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Research Article

Drying of Malaysian *Capsicum annuum* L. (Red Chili) Dried by Open and Solar Drying

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This study evaluated the performance of solar drying in the Malaysian red chili (*Capsicum annuum* L.). Red chilies were dried down from approximately 80% (wb) to 10% (wb) moisture content within 33 h. The drying process was conducted during the day, and it was compared with 65 h of open sun drying. Solar drying yielded a 49% saving in drying time compared with open sun drying. At the average solar radiation of 420 W/m^2 and air flow rate of 0.07 kg/s, the collector, drying system, and pickup demonstrated efficiency rates of approximately 28%, 13%, and 45%, respectively. Evaporative capacity ranged from 0.13 to 2.36 kg/h, with an average of 0.97 kg/h. The specific moisture extraction rate (SMER) of 0.19 kg/kWh was obtained. Moreover, the drying kinetics of *C. annuum* L. were investigated. A nonlinear regression procedure was used to fit three drying models. These models were compared with experimental data on red chilies dried by open sun drying and those dried by solar drying. The fit quality of the models was evaluated using their coefficient of determination (R^2), mean bias error, and root-mean-square error values. The Page model resulted in the highest R^2 and the lowest mean bias and root-mean-square errors.

1. Introduction

In subtropical and tropical countries, a name such as red chili (*Capsicum annuum* L.) is no stranger to the subject, and was a compulsory course in the kitchen. It is a main ingredient in all cooking, as it has high nutritional value. For Malaysian red chili, it was found to be very nutritious, with high vitamin C (175 mg/100 g), calcium (15 mg/100 g), fiber (4.8%), protein (2.8%), iron (1.8 mg/100 g), ash (0.9 mg/100 g), and lipids (0.7 mg/100 g), as shown in Table 1 [1]. The use of red chili is not just for adding food palatability because there are a number of studies that have shown that it is very beneficial for human health. Furthermore, red chili is a good source of antioxidants, being rich in vitamins A and C, minerals, and other phytochemicals, which are an important source of nutrients in the human diet. For contain nutritious of several red chili (*Capsicum annuum*) varieties was reported [2, 3].

Traditionally, red chili is dried directly under the sun. Direct sun drying requires an area with a large, open space and long drying times. It is highly dependent on the availability of sunshine and is susceptible to contamination with foreign materials and insect and fungal infestations, which thrive in moist conditions, rendering red chili unusable. Most agricultural and marine products require drying to preserve the quality of the final product; however, the traditional method of direct sun drying results in low-quality products. As an alternative to open sun drying, solar drying is one of the most attractive and promising applications of solar energy systems. It uses renewable and environment-friendly technology and is economically viable in most developing countries. Much recent research has reported on solar drying of agricultural fruits and vegetables. Thin-layer drying models have also been widely used to analyze the drying of various agricultural [4–11] and marine [12–14] products.

Fudholi et al. [15] reviewed various types of solar drying systems for agricultural and marine products. They reported that the moisture content of fresh chili decreased from 80% to 5% under solar drying in 48 h. Several studies have specifically investigated solar drying systems for red chili. Janjai et al. [16] reported the use of a solar greenhouse dryer for the commercial drying of 1000 kg of fruits or vegetables

Table 1: Concentration of elements (mg/100 g wet weight) [1].

Foodstuffs	Vitamin C (mg/100 g)	Ca (mg/100 g)	Fe (mg/100 g)	Ash (mg/100 g)	Lipids (%)	Protein (%)	Fiber (%)
Red chilli	175.0	15.0	1.8	0.9	0.7	2.8	4.8
Seaweed (*G. changii*)	28.5	651.0	95.6	22.7	3.3	6.9	24.7
Green bean sprouts	14.1	25.0	1.7	0.3	0.2	2.6	0.7
Soya beans, white	7.5	200.0	6.0	4.8	18.9	33.8	5.5
Peas (green, canned)	8.1	25.0	1.9	1.3	0.4	3.4	2.7
Red spinach	48.3	120.0	4.0	1.8	0.3	2.8	1.5
Carrots	9.5	140.0	0.8	0.8	0.1	1.0	1.1
Broccoli	85.0	40.0	0.7	0.8	0.1	4.1	1.0
Lettuce	27.6	50.0	1.5	0.7	0.1	1.2	0.5
Tomato	25.8	12.0	0.8	0.6	0.2	1.4	0.5
Red pumpkin	36.5	21	0.7	0.4	0.1	0.9	0.3
Cabbage	53.0	40	0.6	0.8	0.2	1.6	0.9

in Champasak, Lao People's Democratic Republic. Drying of 300 kg of red chili in this dryer reduced its moisture content from approximately 75% to 15% in 3 days, and the payback period was estimated to be 2.5 years. They also reported on six units of greenhouse dryers installed at agroindustrial sites in Thailand between 2008 and 2009. Kaewkiew et al. [17] investigated the performance of a large-scale greenhouse dryer for drying red chili in Thailand. Drying of 500 kg of red chili using this dryer reduced its moisture content from approximately 74% to 9% in 3 days, and the payback period was estimated to be 2 years. Furthermore, Lhendup [18] conducted a technical and economic performance analysis of solar drying red chili in Bhutan. Hossain and Bala [19] studied a mixed-mode forced convection solar tunnel dryer for drying red chili in Bangladesh, whereas a simulation model was used to evaluate its technical and economical performance [20]. Banout et al. [21] compared the use of a double-pass solar dryer with a cabinet dryer and open sun drying of red chili in central Vietnam. Drying approximately 40 kg of red chili using the double-pass solar dryer reduced its moisture content from approximately 90% to 10% in 32 h (including nights), and the payback period was estimated to be 3.26 years. To our best knowledge, limited information on the performance indices of red chili is currently available and studies on the drying kinetics of Malaysian red chili under a solar drying system have not been reported in the literature. The present study was performed using a double-pass solar collector with a finned absorber. Experiments were conducted to select the best mathematical model to illustrate the drying behaviors of Malaysian red chili dried by open sun drying and that subjected to solar drying. This study also investigated performance indices (drying efficiency, pick-up efficiency, and evaporative capacity).

