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Microwave and hot-air drying of Thai red curry paste

Sudathip Inchuen[1,*], Woatthichai Narkrugsa[1], Pimpen Pornchaloempong[2], Pipat Chanasinchana[2], and Teerapon Swing[2]

[1] Faculty of Agroindustry, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520 Thailand

[2] Department of Food Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520 Thailand

*Corresponding author, Tel. +66812944469; Fax +6623264091; E-mail : sudathip4@hotmail.com

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Abstract: Thai red curry paste was dried with two different drying methods: microwave and hot-air drying. The microwave drying was carried out in a microwave oven with output power of 180, 360 and 540 W, while the hot-air drying was carried out at drying air temperatures of 60, 70 and 80 °C. The drying time of microwave drying process to reduce the moisture content of red curry paste from 2.58 to 0.08 g water/g dry matter was much shorter than that of the hot-air drying process. An increase in the microwave power significantly decreased the drying time. In the hot-air drying, increasing the drying air temperature also significantly decreased the drying time. Microwave drying process of red curry paste consisted of three drying periods, i.e. heating up, constant rate and falling rate periods, while hot-air drying process consisted of two drying periods, i.e. heating up and falling rate periods. To describe the effect of microwave power and drying air temperature on drying kinetics of red curry paste, three different mathematical thin-layer equations, i.e. Lewis, Page and Henderson-Pabis models, were used to fit the drying data. The fitness by these models was evaluated using the coefficient of determination (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE). The Page model provided the best fit to both microwave and hot-air drying experimental data.

Keywords: Thai red curry paste, microwave drying, hot-air drying

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Introduction

Thai red curry paste is one of the most famous kinds of curry paste used to enhance several spicy Thai dishes. It provides the colourful, spicy and authentic aroma of certain dishes. Fresh Thai red curry paste in a semi-solid form has a short shelf life due to its high moisture content (more than 40%). The growing popularity of Thai food around the world creates the need to preserve this product. Drying is one of the preservative methods that can extend the shelf life of red curry paste.

Drying, as a preservation method, is a very important aspect of food processing. Drying can be defined as a simultaneous heat and mass transfer operation in which water activity of the material is lowered by evaporation of water into an unsaturated gas stream [1]. The main attribute of drying is to lower water activity of the product, and consequently to inhibit the growth of microorganisms and decrease chemical reactions to prolong the shelf life of the product at room temperature.

Hot-air drying is the most widely used method to produce dried foods and agricultural products because of their low investment and operation costs. It is mostly suitable for solid materials such as grains, sliced fruits and vegetables, and chunked products [2]. However, a disadvantage of hot-air drying is that it takes a long period of time even at high temperatures that may cause serious damage to the product quality attributes such as flavour, colour, texture and nutrients. Other disadvantages include reduction in bulk density and rehydration capacity of the dried product [3-4]. Therefore, there is a need to optimise conditions to obtain high-quality dried products.

Microwave drying is an alternative drying method which offers a considerable reduction of drying time. Microwave application has been reported to improve product properties resulting in a better aroma and faster and better rehydration with considerable saving in energy [5]. Microwave drying technique effectively improves the final quality of agricultural products such as grains [6], vegetables [7-8] and fruits [9-11]. However, it may result in a poor-quality product if not properly applied [3,12].

Several phenomena related to heat and mass transfers are involved in the drying process. There are numerous empirical equations describing the process which are useful in modelling its kinetics. The mathematical modelling of drying is crucial for the optimisation of operating parameters and performance improvement of the drying system. The drying characteristics of many agricultural products including pepper [13-14], parsley [15], bay leaves [16], mint leaves [17], carrot [18], kale [19], spinach [8], okra [20], amaranth seed [21], aloe vera [22], apple[23-24], grapes[25] and rice[26] have been examined by researchers using various models. However, the modelling of drying of Thai red curry paste have not been found in the literature. The aim of this study, therefore, is to investigate the effect of microwave power and drying air temperature on drying time and drying rate of Thai red curry paste and to obtain the kinetics of microwave and hot air drying of Thai red curry paste by using thin-layer models.

