Mathematical Modeling of Drying Kinetics of Bird's Eye Chilies in a Convective Hot-Air Dryer

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Abstract

The drying kinetics of red bird's eye chilies and the color of the product were investigated in a laboratory scale hot-air dryer under 3 air temperatures of 55, 60 and 65 °C. The 6 mathematical models (Lewis model; Page model; Henderson and Pabis model; Logarithmic model; Modified Page model; and Wang and Singh model) were used to fit the experimental data obtained in order to estimate the moisture ratio as the function of drying time. The results showed that operating temperature enhanced the kinetics of the drying of chilies; the drying times of chilies at 55, 60 and 65 °C were 510, 360 and 330 min, respectively. The experimental drying curves obtained at all operating conditions took place in the falling rate period. Comparing the dried products, it was observed that the red bird's eye chilies dried at a lower temperature had higher Hunter L (lightness), a* (redness) and b* (yellowness) values. The experimental data were fitted to different drying models. The performance of these models was investigated by comparing the determination of coefficient (R^2) and root mean square error (*RMSE*) between the observed and predicted moisture ratios. Among the 6 mathematical models, the Wang and Singh model satisfactorily described the drying kinetics of chilies.

Keywords: Drying kinetics, modeling, hot air dryer, Bird's eye chili, color

Introduction

Hot chili is an important spice and condiment in the tropics and subtropics [1]. Bird's eye chili is a chili pepper of the species *Capsicum frutescens* L. in the family *Solanaceae*, commonly found in South-east Asia. Bird's eye chili is known to contain a high moisture content (80 - 90 % (w.b.)) after harvest. The color can be green or red. It is eaten as a raw and cooked vegetable, and is also used in making paste and sauce. The red bird's eye chili is one of the favorite agricultural products in Thailand. It is used as a spice and also a flavor ingredient in the food industry [2].

Traditionally, in Thailand, some of the bird's eye chilies are preserved by sun drying in the open air and exposed to sunlight after harvest, which usually takes several days, depending on the weather conditions [3]. The farmers expose their chilies to open air on a mat, earthen floor, or the cement floor. This method has several drawbacks, such as being time consuming, being prone to contamination with dust, and attracting insects. Furthermore, this drying technique is not suitable for countries with a long wet season and a low amount of sunlight. Drying time is too long and the quality of dried chilies is not good in term of color, durability, nutritional content, aroma, etc [4]. Therefore, a hot-air dryer, which is far more rapid, is an alternative for moisture removal from a body with the presence of heat. Using this method, a more uniform and hygienic dried product can be produced rapidly [5,6]. Research has been done to reduce drying time and improve the quality of dried chili obtained. Dried chili can be kept longer, because its moisture content is so low that harmful organisms such as yeast and bacteria cannot flourish. Apart from food preservation, drying contributes to a reduction of packaging, storage and transportation costs. Different drying conditions, such as drying temperature, are known to affect the quality of a food product. One of the important criteria of food products is color. Undesirable changes in the color of food products may lead to a decrease in its quality.

In this research, red bird's eye chilies were used as a process element for drying in a convective hot-air dryer. The objective of this research was to study the drying kinetics of chilies in the temperature range of 55 - 65 °C and the effect of the drying temperature on the color of the final product obtained. Finally, the 6 drying models were used in the analysis of drying kinetics to investigate a suitable mathematical model for describing the drying characteristics of chilies.

Materials and methods

Equipments

The drying experiments were carried out using a hot-air dryer, which consisted of an electric heater, a centrifugal fan, 2 drying trays, and a PID temperature controller, as shown in **Figure 1**. This hot air dryer was rectangular, approximately 1.20 m long, 0.40 m wide, and 0.40 m high, with a voltage of 230 V 50 Hz.

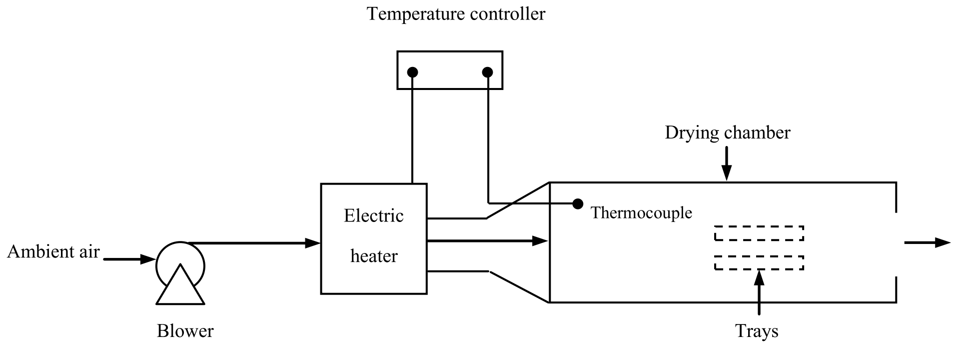

Figure 1 Schematic diagram of hot air dryer.