2. Material and Methods

2.1. Material. Samples of the Malaysian red chili (*C. annuum* L.), also known as cili *bangi*, were obtained from the farm of the Universiti Kebangsaan Malaysia, Selangor, Malaysia. In each experiment, 0.4 kg of fresh red chili was used. About 0.4 kg red chili was taken and kept in an oven dried, which was maintained at $120 \pm 1^{\circ}$C until constant weigh has reached. The initial and final masses of the red chili were recorded with the help of electronic balance. The procedure was repeated for every 1 h interval till the end of drying. Their average moisture content was found to be 80.2% (wb).

2.2. Solar Drying. A solar drying unit was installed at the Green Energy Technology Innovation Park, Universiti Kebangsaan Malaysia, in 2010. The drying system was classified to be of the forced convection indirect type. A schematic diagram of the solar dryer is shown in Figure 1. The solar drying consists of an auxiliary heater, a blower, a drying chamber, and a double-pass solar collector. The collector width and length were 1.2 m and 4.8 m, respectively. The solar collector array consisted of four solar collectors. The upper channel depth was 3.5 cm, whereas the lower depth measured 7 cm. The bottom and sides of the collector were insulated with 2.5 cm thick fiber glass to minimize heat loss. The collector consisted of a glass cover, an insulator, and a black painted aluminum absorber. It was 1.2 m wide and 4.8 m long. In this type of collector, the air initially enters through a channel formed by the glass covering the absorber plate and then through a second channel formed by the back plate and finned absorber plate. The chamber measured 2.4 m in length, 1 m width, and 0.6 m in height.

2.3. Experimental Procedure and Uncertainties. Experiments were done between 8:00 AM and 5:00 PM using 40 kg of red chili, which was divided and equally distributed on eight trays, as shown in Figure 2. Red chili was also placed in a small tray positioned at the center of the dryer to determine moisture loss by means of a Camry R9364 digital electronic balance with an accuracy of 0.01 g on the top center of the drying chamber. Air temperature (ambient temperature, collector inlet temperature, and collector outlet temperature), radiation intensity, and air velocity were measured, as were the air temperature before entering the dryer chamber, the temperature inside the dryer chamber, and the temperature outside the dryer chamber. Relative humidity sensors were installed in the inlet, middle, and outlet sections of the drying

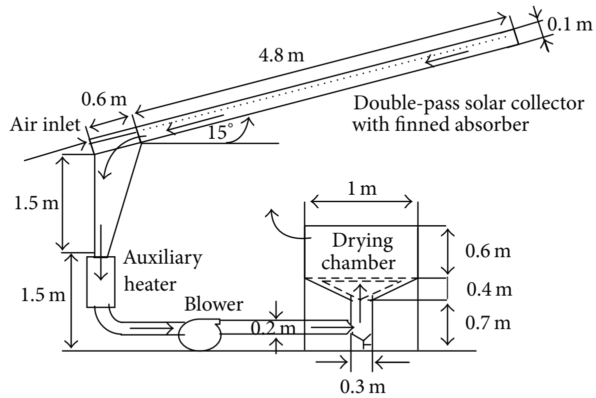

Figure 1: The schematic of a solar drying.

Figure 2: Photograph of Malaysian red chili in drying chamber.

chamber. An air flow DTA 4000 anemometer to determine the air flow velocity in the solar collector was used. T-type thermocouples with an accuracy of 0.018°C and an LI-200 pyranometer with 1% accuracy were used. During the drying process, the temperature and relative humidity in the solar dryer were recorded at 1 min intervals during the experiments with the ADAM Data Acquisition System connected to a computer. Data were averaged for 30 min prior to analysis. Experimental uncertainties analysis was presented in Table 2.

During the measurements of the parameters, the uncertainties that occurred were shown in Table 2. Uncertainties estimation is calculated by El-Sebaii et al. [22]

$$X_R = \left[(x_1)^2 + (x_2)^2 + \cdots (x_n)^2\right]^{1/2}, \quad (1)$$

where X_R: uncertainty in result and $x_1, x_2 \ldots x_n$: uncertainty in the independent variables.

2.4. Estimation of Performances Index. The thermal efficiency of a solar collector is the ratio of useful heat gain to the solar radiation incident on the plane of the collector. It is defined as follows:

$$\eta_c = \frac{mC(T_o - T_i)}{A_c S} \times 100\%, \quad (2)$$

where m: mass flow rate (kg/s), C: specific heat of air (J/kg°C), A_c: collector area (m^2), T_i: inlet air temperature (°C), T_o: outlet air temperature (°C), and S: solar radiation intensity (W/m^2).

System drying efficiency is defined as the ratio of energy required to evaporate moisture to the heat supplied to the dryer. For the solar collector, the heat supplied to the dryer is the solar radiation incident upon the solar collector. The system drying efficiency is a measure of the overall effectiveness of a drying system. For forced convection dryers, typical values are expected. Calculation of the system efficiency for forced convection solar dryers should take into account the energy consumed by the fan/blower. The following expression can then be used [23]:

$$\eta_p = \frac{WL}{A_c S + P_f}, \quad (3)$$

where L: latent heat of vaporization of water at exit air temperature (J/kg), W: mass of water evaporated from the product (kg), and P_f: power fan (W).

The mass of water removed (W) from a wet product can be calculated as follows [24]:

$$W = \frac{m_o(M_i - M_f)}{100 - M_f}, \quad (4)$$

where m_o: initial total crop mass (kg), M_i: initial moisture content fraction on wet basis, and M_f: the final moisture content fraction on wet basis.