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Materials and Methods

Experimental materials

Thai red curry paste produced by Namprick Maesri Limited Partnership (245 Petkasem Road, Nakornpathom, Thailand) was used. Ingredients of this product are: dried red chili 35%, garlic 23%, shallot 20%, salt 7%, lemon grass 6%, sugar 3%, Kaffir lime 2%, galangal 1% and spice (coriander seed, cumin and cardamom) 1%. The paste samples were stored at - 60ºC until experiment time. Prior to each drying experiment, the paste samples were taken out of storage and thawed to 20ºC at room temperature. The moisture content of samples was measured individually according to the hot-air oven method [27]. The initial moisture content of the red curry paste was determined as 258% dry basis. In each drying experiment, 55 ± 1 g paste material were uniformly spread on the translucent plastic sheet with thickness of 1 mm and a dimension of 180 x 180 mm. Each sample was placed at the centre of the drying equipment.

Experimental procedure

A domestic microwave oven (HITACHI, MR-30A, Thailand) with a maximum output of 900 W at 2450 MHz was used for the microwave drying experiments. The dimension of microwave cavity was 520(W) x 376(D) x 292(H) mm. The oven had a carousel in the cavity with a digital panel to regulate the microwave power and the processing time. The paste samples were dried at three different levels of microwave power (180, 360 and 540 W). Moisture loss was periodically measured at 1 min intervals during drying by removing the plastic sheet from the drying equipment and weighing on the digital balance (0.01g accuracy, Shimadzu, BL-200H, Japan). The final temperatures of dried curry paste were measured by an infrared thermometer (Chino, Japan).

A hot-air oven (Path OV663, Thailand) was used for the hot-air drying experiments. The dimension of the oven cavity was 800(W) x 900(D) x 1500(H) mm with a 3-kW heater and a fixed air velocity. The air velocity was measured with an anemometer (Testo 425, GmbH&Co, Germany) and was found to be 9.02 m/s. The paste samples were dried at three different drying air temperatures (60, 70 and 80ºC). The oven was switched on 1 h before the drying process to equilibrate the temperature. Moisture loss was periodically measured at 10-min intervals during drying.

The drying procedure was continued until the weight of the paste samples was reduced to a level corresponding to a moisture content of about 8 %. All weighing processes were completed in less than 10 s during the drying process to avoid loss or gain of moisture to or from the environment.

Modelling of the thin-layer drying curves

Effectively thin-layer modelling of the drying behaviour is important for investigation of drying characteristics of red curry paste. In this study, the microwave drying data at different levels of microwave power and the hot-air drying data at different drying air temperatures were fitted by the three commonly used drying models, i.e. Lewis, Page and Henderson-Pabis.

The Lewis model has been widely applied to predict the thin-layer drying data of cereal and food products exhibiting a decreasing drying rate [21]. It assumes that the internal resistance of water

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diffusion is negligible, resulting in a simple lumped equation, which only takes into account the surface resistance to moisture transfer:

$$MR = \frac{W - W_e}{W_0 - W_e} = \exp\left(-k_L t\right) \tag{1}$$

where MR is the moisture ratio, W is the experimental moisture content, W_e is the equilibrium moisture content, W_0 is the initial moisture content, k_L is a drying parameter in $\min^{-1}$, and t is the time in min.

The Page model is a modified empirical solution of the Lewis model [21]:

$$MR = \frac{W - W_e}{W_0 - W_e} = \exp\left(-k_p t^n\right) \tag{2}$$

where an empirical drying exponent n is introduced to improve the model prediction in addition to the drying parameter k_p in $\min^{-1}$.

The final drying equation selected is the Henderson-Pabis model, modified from Eq. (1) with an empirical constant A and the drying parameter k_H in $\min^{-1}$ [21]:

$$MR = \frac{W - W_e}{W_0 - W_e} = A \exp\left(-k_H t\right) \tag{3}$$

This equation is the simplest approximation to the well-known diffusion model, when only one term of the infinite series is used.

It was assumed that the equilibrium moisture content is zero for microwave and hot air drying. Then the expression can be reduced to: $MR = \frac{W}{W_0}$. The parameters of all models were estimated by using SPSS (Statistical Package for Social Science) software version 11, SPSS Inc., 1989-2001.