Preparation of raw material

The fresh red bird's eye chilies used in this drying experiment were obtained from the local market in Nakorn Si Thammarat, Thailand. All the chilies were washed and absorbed excess water with tissue papers and then allowed to cool to room temperature before further processing. The initial moisture content of the chili samples was 75 ± 0.5% (w.b.) determined by a hot air oven at 105 °C for 12 h [7].

Drying procedure

The red bird's eye chilies were dried in a hot-air dryer. In each experiment, approximately one hundred grams of the bird's eye chilies were used. Firstly, the hot-air dryer was switched on, and the inlet air used to dry the sample was heated up to the desired temperature by an electric heater; the air temperature was measured by a type K thermocouple and controlled by a PID controller (Omron, E5CN, Japan). The air velocity in the dryer, measured with an anemometer (YK-80AM, Japan) with a precision of ± 0.1 m/s, was set at 1.5 m/s. Then the chilies were placed on the stainless steel perforated tray, and the experiment began. The experiments were carried out at the drying air temperatures of 55, 60 and 65 °C at atmospheric pressure. Moisture content of the chilies was measured at various time intervals, ranging from 15 min at the beginning of the drying to 60 min of the last periods of the drying process. The drying experiment was performed until the moisture content of chilies decreased to 10 ± 0.5 % (w.b.). The surface color of the final product was measured by a Hunter colorimeter, which measured 3 parameters: the lightness (L), redness (a*) and yellowness (b*). All experiments were repeated at least 3 times. The average of the moisture ratio at each value was used for drawing the drying curves.

Mathematical modeling of drying curves

The experimental drying data was graphically analyzed in term of moisture ratio with drying time. Initially, the experimental drying data, which was measured in terms of moisture content (w.b.), was converted into dry basis (d.b.). Then, the moisture content on dry basis was used for calculating the moisture ratio (*MR*) of the chilies at any time by the following equation;

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_0, M_t and M_e are the initial moisture content (d.b.), moisture content (d.b.) at any time (min), and equilibrium moisture content (d.b.), respectively.

The drying kinetics data of bird's eye chilies were fitted to published drying models, namely, Lewis, Page, Henderson and Pabis, Logarithmic, Modified Page, and Wang and Singh, as shown in **Table 1**.

Table 1 Mathematical models for describing drying kinetics

Model name	Model expression	References
Lewis	$MR = \exp(-k\,t)$	[8]
Page	$MR = \exp(-k\,t^n)$	[9]
Henderson and Pabis	$MR = a\exp(-kt)$	[10]
Logarithmic	$MR = a + b\ln t$	[11,12]
Modified Page	$MR = \exp(-k\,t)^n$	[13]
Wang and Singh	$MR = 1 + at + bt^2$	[14]

These models were fitted to the experimental data in their linearized forms using regression technique. The coefficient of determination (R^2) was one of the main criteria for selecting the best equation. In addition to the coefficient of determination, the root mean square error (*RMSE*) of the deviations between the experimental and calculated values for models was used to determine the best fit. These parameters can be described as follows;

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp,i})^2} \tag{2}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2\right]^{\frac{1}{2}} \tag{3}$$

where $MR_{exp,i}$ is the experimental data, $MR_{pre,i}$ is the predicted data, $\overline{MR}_{exp}$ is the mean value of experimental data, and N is the number of experimental data points. The best model describing the drying kinetics of chilies was chosen as one with the highest coefficient of determination and the least root mean square error [15-17].

Results and discussion

Drying characteristics

The profiles of moisture content changes at various drying times in 3 different operational temperatures (55, 60 and 65 °C) are shown in **Figure 2**.

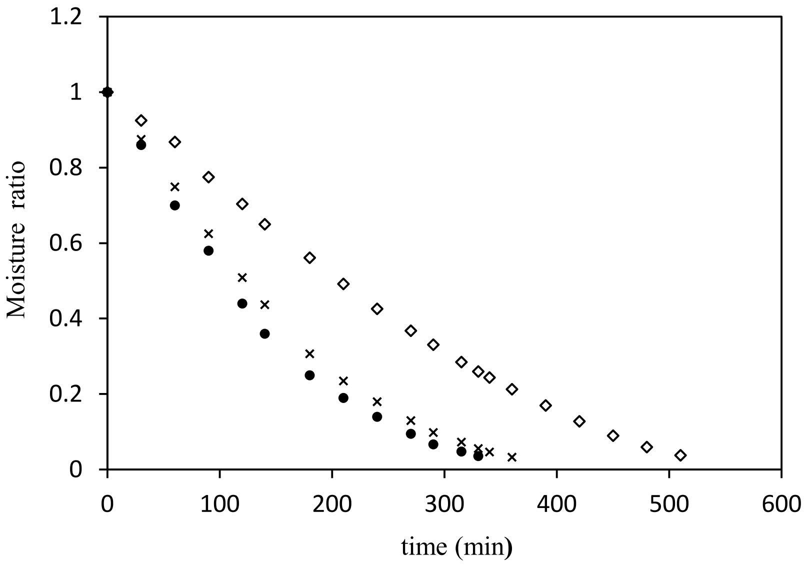

Figure 2 Drying curves of chilies at different temperatures: (◇) 55 °C, (×) 60 °C, (•) 65 °C.