Pick-up efficiency determines the efficiency of moisture removal by the drying air from the product [25], expressed as

$$\eta_p = \frac{h_0 - h_i}{h_{as} - h_i} = \frac{W}{\upsilon\rho t(h_{as} - h_i)}, \quad (5)$$

where h_o: absolute humidity of air leaving the drying chamber (%), h_i: absolute humidity of air entering the drying chamber (%), h_{as}: absolute humidity of the air entering the dryer at the point of adiabatic saturation (%), υ: volumetric airflow (m^3/s), ρ: density of air (kg/m^3), and t: drying time (s).

Evaporative capacity was used in this study as a performance index for solar dryers according to Jannot and Coulibaly [26]. It is the weight of water that can be extracted by the air flow from the products to be dried, defined as follows:

$$E = m_{da}(X_{2m} - X_a), \quad (6)$$

where E: evaporative capacity (kg/h), m_{da}: mass flow rate of dry air (kg/s), X_{2m}: dryer outlet absolute humidity, and X_a: ambient absolute humidity.

Desai et al. [27] evaluated time savings in drying chili using solar drying compared with open sun drying. The performance of solar drying compared with open sun drying was calculated using the following equation:

$$\text{Saving in drying time (\%)} = \frac{t_{OS} - t_{SD}}{t_{OS}} \times 100, \quad (7)$$

where t_{OS}: time taken for drying the product in open sun (h) and t_{SD}: time taken for drying in solar drying (h).

The specific moisture extraction rate (SMER), which is the energy required for removing one kg of water, SMER was calculated using (8) as reported by Shanmugam and Natarajan [28]

$$\mathrm{SMER} = \frac{W}{P_t}, \tag{8}$$

where SMER: specific moisture extraction rate (kg/kWh), W: mass of water evaporated from the product (kg), and P_t: total energy input to the dryer (kWh).

2.5. Mathematical Modeling of Drying Curves. Moisture content was expressed as percentage wet basis and then converted to grams of water per gram of dry matter. The experimental drying data for red chili were fitted to exponential thin-layer drying models using nonlinear regression analysis. The moisture ratio (MR) can be calculated as

$$\mathrm{MR} = \frac{M - M_e}{M_i - M_e}, \tag{9}$$

where M: the moisture content at any time t, M_e: equilibrium moisture content, and M_i: initial moisture content with all expresses in dry basis. The moisture content dry basis is

$$M = \frac{w(t) - d}{d}, \tag{10}$$

where $w(t)$: mass of wet materials at instant t (kg) and d: mass of dry materials (kg).

The drying rate (DR) is expressed as the amount of evaporated moisture over time. It is defined as follows [29]:

$$\mathrm{DR} = \frac{M_{t+dt} - M_t}{dt}, \tag{11}$$

where M_t: moisture content at time t and M_{t+dt}: moisture content at time $t + dt$.

This study used the coefficient of determination (R^2) as one of the primary criteria for selecting the best model for comparison with the experimental data. In addition to R^2, mean bias error (MBE) and root-mean-square error (RMSE) were used to analyze the relative goodness of fit. The model with the highest coefficient of determination and the lowest RMSE was selected as the best model describing the drying behavior of red chili [30–34]. This parameter can be calculated as follows:

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2,$$
$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]^{1/2}, \tag{12}$$

where $\mathrm{MR}_{\mathrm{exp},i}$: experimental value of moisture ratio, $\mathrm{MR}_{\mathrm{pre},i}$: simulated value of moisture ratio, and N: number of data points (observations).

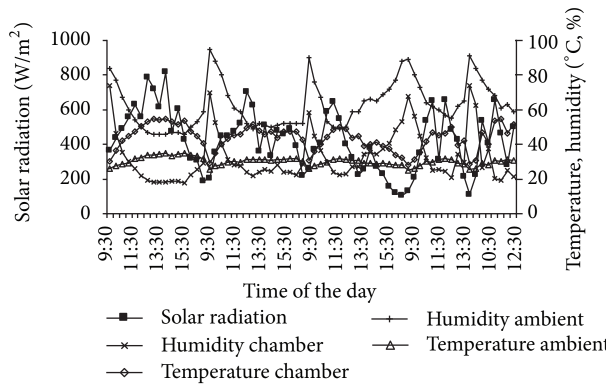

FIGURE 3: Temperatures (ambient and chamber), relative humidity of chamber, ambient humidity, and solar radiation on March 16, 2012, to March 20, 2012.

3. Results and Discussion

3.1. Performances Index. The drying process was conducted only from 9:00 AM to 5:00 PM. During the night, the solar dryer was shut down. Drying continued until the next day, and the process was repeated until the required equilibrium moisture content was reached.

The daily mean values of drying chamber air temperature, drying chamber relative humidity, and solar radiation during the 5 days (33 h) varied from approximately 28 to 55°C, 18% to 74%, and 104 to 820 W/m^2, respectively, with their corresponding average values being 45°C, 30%, and 420 W/m^2, respectively, as shown in Figure 3. The drying temperature and relative humidity under solar drying varied continuously with increasing drying time. The results revealed that the drying temperature in solar drying was greater than the ambient temperature, whereas the relative humidity under this system was lower than the ambient relative humidity. In addition, the drying temperature and relative humidity values significantly differed at approximately 15°C and 30%, respectively, within the 33 h drying period. This explicitly indicates that the DR in solar drying is higher than that in open sun drying. On the other hand, the efficiency of the collector varied from 11% to 74%, with the average value of approximately 28%, at the drying air flow rate of 0.07 kg/s. The thermal efficiency rates for the 5 days of drying are shown in Figure 4, which illustrates that the thermal efficiency of the collector is increased at low solar radiation.