The drying rate of red curry paste during the drying experiment was calculated using the following equation:

$$Drying\ rate = \frac{W_{t+td} - W_t}{dt} \tag{4}$$

where W_t is the moisture content (g water/g dry matter) at time t, W_{t+td} is the moisture content at time $t+dt$, and t is drying time (min).

Statistical analysis

The statistical analysis of data was carried out using SPSS (Statistical Package for Social Science) software version 11, SPSS Inc., 1989-2001, for the analysis of variance (ANOVA) in determining significant differences between different drying methods at a confidence level of 95% ($p < 0.05$). Variable means were compared by Duncan's Multiple Range Test. The fitness of the tested mathematical models to the experimental data was evaluated with the coefficient of determination (R^2),

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reduced chi-square (χ^2) and root mean square error (RMSE). The higher R^2 the values and the lower the $\chi^2$and RMSE values, the better is the fitness. The $\chi^2$and RMSE can be calculated as follows:

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

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2} \quad (6)$$

where $MR_{\exp,i}$ is the *i*th experimental moisture ratio, $MR_{pre,i}$ is the *i*th predicted moisture ratio, N is the number of observations, and z is the number of constants in the drying model.

Results and Discussion

Drying behaviour

Thai red curry paste was dried with two different drying methods: microwave and hot-air drying, to reduce the moisture content of red curry paste from 2.58 to 0.08 g water/g dry matter. The influence of microwave power and drying air temperature on the moisture content versus drying time curve are shown in Figure 1. The drying time to reach the final moisture content for microwave drying was 23, 12 and 8 min at 180, 360 and 540 W respectively, while that for hot-air drying was 240, 180 and 130 min at 60, 70 and 80 ºC respectively. The time required for microwave drying of red curry paste was much shorter than for hot-air drying. This phenomenon indicated that the mass transfer of drying sample was rapid during microwave heating because the microwave penetrated directly into the sample. The heat was generated inside the sample and provided fast and uniform heating throughout the entire product, thus creating a large vapour pressure differential between the centre and the surface of product and allowing rapid transport and evaporation of water. An increase in microwave power significantly shortened the drying time. Similar results were found by Sunmu et al. [28], Alibas Ozkan et al. [8] and Wang et al. [24] on the study of microwave drying of carrot, spinach and apple pomace respectively. Varith et al. [11] also found that drying time for combined microwave-hot air drying of peeled longan was shortened by increasing the microwave power. In hot-air drying, increasing of drying air temperature also shortened the drying time significantly. Similar results were found by Doymaz [20], Abalone et al. [21] and Vega et al. [22] for hot-air drying of okra, amaranth seeds and aloe vera respectively.

The drying rate was calculated as the quantity of moisture removed per unit time per unit dry matter. The drying rate plotted against moisture content during microwave and hot-air drying was shown in Figure 2. It can be seen that the thin-layer microwave drying process of red curry paste consisted of three drying periods: heating up, constant rate, and falling rate periods, while the hot-air drying process exhibited only two drying periods: heating up and falling rate periods. The microwave drying rate results agreed with the study of parsley and mint leaf microwave drying as reported by Soysal [15] and Özber and Dadali [17]. Those researchers found that after a short heating up period, a

