overall desirability values (>0.7)

MC %wb	T $^\circ\text{C}$	MW W	DR (kg water h^{-1})	DE ($\text{m}^2 \text{s}^{-1}$)	L^* -	a^* -	b^* -	$^\circ\text{Hue}$ -	Hardness (N)
53.60	78.02	300.00	0.16	329.87	24.39	9.37	12.01	51.86	4.76
53.47	77.95	300.00	0.16	330.70	24.39	9.38	12.01	51.85	4.76
53.80	78.12	300.00	0.16	328.67	24.39	9.37	12.02	51.87	4.76
54.10	78.28	300.00	0.16	326.79	24.39	9.37	12.02	51.89	4.77
53.15	77.78	300.00	0.16	332.62	24.39	9.38	12.01	51.83	4.76
54.49	78.47	300.00	0.16	324.33	24.39	9.37	12.03	51.91	4.77
52.57	77.45	300.00	0.16	336.07	24.39	9.38	12.00	51.79	4.75
52.72	77.97	300.00	0.16	336.31	24.36	9.38	12.01	51.82	4.75
52.10	77.18	300.00	0.16	338.80	24.39	9.39	11.99	51.76	4.75
52.56	78.37	300.00	0.16	338.57	24.33	9.38	12.01	51.83	4.75
55.56	78.99	300.00	0.16	317.49	24.39	9.36	12.04	51.97	4.78
52.34	78.37	300.00	0.16	340.17	24.32	9.38	12.01	51.83	4.74
54.75	79.39	300.00	0.16	324.57	24.33	9.36	12.05	51.96	4.76
51.74	78.29	300.00	0.16	344.48	24.31	9.39	12.01	51.80	4.74
51.77	78.40	300.00	0.16	344.52	24.30	9.39	12.01	51.81	4.74
51.20	76.64	300.00	0.15	343.86	24.39	9.40	11.97	51.70	4.74
54.35	79.69	300.00	0.16	328.39	24.30	9.37	12.05	51.96	4.76
52.99	79.57	300.00	0.16	338.40	24.26	9.38	12.04	51.90	4.74
53.88	79.88	299.99	0.16	332.41	24.27	9.37	12.05	51.95	4.75
49.04	75.15	300.00	0.15	355.04	24.39	9.42	11.93	51.54	4.71
60.34	80.00	300.00	0.17	283.11	24.46	9.32	12.09	52.18	4.82
49.26	69.28	300.00	0.15	335.70	24.74	9.43	11.81	51.25	4.73

Conclusions

Convective hot air drying combined with microwave heating was used to investigate the drying characteristics and physical and textural properties of eri silkworm. From several empirical drying models, the Page model was chosen as the most suitable based on highest R^2 and lowest χ^2 to describe drying behavior. The Page model parameters correlated with initial moisture content, drying temperature and microwave energy for power and Arrhenius functions. Quality aspects as color and hardness of eri silkworm dried at high microwave power and low initial moisture content were acceptable compared with commercial eri silkworm snacks. ESP could be optimally dried at initial MC of 54%wb under air temperature of 78°C assisted with microwave energy of 300 W.