The experimental results showed that solar drying without auxiliary heating of 40 kg of dry red chili required approximately 10% water content within 33 h (5 days of drying) to yield 8 kg of dried red chili. However, the weight of water evaporated from the red chili obtained using (3) was 31.1 kg. Adding $L = 2407$ kJ/kg (668 Wh/kg), $t = 33$ h, and $S = 420$ W/m^2 to (3) yielded a drying efficiency of 12.7%. Equation (5) and a psychometric chart determined the pick-up efficiency to be 44.9%. Evaporative capacity, which ranged from 0.13 to 2.36 kg/h, with an average of 0.97 kg/h, was calculated using (6). Evaporative capacity increased with increasing solar radiation.

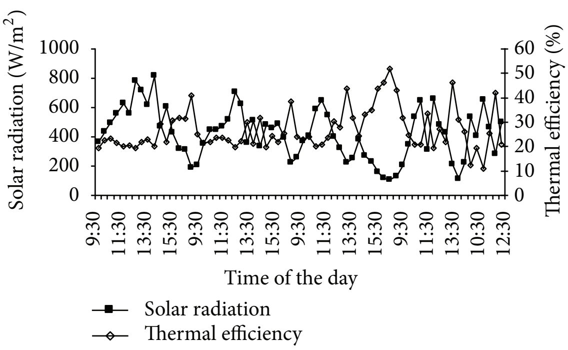

Figure 4: Efficiency of collector as compared to solar radiation with constant air flow rate 0.07 kg/s at March 16,2012 to March 20, 2012.

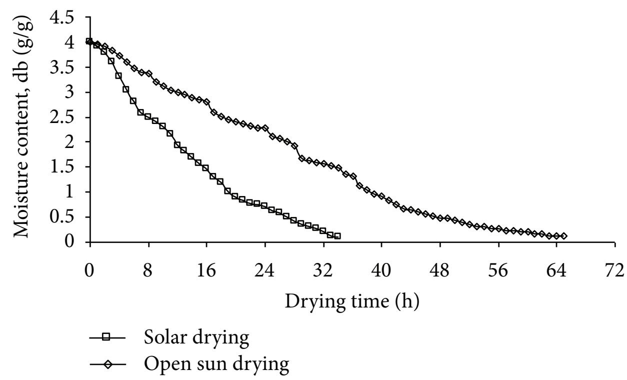

Figure 5: Moisture content variation with drying time (dry basis).

Table 2: Uncertainties during the measurements of the parameters.

Parameters	Unit	Uncertainty comment
Ambient air temperature	°C	±0.15
Collector inlet temperature	°C	±0.24
Collector outlet temperature	°C	±0.24
Chamber temperature	°C	±0.24
Solar intensity	W/m^2	±0.4
Air velocity	m/s	±0.2
Relative humidity	%	±0.17

Table 3 compares the experimental results of the present and previous studies. Drying of red chili in solar drying reduced the moisture content from approximately 80% to approximately 10% in 33 h. At the average solar radiation of 420 W/m^2 and air flow rate of 0.07 kg/s, the collector, drying system, and pick-up efficiencies were approximately 28%, 13%, and 45%, respectively. According to (6), a 49% saving in drying time was obtained for solar drying compared with open sun drying. Kaleemullah and Kailappan [36] studied the drying kinetics of red chili in a rotary dryer. They conducted drying experiments at the temperature range of 50–65°C for 19–33 h and observed that the quality of red chili drying increased and drying time increased at low drying temperature. In contrast, with an increase in the drying temperature, the quality of red chili drying and drying time both decreased. However, they concluded that the performance of red chili dried at 55°C was the best in terms of drying time and quality of red chili drying.

3.2. Drying Curves. The results of the drying kinetic curves, namely, the drying curve, the DR curve, and the characteristic drying curve, of red chili using open sun drying and solar drying are shown in Figures 5–7. The drying curve showed the profile change in moisture content (M) versus drying time (t), the DR curve illustrated the DR profile (dM/dt) versus drying time (t), and the drying characteristic curve revealed the DR profile (dM/dt) versus moisture content (dry basis) (M).

Figure 5 demonstrates a reduction in moisture content (dry basis) for solar drying. At low drying time (under open sun drying), the moisture content of red chili increased, slowing down the drying process as the drying time increased. Figure 6 shows the dry basis moisture content versus drying time. Figure 7 shows drying characteristic curves: DR versus dry basis moisture content. According to this graph, the DR was higher in solar drying, indicating that the time required to dry the material up to equilibrium moisture content is shorter under this method.

3.3. Drying Modeling. Three drying models were fitted with the experimental data on open sun drying and solar drying of red chili: the Newton model, the Page model, and the Henderson-Pabis model. The experimental data fitted these models in the form of changes in moisture content versus drying time, which were calculated using Excel software. Constants were calculated by a graphical method. The results of fitting are listed in Table 4, which shows a constant drying and precision fit for each model. The model with the highest R^2 and the lowest MBE and RMSE was selected to better estimate the drying curve.

The Newton model represents the relationship between MR and drying time, the exponential equation curves for which are shown in Figures 8 and 9. These figures clearly showed k constants of 0.0497 and 0.0899 for open sun drying and solar drying, respectively. The Page equation can also be expressed as follows:

$$\ln(-\ln \mathrm{MR}) = \ln k + n \ln t. \tag{13}$$

Equation (13) is the relationship $\ln(-\ln \mathrm{MR})$ versus t; the curves of this logarithmic equation are shown in Figures 10 and 11. According to these figures, k constants of 0.0091 and 0.0244 were obtained for open sun drying and solar drying, respectively. The n constants are clearly shown in the figures as well. The Henderson-Pabis equation can also be written as

$$\ln \mathrm{MR} = -kt + \ln a. \tag{14}$$

From (14), a plot of $\ln \mathrm{MR}$ versus drying time gives a straight line with intercept $\ln(a)$ and slope k. Graphs of $\ln \mathrm{MR}$ versus drying time are shown in Figures 12 and 13. These figures clearly showed k constants of 0.0641 and 0.1090 for open sun drying and solar drying, respectively.

Table 3: Performances of solar drying compared with open sun drying and several solar drying in references.