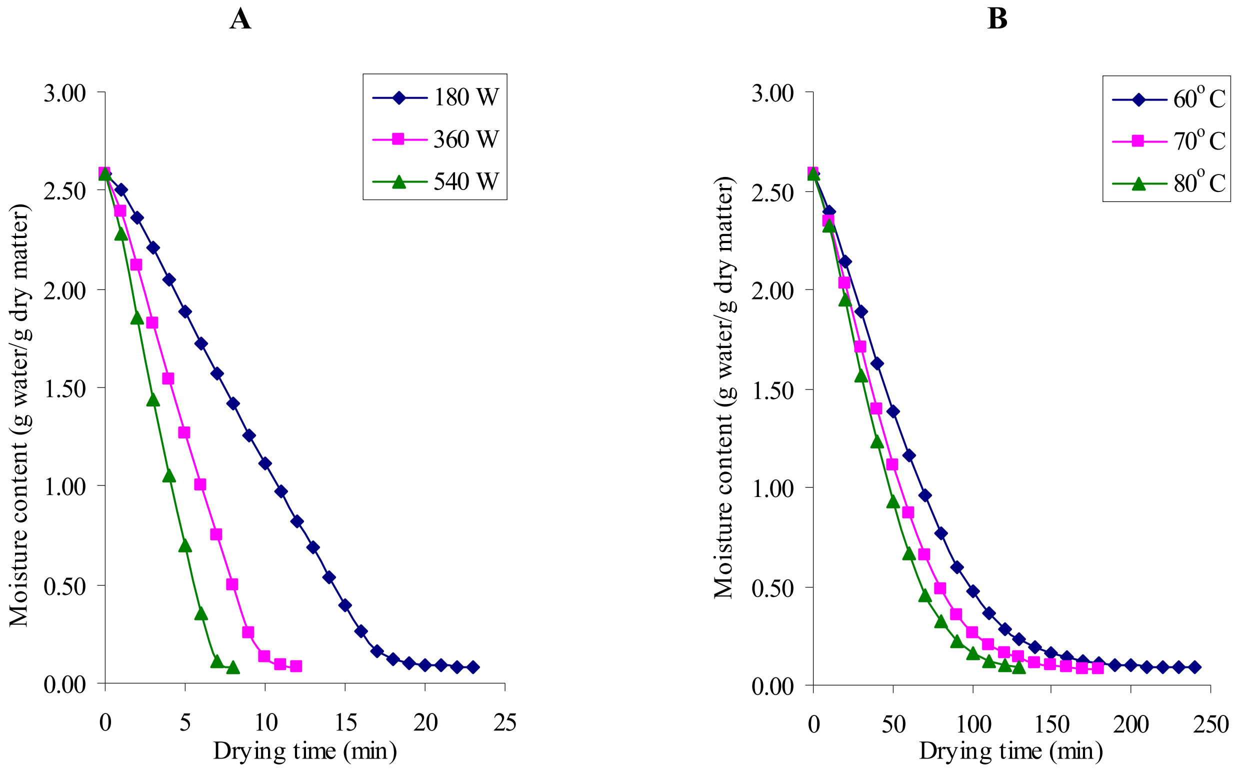

Figure 1. Moisture content versus drying time curves during microwave drying (A) and hot-air drying (B)

