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Thin-Layer Drying Models for Dehumidified Hot Air Drying of Germinated Brown Rice

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Abstract

This study aimed to evaluate suitable thin-layer drying models for germinated brown rice (GBR) undergoing dehumidified hot air drying. Dehumidified hot air drying of GBR to the final moisture content of 12% wet basis was conducted in a hot air drying system with a desiccant wheel (HA-DW). Drying curves as influenced by drying temperature (80,100, and 120°C) and air flow rate (0.04, 0.06, and 0.08 m^3/s) were plotted. The shortest drying time of 45 min was achieved by drying GBR at the highest drying temperature of 120°C and the greatest air flow rate of 0.08 m^3/s. Comparison of R^2 and RMSE values of selected 8 drying models showed that the Midilli et al. model gave better fit. The average R^2 and RMSE of of 0.9991 and 0.0045 were achieved respectively.

Keywords: Drying modeling, Desiccant wheel, Hot air drying, Germinated brown rice.

1. Introduction

Thin-layer drying is the process of removal of water from a material by passing drying air through a thin layer of the material until reaching the desirable moisture content. Moisture removal from agricultural products typically presents direct relationship among drying temperature, drying air velocity, relative air humidity, and variety and maturity (Yadollahinia et al., 2008). One of the most important studies on thin-layer drying of materials is the study on mathematical modeling of the drying process. Drying model is significantly useful in selection of the ideal drying conditions. It can be used to estimate a drying curve and predict drying behavior of materials such as moisture content, drying time, and heat and mass transfer. It also provides important parameters of drying optimization and product quality improvement (Giri and Prasad, 2007).

Although thin-layer drying modeling has been reported in numerous research, there is no study on modeling of drying process of hot air drying system with a desiccant wheel (HA-DW). The HA-DW system was developed to provide dehumidified air in the drying system. Low relative humidity in the drying chamber could contribute to higher drying rate, shorter drying time and moisture homogeneity inside the drying material (Dina et al., 2015; Naidu et al., 2016). Moreover, the dehumidification system may offer several advantages such as low initial costs, environmental friendliness, and energy saving (Madhiyanon et al., 2007).

Regarding to the drying material of this study, i.e. germinated brown rice (GBR), it is promoted for high nutrients such as γ-aminobutyric acid (GABA), dietary fibre, oryzanol, vitamin E and vitamin B (Kaosa-ard and Songsermpong, 2012). GABA has several physiological advantages such as being an inhibitory neurotransmitter in the cerebrospinal fluid of mammals (Liao et al., 2003), reducing plasma cholesterol level (Miura et al., 2006), improving blood glucose level (Seiki et al., 2005), and preventing chronic alcohol-related diseases (Oh et al., 2003).

Therefore, the present study was focused on developing thin-layer drying models of drying of GBR using the HA-DW system. Drying characteristics of GBR drying using the HA-DW system were also discussed.

2. Materials and Methods

2.1 Experimental Material

Brown rice of khao Dawk Mali 105 variety was used as a sample of this study. The sample was vacuum-packed and stored at 4°C. Before using in each experiment, it was brought to room temperature.

To prepare GBR, the brown rice sample was soaked at 35°C for 4 h and germinated at the same temperature for

20 h. The GBR has a moisture content up to 30-33% (w.b). The final moisture content required for dried GBR is 10-13% w.b. for safe storage (Jongyingcharoen and Cheevitsopon, 2016).

2.2 Experimental Dryer

Figure 1 shows an experimental set-up of the HA-DW system. The system is composed of three main components including a rotary DW, a dryer, and an air-to-air heat exchanger.

The rotary DW with silica gel (a desiccant material) was combined to a hot air drying system. The stainless steel DW was 700 mm diameter × 50 mm thickness. It was divided into two equal sections, i.e. adsorption and regeneration sections. These sections were run simultaneously by means of continuous rotaion between the ambient humid air through the adsorption section and the heated regenerative air through the regeneration section. It was driven by a motor (RS Motor Industry, Taiwan) at 0.5 rpm. Lower relative humidity of 8-13% was achieved in this system.