Load	M (%wb)		Drying time, t (h)		Saving in t	Efficiency (%)			E	SMER	References
(kg)	M_i	M_t	OS	SD	(%)	Thermal	Drying	Pickup	(kg/h)	(kg/kWh)	
300	75	10	45	27	40	—	—	—	—		[16]
500	74	9	70	30	57	—	—	—	—		[17]
35	77	9	48	30	38	—	—	—	—		[28]
38	90	10	—	32	—	62	24	22	—		[21]
40	73	9	—	24	—	—	21	—	—	0.87	[35]
	567 db	10 db	—	18	—	30	15	23	—		[18]
40	80	10	65	33	49	28	13	45	0.97	0.19	This paper

Table 4: Results of nonlinear regression analysis.

Model name	Method drying	Model coefficients and constants	R^2	MBE	RMSE
Newton	Open sun drying	$k = 0.0497$	0.8421	0.0214	0.1462
	Solar drying	$k = 0.0899$	0.8549	0.0090	0.0950
Page	Open sun drying	$k = 0.0091$; $n = 1.3933$	0.9857	0.0018	0.0420
	Solar drying	$k = 0.0244$; $n = 1.3900$	**0.9887**	**0.0007**	**0.0257**
Henderson and Pabis	Open sun drying	$k = 0.0641$; $a = 1.8735$	0.9032	0.0179	0.1338
	Solar drying	$k = 0.1090$; $a = 1.5521$	0.8920	0.0083	0.0912

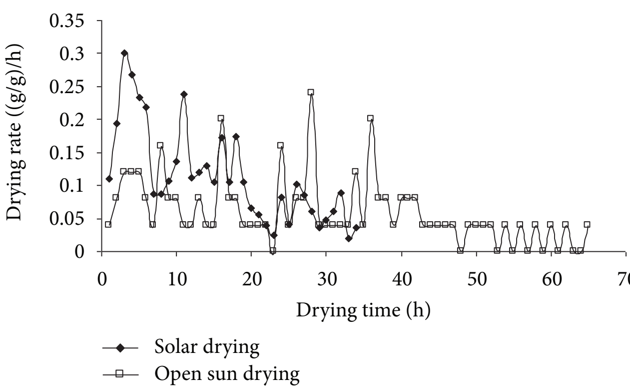

Figure 6: Drying rate curves: dry basis moisture content versus drying time.

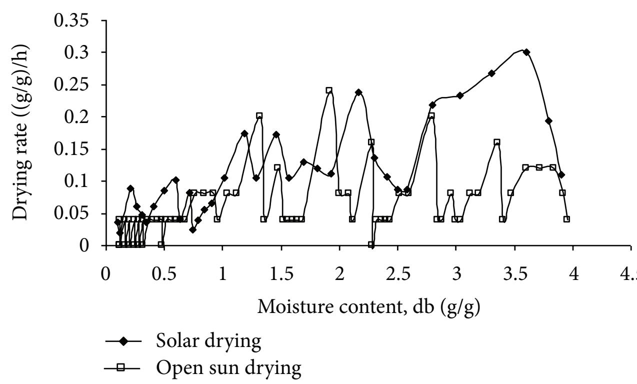

Figure 7: Drying characteristic curves: DR versus dry basis moisture content.

The results presented in Table 4 show that the Page drying model exhibited the highest value of R^2 (0.9887) and the lowest values of MBE (0.0007) and RMSE (0.0257), compared with the Newton and Henderson-Pabis models. Accordingly, the Page model was selected to represent the thin-layer drying behavior of red chili. This is in accordance with the findings of Fudholi et al. [32–34], who reported that the Page model had a better fit to drying seaweeds compared with the Newton and Henderson-Pabis models. Similarly, Azoubel et al. [37] reported that the Page model clearly improved the simulation in comparison with the results obtained using the diffusion model and had the best fit to the experimental data, with the average errors calculated ranging from 1.89% to 12.76% and R^2 values greater than 0.99. The Page model has been reported to exhibit a better fit than other models in accurately simulating the drying curves of chili [38, 39], rapeseed [40], green beans [41], okra [42], and kiwi [43], among others.

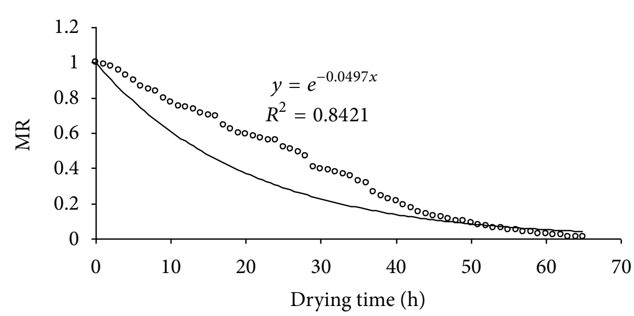

Figure 8: Plot of MR versus drying time (Newton's model) for open sun drying of red chili

Figures 14 and 15 show the plots of the observed MR against the predicted values for the Page models of open sun drying and solar drying of red chili, respectively. The data indicate

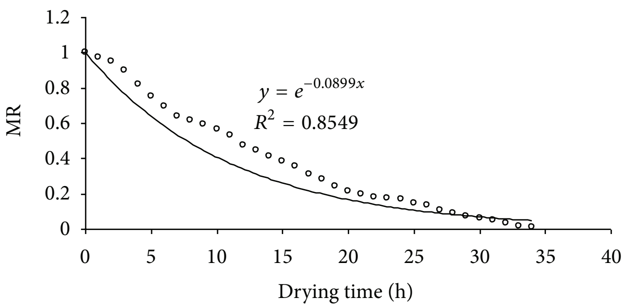

Figure 9: Plot of MR versus drying time (Newton's model) for solar drying of red chili.