From the drying curves, it is seen that the increase in temperature reduced the total drying time needed to achieve the required moisture content 10 % (w.b.) of the dried chilies. The reason is, according to kinetic theory, due to the increased energy of water molecules as temperature is increased. Hence, the escaping of molecules becomes easier from the medium and faster at a higher temperature. As shown in **Table 2**, the total drying time required to reduce the moisture ratio to any given level was 510, 360 and 330 min at 55, 60 and 65 °C, respectively.

Table 2 Total drying times of chilies at 55, 60 and 65 °C

Drying temperature (°C)	Drying time (min)
55	510
60	360
65	330

Figure 3 shows the variations of drying rate with moisture ratio of bird's eye chilies at different temperatures. It can be noticed that there was no constant rate period in the drying of bird's eye chilies under experimental conditions, and the drying curves showed only a falling-rate drying period. At the beginning of the drying process, drying rate increased with the increase of temperature of the drying air. From the experimental results, the drying rates were 0.15, 0.25 and 0.30 kg water/(kg dry matter.h) at 55, 60 and 65 °C, respectively. The highest value of drying rate was obtained during the experiment at 65 °C. The main reason for above results is that the higher temperatures speed up the diffusion of water from the interior of the solid to the surface.

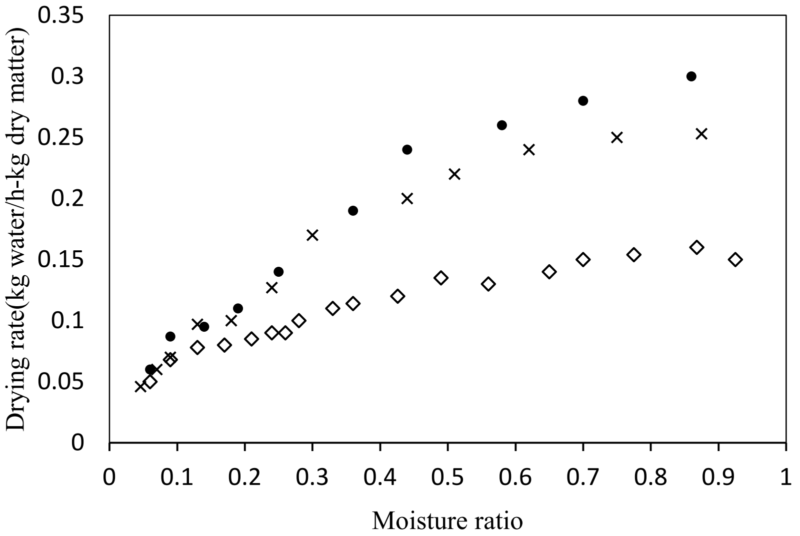

Figure 3 Variation of drying rate with moisture ratio at different temperatures: (◇) 55 °C, (×) 60 °C, (•) 65 °C.

Color of dried bird's eye chili

From the experiments, it was observed that the red chilies dried at higher temperature had more dull red; the red color of chilies faded out from bright red to dull red and a darker color (less lightness).

Table 3 Comparison of color parameters of dried chilies at different temperatures.

Drying temperature (°C)	Drying time (min)		
	L	a*	b*
55	33.74	27.86	22.72
60	32.29	26.82	20.93
65	31.02	24.26	18.46

Table 3 shows the color parameters of dried red chilies in terms of the lightness (L), redness (a*) and yellowness (b*) values. These results indicated that the color of dried chilies was slightly dependent on the air temperature used in the drying of the product. The values of L, a* and b* for dried chilies obtained at higher temperature were lower than those for dried chilies obtained at lower temperature. For instance, the redness (a*) value decreased from 27.86 to 24.26 when at a higher temperature. This result is in agreement with previous literature studies on the drying of red chilies [6,18,19]. The reason for reduction of red color is that, according to literature, the red color is mainly due to carotenoid pigments [20], so the red chilies dehydrated at higher temperature had a lower a* value that may be due to carotenoid destruction [21,22].