The cylindrical drying chamber was 200 mm inner diameter x 300 mm length. The blowers (1 HP, MA40B, EuroVent, Thailand) were used to supply air for drying and regeneration, respectively. The air was heated to required temperatures by 3.74-kW electrical heaters (Technology Instruments, Thailand).

The heat exchanger was made of aluminium with a heat exchanging area of 50 m2. It was designed to receive the inlet heated air from the drying unit and exchange the heat to the inlet ambient air for regenerating the DW.

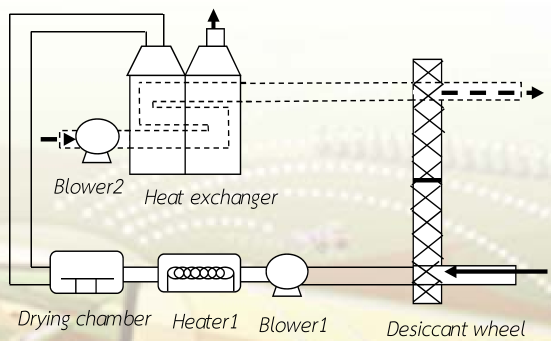

Figure 1 A schematic diagram of a HA-DW system

2.3 Experimental Procedure

The drying experiments were conducted at the drying temperatures of 80, 100 and 120°C and the flow rate of 0.04, 0.06 and 0.08 m3/s. The fixed temperature of 90°C and flow rate of 0.04 m3/s was used for the regeneration process. GBR of 1-cm grain bed depth (180 g) was fed into the drying chamber and dried until reaching the final moisture content of 12% w.b. During the process of drying, the sample was weighed at each predetermined interval for moisture content measurement. To determine its dry matter content, the sample was dried in a hot air oven at 105°C for 24 h (AOAC, 2005). The experiments were duplicated.

2.4 Theoretical Considerations

2.4.1 Calculation of Moisture Ratio and Drying Rate

The moisture ratio (MR) and drying rate (DR) were calculated as follows:

$$\mathrm{MR} = \frac{M_t - M_e}{M_i - M_e} \quad (1)$$

$$\mathrm{DR} = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

where Mi, Mt, Me and Mt+dt are moisture content (g water/g dry matter) at initial, specific time, equilibrium and t+dt, respectively and t is drying time (min). However, Me was assumed to be zero for drying at high temperature (Sripinyowanich and Noomhorm, 2011).

2.4.2 Mathematical Modeling of Drying Curves

The drying characteristics of GBR drying using HA-DW were modeled based on 8 thin-layer drying models as shown in Table 1.

Table 1 Thin layer drying models applied for HA-DW drying of GBR

Model No	Model name	Model
1	Lewis	MR=exp(-kt)
2	Page	MR=exp(-kt^n)
3	Henderson and	MR=aexp(-kt)
4	Pabis	MR=aexp(-kt)+c
5	Logarithmic Two term	MR=aexp(-k0t) +bexp(-k1t)
		MR=(aexp(-kt))+
6	Approximation of	(1-a)exp(-kbt))
7	diffusion	MR=aexp(-ktn)+bt
8	Midilli et al.	MR=1+at+bt2
	Wang and Singh	

Coefficient of determination (R2) and root mean square error (RMSE) were used to evaluate goodness of fit of the models to the experimental data. The higher the R2 and the lower the RMSE were indicated the best the model fit. These statistical criteria were calculated as follows:

$$R^2 = \frac{\sum_{i=1}^{n} MR_{pre,i} \times MR_{exp,i}}{\sqrt{\sum_{i=1}^{n} (MR_{pre,i})^2 \times \sum_{i=1}^{n} (MR_{exp,i})^2}} \qquad (3)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n} (MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \qquad (4)$$

where MRexp,i and MRpre,i are the ith experimental and predicted moisture ratio, respectively. N is the number of observations.