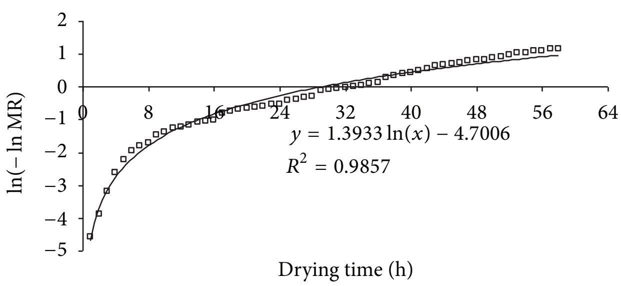

Figure 10: Plot of ln(−ln MR) versus drying time (Page's model) for open sun drying of red chili.

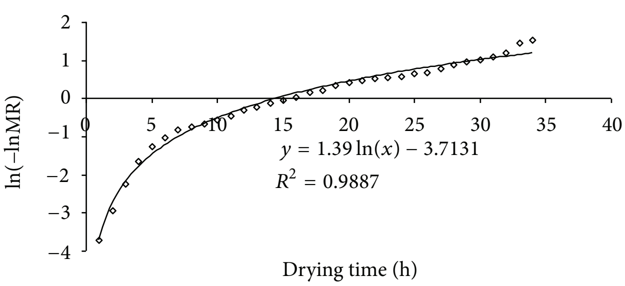

Figure 11: Plot of ln(−ln MR) versus drying time (the Page model) for solar drying of red chili.

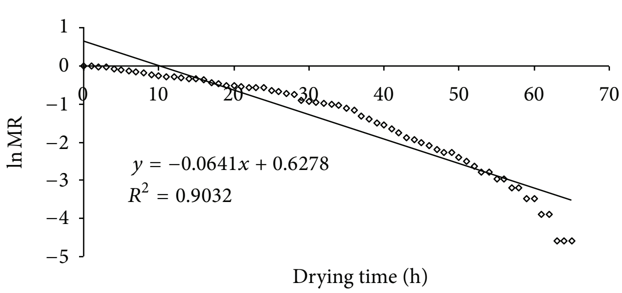

Figure 12: Plot of ln MR versus drying time (the Henderson and Pabis model) for open sun drying of red chili.

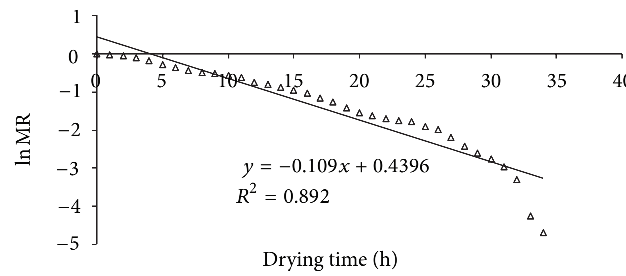

Figure 13: Plot of ln MR versus drying time (the Henderson and Pabis model) for solar drying of red chili.

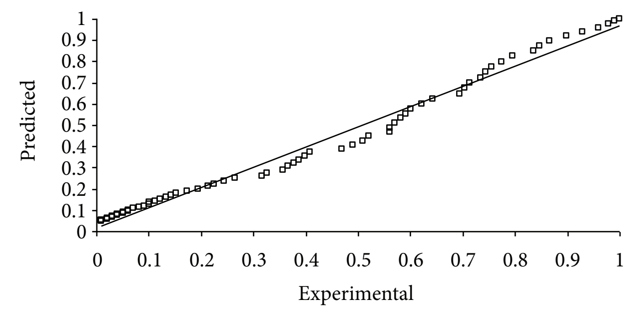

Figure 14: Comparison of experimental MR with predicted MR from the Page model for open sun drying of red chili.

the suitability of the developed model to describe the drying behavior of red chili.

4. Conclusion

Solar drying of the Malaysian red chili was evaluated in this study using kinetic curves. The Page model clearly showed a better fit to the experimental data compared with the Newton and Henderson-Pabis models. It resulted in the highest R^2 and the lowest MBE and RMSE. At the average solar radiation of approximately 420 W/m^2 and air flow rate of 0.07 kg/s, the collector, drying system, and pickup demonstrated efficiency rates of approximately 28%, 13%, and 45%, respectively. A maximum and a minimum of the collector efficiency about

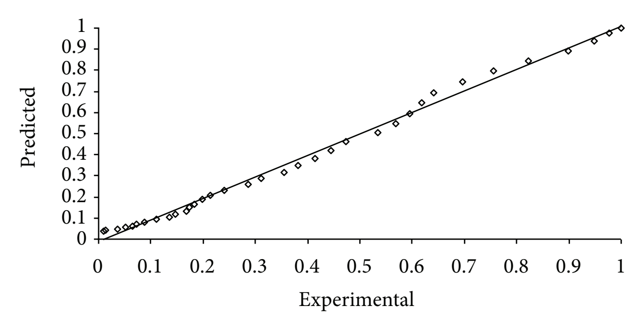

Figure 15: Comparison of experimental MR with predicted MR from the Page model for solar drying of red chili.

52% and 11%, respectively, were observed, and the drying temperature varied between 28°C and 55°C, with an average of approximately 44°C. The specific moisture extraction rate (SMER)of 0.19 kg/kWh was obtained. Solar drying of red chili took 33 h to reduce its moisture content of approximately 80% (wb) to 10% (wb). It was compared with open sun drying, which required 65 h of processing. A 49% saving in drying time was recorded for solar drying relative to open sun drying. Moreover, the evaporative capacity of solar drying ranged from 0.13 to 2.36 kg/h, with an average of 0.97 kg/h.