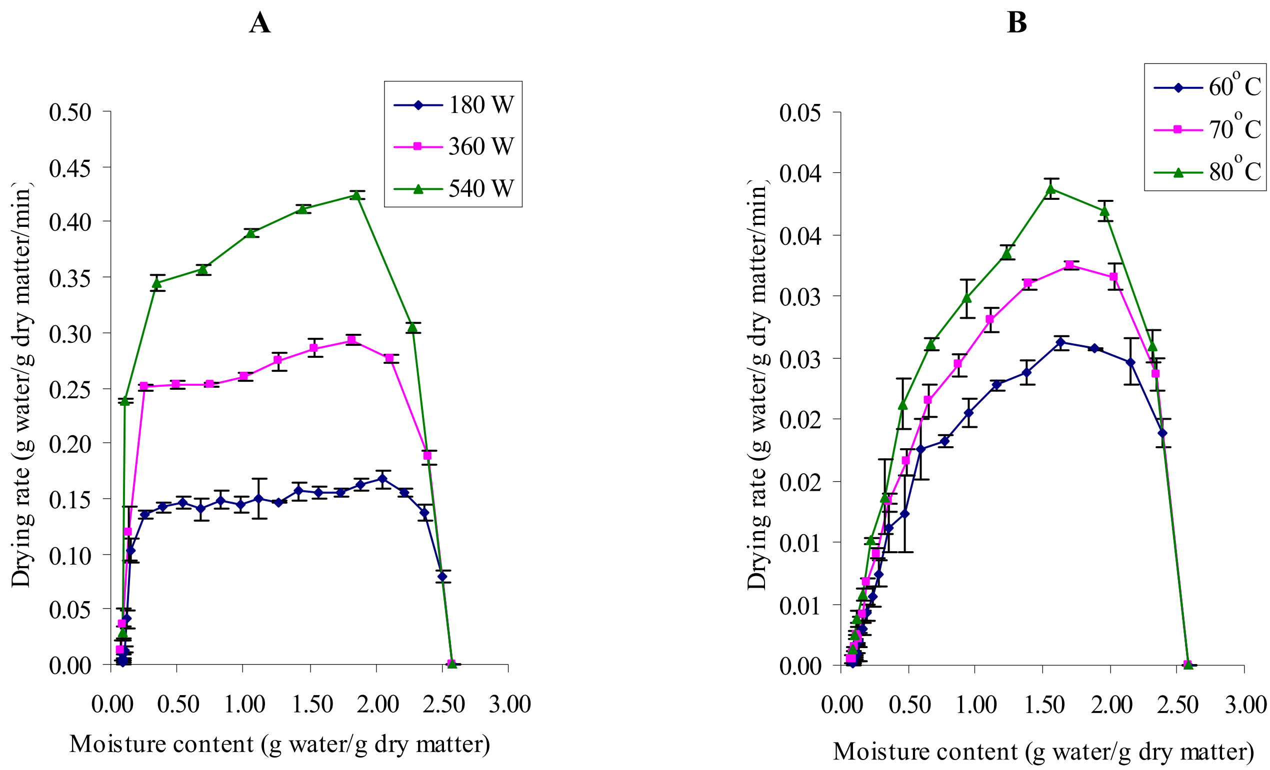

Figure 2. Drying rate versus moisture content curves during microwave drying (A) and hot-air drying (B)

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constant rate and falling rate periods were observed. However, Maskan [5,10] reported only falling rate period in microwave drying of banana and kiwi fruit. In hot-air drying, similar results were reported for red bell pepper [14] and strawberry [29]. Vega et al. [22] also reported that in the hot-air drying process of products of vegetal origin, the constant rate period was not observed, and there was a marked falling rate period due to the quick moisture removal from the samples. However, opposite observation was reported by Maskan [5] who stated that a short constant rate period during the drying of high moisture content products was observed by using lower drying temperatures such as 40-50 ºC.

At the beginning of drying period in microwave drying, the microwave energy is converted into thermal energy within the moist samples, resulting in increased paste temperature with time. For hot-air drying, the paste heats up due to heat transfer from the air to the paste. Once the vapour pressure in the paste is higher than that of the environment, the paste starts to lose moisture, but at a slow rate. As the microwave power and drying air temperature increase, the drying rate during the heating up period significantly increases, the mass transfer rapidly occurring in the higher microwave power and drying air temperature.

After a short heating up period, a constant rate period was observed only during microwave drying, but not during conventional hot-air drying. This was because the air in the microwave oven was saturated and formed a thick film around the paste, preventing effective evaporation of moisture from the paste. Thus, a constant rate period was observed. In this period, thermal energy that was converted from microwave energy was used for moisture vaporisation, the rate of which depends on the microwave power.

The final period was the falling rate period in which the moisture content decreased to 0.08 g water/g dry matter for all drying conditions. In microwave drying, this period started at moisture content of 0.25-0.35 g water/g dry matter, while in hot-air drying it started at moisture content of 1.50-1.63 g water/g dry matter. Results showed that in hot-air drying, this period started at a high moisture content. It was possible that in this case the paste surface became dry and prevented effective moisture removal from the surface. Meanwhile, the microwave remained heating the moisture inside the product so that its temperature increased continuously. After this period, therefore, the paste burned and became non-usable as the dried product temperature reached 83.8, 95.4 and 96.6 ºC at the microwave power of 180, 360 and 540 W respectively. The results suggested that microwave drying should not be continued after the constant rate period.

Drying models

To describe the effect of microwave power and drying air temperature on the kinetics of red curry paste drying, three different thin-layer drying models, i.e. Lewis, Page and Henderson-Pabis were used. The drying parameter k_L in Eq. (1), k_p and n in Eq. (2), and k_H and A in Eq. (3) were estimated for each drying method. The coefficient of determination (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) were used to assess the best model characterising the drying curves. The estimated parameters and statistical analysis of the models for a given drying condition are presented in Table 1. The analysis of variance (ANOVA) at 95% confidence level indicated that microwave power and drying air temperature significantly affected (p<0.05) the drying parameters k_L, k_p and k_H. However, k_p showed no statistical difference ($p \geq 0.05$) with respect to drying air temperature. Azzouz