Evaluation of the drying models

The moisture content data obtained at different drying air temperatures were converted into moisture ratio expressions and then curve fitting computations with drying time (min) were performed for all 6 drying models given in **Table 1**. The drying coefficients (a, b, k and n) obtained from these models are given in **Table 4**. The statistical analyses undertaken on the drying data to evaluate the models for different temperatures, such as coefficient of determination and root mean square error obtained using Eqs. (2) and (3), are shown in **Table 5**.

From statistical analysis results**,** the values of R^2 obtained from all the models varied from 0.8895 to 0.9990, and the *RMSE* values varied between 0.008739 and 0.087830. It was found that the higher R^2 values and the lower RMSE values were obtained from the Wang and Singh model, where the R^2 and *RMSE* values varied between 0.9981 to 0.9990 and 0.008739 to 0.012983, respectively. Therefore, the Wang and Singh model may be assumed to represent the thin-layer drying behavior of bird's eye chilies.

Validation of the selected model was confirmed by comparing the predicted moisture contents with the measured moisture contents at different drying conditions. The plots of experimental and predicted moisture ratio with drying time are given in **Figure 4**. It shows that the Wang and Singh model is in good agreement with the experimental results.

Table 4 Prediction of model coefficients.

Model	Drying temperature (°C)	k	n	a	b
Lewis	55	0.00480			
	60	0.00820			
	65	0.00890			
Page	55	0.00067	1.320		
	60	0.00135	1.310		
	65	0.00183	1.280		
Henderson and Pabis	55	0.00580	1.425		
	60	0.00940	1.374		
	65	0.01000	1.302		
Logarithmic	55			2.3090	–0.353
	60			2.2490	–0.375
	65			2.1850	–0.370
Modified Page	55	0.00395	1.320		
	60	0.00651	1.310		
	65	0.00728	1.280		
Wang and Singh	55			–0.0029	2×10^{-6}
	60			–0.0049	6×10^{-6}
	65			–0.0055	8×10^{-6}

Table 5 Results of statistical analyses obtained from the selected models.

Model	Drying temperature (°C)	R^2	*RMSE*
Lewis	55	0.8895	0.087164
	60	0.9503	0.079126
	65	0.9628	0.066903
Page	55	0.9865	0.023354
	60	0.9955	0.011941
	65	0.9978	0.009068
Henderson and Pabis	55	0.9274	0.081665
	60	0.9716	0.054251
	65	0.9790	0.039630
Logarithmic	55	0.9380	0.065365
	60	0.9780	0.038327
	65	0.9860	0.029368
Modified Page	55	0.9865	0.107421
	60	0.9955	0.087830
	65	0.9978	0.077222
Wang and Singh	55	0.9990	0.012983
	60	0.9990	0.008739
	65	0.9981	0.011010

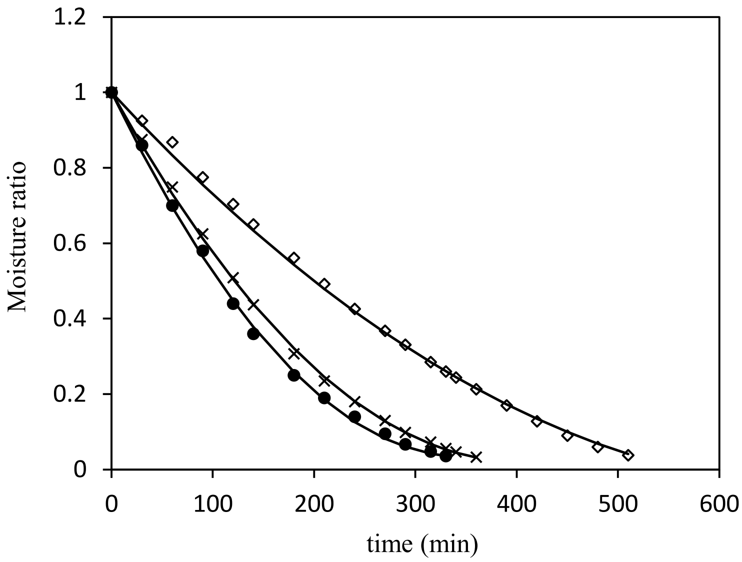

Figure 4 Comparison between experimental data and best fit of Wang and Singh model at different temperatures: (◇) 55 °C, (×) 60 °C, (•) 65 °C, (–) prediction.

Conclusions

In this study, the influence of air temperature (55, 60 and 65 °C) on the drying kinetics and color of red bird's eye chilies was investigated. It was found that the drying kinetics of bird's eye chilies took place in the falling rate period, under experimental conditions. The color of the product was dependent on the temperature of the air used in drying: higher air temperature produced greater color loss. Finally, the results obtained from fitting the experimental data to the 6 empirical kinetics models can be concluded that the Wang and Singh model, which gave a higher coefficient of determination (R^2) and a lower root mean square error (*RMSE*), was considered the best for describing the dehydration kinetics of bird's eye chilies.

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