Nomenclature

A_c: Collector area (m^2)
a: Drying constant
C: Specific heat of air ($J\,kg^{-1}{}^\circ C^{-1}$)
d: Mass of dry materials
E: Evaporative capacity (kg/h)
exp: Exponential
H: Relative humidity (%)
h_o: Absolute humidity of air leaving the drying chamber (%)
h_i: Absolute humidity of air entering the drying chamber (%)
h_{as}: Absolute humidity of the air entering the dryer at the point of adiabatic saturation (%)
k: Drying constant
L: Latent heat of vaporization of water at exit air temperature (J/kg)
M: Moisture content
M_e: Equilibrium moisture content
M_i: Initial moisture content
m: Mass flow rate (kg/s)
N: Number of observations
n: Drying constant
S: Solar radiation (W/m^2)
R^2: Coefficient of determination
RMSE: Root-mean-square error
T: Temperature (°C)
t: Drying time;
t_{OS}: Time taken for drying the product in open sun
t_{SD}: Time taken for drying in solar drying

v: Volumetric airflow (m^3/s)
W: Mass of water evaporated from the product
w: Mass of wet materials
X_{2m}: Dryer outlet absolute humidity
X_a: Ambient absolute humidity
ρ : Density of air (kg/m^3)
η : Efficiency.

Subscripts

c: Chamber
f: fan
i: inlet
o: outlet
exp: experimental
pre: prediction.

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References

[1] M. H. Norziah and C. Y. Ching, "Nutritional composition of edible seaweed *Gracilaria changgi*," *Food Chemistry*, vol. 68, no. 1, pp. 69–76, 2000.

[2] A. H. Simonne, E. H. Simonne, R. R. Eitenmiller, H. A. Mills, and N. R. Green, "Ascorbic acid and provitamin A contents in unusually colored bell peppers (*Capsicum annuum* L.)," *Journal of Food Composition and Analysis*, vol. 10, no. 4, pp. 299–311, 1997.

[3] J. L. Guil-Guerrero, C. Martínez-Guirado, M. M. Rebolloso-Fuentes, and A. Carrique-Pérez, "Nutrient composition and antioxidant activity of 10 pepper (*Capsicum annuun*) varieties," *European Food Research and Technology*, vol. 224, no. 1, pp. 1–9, 2006.

[4] A. O. Dissa, J. Bathiebo, S. Kam, P. W. Savadogo, H. Desmorieux, and J. Koulidiati, "Modelling and experimental validation of thin layer indirect solar drying of mango slices," *Renewable Energy*, vol. 34, no. 4, pp. 1000–1008, 2009.

[5] M. Aktaş, I. Ceylan, and S. Yilmaz, "Determination of drying characteristics of apples in a heat pump and solar dryer," *Desalination*, vol. 238, no. 1–3, pp. 266–275, 2009.

[6] R. P. F. Guiné, D. M. S. Ferreira, M. J. Barroca, and F. M. Gonçalves, "Study of the drying kinetics of solar-dried pears," *Biosystems Engineering*, vol. 98, no. 4, pp. 422–429, 2007.

[7] A. O. Dissa, D. J. Bathiebo, H. Desmorieux, O. Coulibaly, and J. Koulidiati, "Experimental characterisation and modelling of thin layer direct solar drying of Amelie and Brooks mangoes," *Energy*, vol. 36, no. 5, pp. 2517–2527, 2011.

[8] B. M. A. Amer, M. A. Hossain, and K. Gottschalk, "Design and performance evaluation of a new hybrid solar dryer for banana," *Energy Conversion and Management*, vol. 51, no. 4, pp. 813–820, 2010.

[9] E. K. Akpinar, "Drying of mint leaves in a solar dryer and under open sun: modelling, performance analyses," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2407–2418, 2010.

[10] A. Akbulut and A. Durmuş, "Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer," *Energy*, vol. 35, no. 4, pp. 1754–1763, 2010.

[11] D. F. Basri, A. Fudholi, and M. H. Ruslan, "Drying characteristics of the borneo *Canarium odontophyllum* (dabai) fruit," *The American Journal of Agricultural and Biological Science*, vol. 7, no. 3, pp. 347–356, 2012.

[12] B. R. Chavan, A. Yakupitiyage, and S. Kumar, "Drying performance, quality characteristics, and financial evaluation of Indian Mackerel (*Rastrilliger kangurta*) dried by a solar tunnel dryer," *Thammasat International Journal of Science and Technology*, vol. 16, no. 2, pp. 11–25, 2011.

[13] G. M. Kituu, D. Shitanda, C. L. Kanali et al., "Thin layer drying model for simulating the drying of Tilapia fish (*Oreochromis*

niloticus) in a solar tunnel dryer," *Journal of Food Engineering*, vol. 98, no. 3, pp. 325–331, 2010.

[14] A. Fudholi, M. Y. Othman, M. H. Ruslan, M. Yahya, A. Zaharim, and K. Sopian, "Techno-economic analysis of solar drying system for seaweed in Malaysia," in *Procceedings of the 7th IASME/WSEAS International Conference on Energy, Environment, Ecosystems and Sustainable Development (EEESD '11)*, pp. 89–95, 2011.

[15] A. Fudholi, K. Sopian, M. H. Ruslan, M. A. Alghoul, and M. Y. Sulaiman, "Review of solar dryers for agricultural and marine products," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 1–30, 2010.

[16] S. Janjai, P. Intawee, J. Kaewkiew, C. Sritus, and V. Khamvongsa, "A large-scale solar greenhouse dryer using polycarbonate cover: modeling and testing in a tropical environment of Lao People's Democratic Republic," *Renewable Energy*, vol. 36, no. 3, pp. 1053–1062, 2011.

[17] J. Kaewkiew, S. Nabneaan, and S. Janjai, "Experimental investigation of the performance of a large-scale greenhouse type solar dryer for drying chilli in Thailand," *Procedia Engineering*, vol. 32, pp. 433–439, 2012.

[18] T. Lhendup, "Technical and financial feasibility of a solar dryer in Bhutan," *Energy for Sustainable Development*, vol. 9, no. 4, pp. 17–24, 2005.