3. Results and Discussion

3.1 Drying Characteristics

Drying curves of HA-DW drying of GBR at different drying temperatures are shown in Figures 2-4 for the air flow rates of 0.04-0.08 m^3/s, respectively. The results show that increasing drying temperature and air flow rate increased the drying rate and consequently decreased the drying time. As shown in Table 2, the shortest drying time of 45 min was achieved by drying GBR at the highest drying temperature of 120°C and the greatest air flow rate of 0.08 m^3/s. The greatest maximum drying rate of 0.0125 g water/g dry matter·min was achieved at this condition as well.

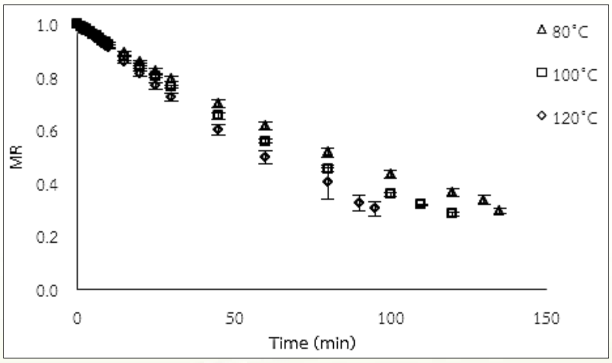

Figure 2 Drying curves of HA-DW drying of GBR at 0.04 m^3/s and different drying temperatures.

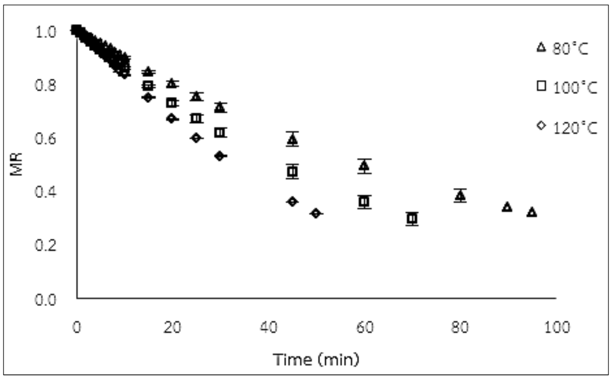

Figure 3 Drying curves of HA-DW drying of GBR at 0.06 m^3/s and different drying temperatures.

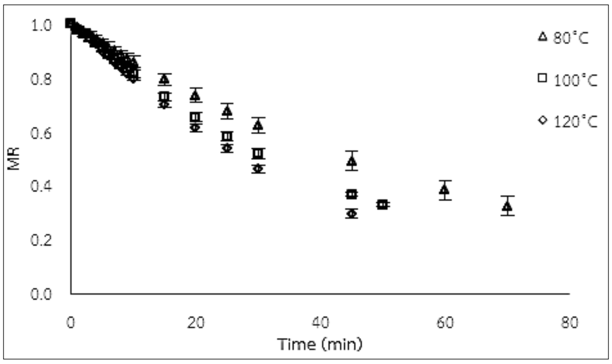

Figure 4 Drying curves of HA-DW drying of GBR at 0.08 m^3/s and different drying temperatures.

Table 2 Drying time and maximum DR for HA-DW system of GBR.

Drying condition		Drying time	Maximum DR
Q (m^3/s)	T (°C)	(min)	(g water/g dry matter min)
0.04	80	130	0.0039
	100	120	0.0043
	120	95	0.0047
0.06	80	95	0.0055
	100	70	0.0083
	120	50	0.0087
0.08	80	70	0.0074
	100	50	0.0100
	120	45	0.0125

From Figures 5-7, like general pattern of drying rate curve of hot air drying of an agricultural material, there were two drying rate periods observed for HA-DW drying of GBR, including the heating up and falling rate period.

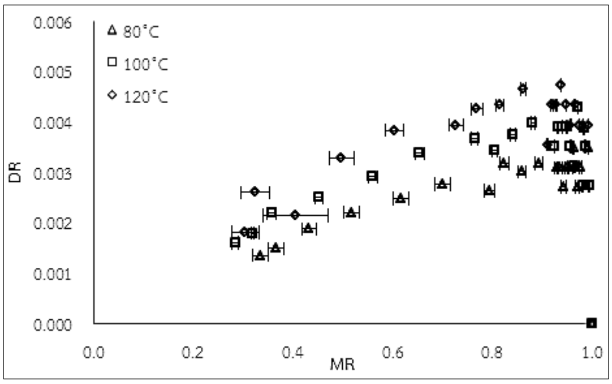

Figure 5 Drying rate curves of HA-DW drying of GBR at 0.04 m^3/s and different drying temperatures.