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Table 1. Estimated coefficients and statistical analysis of three thin-layer drying models

Drying method	Model	Model constant		R^2	χ^2	*RMSE*
	Lewis $MR = \frac{W - W_e}{W_0 - W_e} = \exp(-k_L t)$	k_L (min $^{-1}$)*				
Microwave drying						
180 W		0.1423 [c]		0.9543	0.0210	0.1419
360 W		0.2515 [b]		0.9453	0.0224	0.1438
540 W		0.3616 [a]		0.9427	0.0224	0.1412
Hot-air drying						
60 ºC		0.0163 [f]		0.9893	0.0032	0.0551
70 ºC		0.0210 [e]		0.9940	0.0037	0.0593
80 ºC		0.0261 [d]		0.9917	0.0071	0.0809
	Page $MR = \frac{W - W_e}{W_0 - W_e} = \exp(-k_p t^n)$	k_p (min $^{-1}$)*	n*			
Microwave drying						
180 W		0.0267 [c]	1.5692 [b]	0.9903	0.0012	0.0330
360 W		0.0640 [b]	1.5876 [b]	0.9880	0.0011	0.0307
540 W		0.1097 [a]	1.6173 [a]	0.9883	0.0011	0.0288
Hot-air drying						
60 ºC		0.0051 [d]	1.2378 [e]	0.9847	0.0024	0.0391
70 ºC		0.0056 [d]	1.2793 [d]	0.9920	0.0005	0.0212
80 ºC		0.0045 [d]	1.3892 [c]	0.9977	0.0001	0.0095
	Henderson-Pabis $MR = \frac{W - W_e}{W_0 - W_e} = A\exp(-K_H t)$	k_H (min $^{-1}$)*	A*			
Microwave drying						
180 W		0.1765 [c]	1.7077 [a]	0.9383	0.0429	0.1982
360 W		0.3130 [b]	1.6695 [a]	0.9263	0.0555	0.2166
540 W		0.4442 [a]	1.5966 [b]	0.9187	0.0613	0.2182
Hot-air drying						
60 ºC		0.0163 [e]	1.0048 [e]	0.9617	0.0038	0.0581
70 ºC		0.0220 [e]	1.1223 [d]	0.9830	0.0023	0.0449
80 ºC		0.0289 [d]	1.2904 [c]	0.9893	0.0086	0.0860

* Means within column with different superscripts are significantly different (p<0.05).

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et al. [30] reported that drying parameter *k* of the Page and Modified Page models was a function of both air temperature and initial moisture content of the product, and was much higher in microwave drying than in hot-air drying. As microwave power increased, the drying parameters significantly increased. Similar results were obtained by Maskan [5], Vega et al. [22] and Wang et al. [24] on the study of banana, aloe vera and apple pomace respectively.

Results showed that the microwave drying parameters were higher than those of hot-air drying. Parameters *n* and *A* were significantly different (p<0.05) due to different drying methods. Parameter *n* increased as the microwave power and drying air temperature increased. On the other hand, parameter *A* increased as the microwave power decreased and drying air temperature increased. The results agreed with reports on several fruits, such as fruits with and without skin [31], grapes [30] and figs [32]. However, some studies showed different results, in which parameter n of beans, potatoes, pears [33] and red bell pepper [14] was constant with temperature.

Among the three, the Page model provided the best explanation for microwave and hot-air drying behaviour due to a higher coefficient of determination (R^2 = 0.9847-0.9977), lower chi-square (χ^2 = 0.0001-0.0024) and lower RMSE (0.0095-0.0391) than those from other models. Several authors reported good results when applying the Page model on drying kinetics of foods, such as red pepper [13], bay leaves [16], okra [20], amaranth seed [21], nettle leaves [8], sultana grapes [25], avocado and banana [34], and rosemary leaves [35]. Comparison between experimental and predicted results from the Page model is illustrated in Figure 3.