[19] M. A. Hossain and B. K. Bala, "Drying of hot chilli using solar tunnel drier," *Solar Energy*, vol. 81, no. 1, pp. 85–92, 2007.

[20] M. A. Hossain, J. L. Woods, and B. K. Bala, "Optimisation of solar tunnel drier for drying of chilli without color loss," *Renewable Energy*, vol. 30, no. 5, pp. 729–742, 2005.

[21] J. Banout, P. Ehl, J. Havlik, B. Lojka, Z. Polesny, and V. Verner, "Design and performance evaluation of a Double-pass solar drier for drying of red chilli (*Capsicum annum* L.)," *Solar Energy*, vol. 85, no. 3, pp. 506–515, 2011.

[22] A. A. El-Sebaii, S. Aboul-Enein, M. R. I. Ramadan, S. M. Shalaby, and B. M. Moharram, "Thermal performance investigation of double pass-finned plate solar air heater," *Applied Energy*, vol. 88, no. 5, pp. 1727–1739, 2011.

[23] J. Banout and P. Ehl, "Using a double-pass solar drier for drying of bamboo shoots," *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, vol. 111, no. 2, pp. 119–127, 2010.

[24] K. E. J. Al-Juamily, A. J. N. Khalifa, and T. A. Yassen, "Testing of the performance of a fruit and vegetable solar drying system in Iraq," *Desalination*, vol. 209, no. 1–3, pp. 163–170, 2007.

[25] M. H. Ruslan, A. Fudholi, M. Y. Othman et al., "The double-pass solar dryer for drying palm oil fronds," in *Proceedings of the 10th WSEAS international conference on System science and simulation in engineering (ICOSSSE '11)*, pp. 143–149, Penang, Malaysia, 2011.

[26] Y. Jannot and Y. Coulibaly, "the "evaporative capacity" as a performance index for a solar-drier air-heater," *Solar Energy*, vol. 63, no. 6, pp. 387–391, 1998.

[27] S. Desai, V. Palled, and M. Anantachar, "Performance evaluation of farm solar dryer for chilly drying," *Karnataka Journal of Agricultural Sciences*, vol. 22, no. 2, pp. 382–384, 2009.

[28] V. Shanmugam and E. Natarajan, "Experimental investigation of forced convection and desiccant integrated solar dryer," *Renewable Energy*, vol. 31, no. 8, pp. 1239–1251, 2006.

[29] S. Meziane, "Drying kinetics of olive pomace in a fluidized bed dryer," *Energy Conversion and Management*, vol. 52, no. 3, pp. 1644–1649, 2011.

[30] M. Ibrahim, K. Sopian, and W. R. W. Daud, "Study of the drying kinetics of Lemon grass," *The American Journal of Applied Sciences*, vol. 6, no. 6, pp. 1070–1075, 2009.

[31] M. Y. Othman, A. Fudholi, K. Sopian, M. H. Ruslan, and M. Yahya, "Analisis kinetik pengeringan rumpai laut *Gracilaria cangii* menggunakan sistem pengering suria (drying kinetics analysis of seaweed *Gracilaria cangii* using solar drying system)," *Sains Malaysiana*, vol. 41, no. 2, pp. 245–252, 2012.

[32] A. Fudholi, M. Y. Othman, M. H. Ruslan, M. Yahya, A. Zaharim, and K. Sopian, "The effects of drying air temperature and humidity on drying kinetics of seaweed," in *Recent Research in Geography, Geology, Energy, Environment and Biomedicine*, pp. 129–133, Corfu, Greece, 2011.

[33] A. Fudholi, M. Y. Othman, M. H. Ruslan, M. Yahya, A. Zaharim, and K. Sopian, "Design and testing of solar dryer for drying kinetics of seaweed in Malaysia," in *Recent Research in Geography, Geology, Energy, Environment and Biomedicine*, pp. 119–124, Corfu, Greece, 2011.

[34] A. Fudholi, M. H. Ruslan, L. C. Haw et al., "Mathematical modeling of brown seaweed drying curves," in *Proceedings of the WSEAS International Conference on Applied Mathematics in Electrical and Computer Engineering*, pp. 207–211, 2012.

[35] M. Mohanraj and P. Chandrasekar, "Performance of a forced convection solar drier integrated with gravel as heat storage material for chili drying," *Journal of Engineering Science and Technology*, vol. 4, no. 3, pp. 305–314, 2009.

[36] S. Kaleemullah and R. Kailappan, "Drying kinetics of red chillies in a rotary dryer," *Biosystems Engineering*, vol. 92, no. 1, pp. 15–23, 2005.

[37] P. M. Azoubel, M. D. A. M. Baima, M. D. R. Amorim, and S. S. B. Oliveira, "Effect of ultrasound on banana cv Pacovan drying kinetics," *Journal of Food Engineering*, vol. 97, no. 2, pp. 194–198, 2010.

[38] T. Y. Tunde-Akintunde, "Mathematical modeling of sun and solar drying of chilli pepper," *Renewable Energy*, vol. 36, no. 8, pp. 2139–2145, 2011.

[39] I. Doymaz and M. Pala, "Hot-air drying characteristics of red pepper," *Journal of Food Engineering*, vol. 55, no. 4, pp. 331–335, 2002.

[40] L. A. Duc, J. W. Han, and D. H. Keum, "Thin layer drying characteristics of rapeseed (*Brassica napus* L.)," *Journal of Stored Products Research*, vol. 47, no. 1, pp. 32–38, 2011.

[41] I. Doymaz, "Drying behaviour of green beans," *Journal of Food Engineering*, vol. 69, no. 2, pp. 161–165, 2005.

[42] I. Doymaz, "Drying characteristics and kinetics of okra," *Journal of Food Engineering*, vol. 69, no. 3, pp. 275–279, 2005.

[43] S. Simal, A. Femenia, M. C. Garau, and C. Rosselló, "Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit," *Journal of Food Engineering*, vol. 66, no. 3, pp. 323–328, 2005.