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References

- AOAC. (1995). Official Methods of Analysis. 16th Edition, Association of Official Analytical Chemists, Washington DC.
- Babalís, S.J. and Belessiotis, V.G. (2004). Influence of the drying conditions on the drying constants and moisture diffusivity during the thin layer drying of figs. *J. Food Eng.*, 65:449-458.
- Bingol, G., Pan, Z., Roberts, J.S., Devres, Y.O., and Balaban, M.O. (2008). Mathematical modelling of microwave-assisted convective heating and drying of grapes. *Int. J. Agric. Biol. Eng.*, 1(2):46-54.
- Çelen, S. (2019). Effect of microwave drying on the drying characteristics, color, microstructure, and thermal properties of Trabzon Persimmon. *Foods*, 8(8):1-19.
- Crank, J. (1975). *Mathematics of Diffusion*. 2nd ed. Oxford University Press, London, UK, 414p.
- Chandrasekaran, S., Ramanathan, S., and Basak, T. (2013). Microwave food processing - A review. *Food Res. Int.*, 52:243-261.
- De Foliat, G.R. (1997). An overview of the role of edible insects in preserving biodiversity. *Ecol. Food Nutr.*, 36(2-4):109-132.
- Doymaz, İ. (2011). Thin-layer drying characteristics of sweet potato slices and mathematical modelling. *Heat Mass Transfer*, 47:277-285.
- Doymaz, İ. (2012). Evaluation of some thin-layer drying models of persimmon slices (*Diospyros kaki* L.). *Energy Convers. Manag.*, 56:199-205.
- Falade, K.O. and Solademi, O.J. (2010). Modelling of Air drying of fresh and blanched sweet potato slices. *Int. J. Food Sci. Technol.*, 45(2):278-288.
- Jiao, A., Xu, X., and Jin, Z. (2014). Modeling of dehydration-rehydration of instant rice in combined microwave-hot air drying. *Food Bioprod. Process.*, 92:259-265.
- Karacabey, E., Baltacıoğlu, C., and Çevik, M. (2011). Microwave drying of Jerusalem artichoke (*Helianthus tuberosus* L.). *Akademik Gıda.*, 9(6):13-22.
- Longvah, T., Mangthya, K., and Ramulu, P. (2011). Nutrient composition and protein quality evaluation of eri silkworm (*Samia ricini*) prepupae and pupae. *Food Chem.*, 128:400-403.
- Midilli, A.H. Kucuk, H., and Z. Yapar, Z. (2002). A new model for single layer drying. *Dry. Technol.*, 20(7):1,503-1,513.
- Mirzaee, E., Rafiee, S., and Keyhani, A. (2010). Evaluation and selection of thin-layer models for drying kinetics of apricot (cv. NASIRY). *Agric. Eng. Int.: CIGR J.*, 12(2):111-116.
- Mujumdar, A.S. and Devahastin, S. (2000). Fundamental principles of drying (pp. 1-22) in S. Devahastin (Ed.) *Mujumdar's Practical Guide to Industrial Drying*. Exergex, Brossard.
- Mujumdar, A.S. (Ed.) (2007). *Handbook of Industrial Drying*. 3rd edition. CRC press, Boca Raton.
- Nowak, V., Persijn, D., Rittenschober, D., and Charrondiere, U. R. (2016). Review of food composition data for edible insects. *Food Chem.*, 193:39-46.
- Paengkanya, S., Soponronnarit, S., and A. Nathakaranakule. (2015). Application of microwaves for drying of durian chips. *Food Bioprod. Process.*, 96:1-11.
- Raksakantong, P., Meeso, N., Kubola, J., and Siriamornpun, S. (2010). Fatty acids and proximate composition of eight Thai edible tericolous insects. *Food Res. Int.*, 43(1):350-355.
- Serowik, M., Figiel, A., Nijman, M., Pudlo, A., Chorazyk, D., Kopec, W., Krokosz, D., and Rychicka-Rybska, J. (2018). Drying characteristics and properties of microwave-assisted spouted bed dried semi-refined carageenan. *J. Food Eng.*, 221:20-28.
- Sharma, G.P., and Prasad, S. (2006). Optimization of process parameters for microwave drying of garlic cloves. *J. Food Eng.*, 75:441-446.
- Silva, F.A., Marsaioli Jr., A., Maximo, G.J., Silva, M.A.A.P., and Gonçalves, L.A.G. (2006). Microwave assisted drying of macadamia nuts. *J. Food Eng.*, 77:550-558.
- Srikiatden, J. and Roberts, J.S. (2007). Moisture transfer in solid food materials: a review of mechanisms, models, and measurements. *Int. J. Food Prop.*, 10(4):739-777.
- Tirawanichakul, S., Saenaratana, N., Boon-yakiat, P., and Tirawanichakul, Y. (2011). Microwave and hot air drying of cashew nut: drying kinetics and quality aspects. *Proceeding of IEEE Colloquium on Humanities, Science and Engineering Research*, Renang, p. 825-830.
- Tulek, Y. (2011). Drying kinetics of oyster mushroom (*Pleurotus ostreatus*) in a convective hot air dryer. *J. Agr. Sci. Tech.*, 13:655-664.
- Usub, T., Lertsatitthakorn, C., Poomsa-ad, N., Wiset, L., Siriamornpun, S. and Soponronnarit, S. (2010). Thin layer solar drying characteristics of silkworm pupae. *Food Bioprod. Process.*, 88:149-160.
- van Huis, A., Van Itterbeeck, J. Klunder, H. Mertens, E. Hal-loran, A. Muir, G., and Vantomme, P. (2013). Edible insects: Future prospects for food and feed security. In: *Food and Agri-culture Organization of the United Nations (FAO) Forestry Paper*, vol. 171. p. 67-79.
- Walde, S.G., Balaswamy, K., Velu, V., and Roa, D.G. (2002). Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). *J. Food Eng.*, 55:271-276.
- Wray, D. and Ramaswamy, H.S. (2015). Novel concepts in microwave drying of foods. *Dry. Technol.*, 33:769-783.
- Yates-Doerr, E. (2015). The world in a box? Food security, edible insects, and "One World, One Hearth" collaboration. *Social Science and Medicine*, 129:106-112.
- Yousefi, A., Niakousari, M., and Moradi, M. (2013). Microwave assisted hot air drying of papaya (*Carica papaya* L.) pretreated in osmotic solution. *Afr. J. Agric. Res.*, 8(25):3,229-3,235.