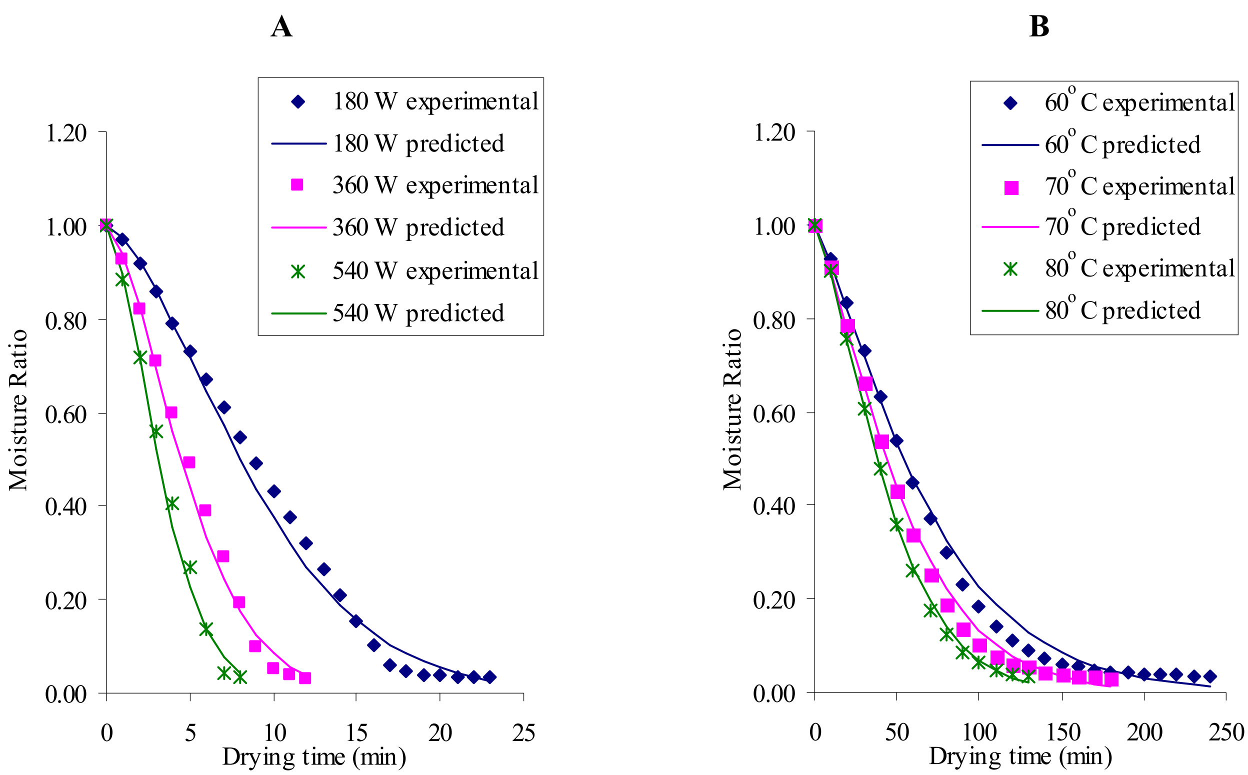

Figure 3. Comparison between experimental and predicted curves of moisture ratio vs. drying time by Page model for red curry paste during microwave drying (A) and hot-air drying (B)

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Conclusions

The effects of microwave and hot-air drying methods on drying behaviour of Thai red curry paste were examined in this study. It was found that the time required for microwave drying to reduce the moisture content from 2.58 to 0.08 g water/g dry matter was 23, 12 and 8 min at 180, 360 and 540 W respectively. This was much shorter than that for hot-air drying, which was 240, 180 and 130 min at 60, 70 and 80 ºC respectively. An increase in microwave power and drying air temperature shortened the drying time for both processes. Microwave drying of red curry paste showed three drying periods, i.e. heating up, constant rate and falling rate periods, while hot-air drying exhibited only heating up and falling rate periods. The Page model provided the best prediction for both microwave and hot-air drying processes. The drying parameters k_p and n were estimated. Both parameters increased with an increase in microwave power. The k_p and n values for microwave drying were 0.0267, 0.0640 and 0.1097 min^{-1}, and 1.5692, 1.5876 and 1.6173 at 180, 360 and 540 W respectively. However, there was no significant difference between k_p values of hot-air drying at various drying air temperatures. The k_p and n values for the hot-air drying were 0.0051, 0.0056 and 0.0045 min^{-1}, and 1.2378, 1.2793 and 1.3892 at 60, 70 and 80 ºC respectively.

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