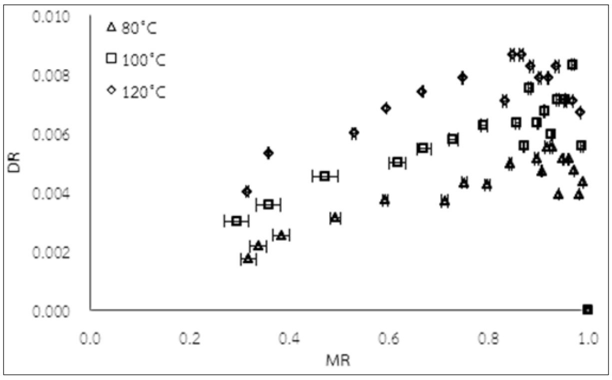

Figure 6 Drying rate curves of HA-DW drying of GBR at 0.06 m^3/s and different drying temperatures

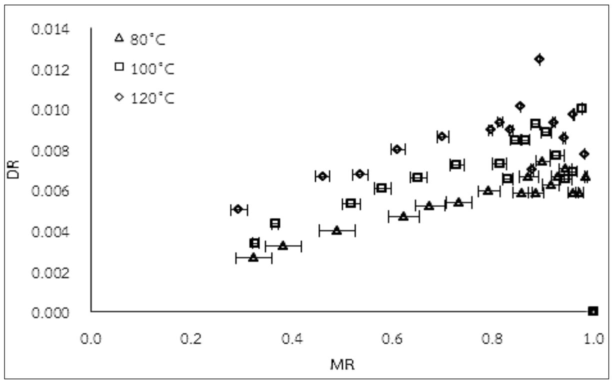

Figure 7 Drying rate curves of HA-DW drying of GBR at 0.08 m^3/s and different drying temperatures.

3.2 Mathematical drying method

The results of drying model constant and coefficients and statistical crieria (R^2 and RMSE) expressing goodness to fit of the models are shown in Table 3. This table shows only four models having the R^2 values greater than 0.998 (Page, Logarithmic, Midilli et al. and Wang and Singh models, respectively). Comparison of R^2 and RMSE values of the selected drying models showed that the Midilli et al. model gave better fit. The average values of two parameters (R^2 and RMSE) were 0.9991 and 0.0045, respectively. Figures 8-10 present the comparison between the experimental data of HA-DW drying of GBR to the predicted data given by the Midilli et al. model at each air flow rate and different drying temperatures. It can be seen that there was a very good agreement between the experimental and predicted moisture ratios at each drying time.

Table 3 Constants, coefficients and statistical crieria (R^2 and RMSE) for HA-DW drying of GBR.

Model No.	Condition Q (m^3/s)	T (°C)	Constant and coefficient		R^2	RMSE
2	0.04	80	k=0.0063	n=1.0620	0.99957	0.00500
		100	k=0.0047	n=1.1700	0.99273	0.02097
		120	k=0.0072	n=1.1150	0.99934	0.00601
	0.06	80	k=0.0096	n=1.0500	0.99995	0.00164
		100	k=0.0132	n=1.0620	0.99983	0.00281
		120	k=0.0131	n=1.1450	0.99994	0.00164
	0.08	80	k=0.0143	n=1.0280	0.99997	0.00113
		100	k=0.0186	n-=1.046	0.99991	0.00204
		120	k=0.0179	n=1.1070	0.99990	0.00208

Model No.	Condition Q (m^3/s)	T (°C)	Constant and coefficient				R^2	RMSE
4	0.04	80	k=0.0065	a=1.1900	c= -0.1895		0.99967	0.00435
		100	k=0.0055	a=1.5130	c= -0.5057		0.99186	0.02219
		120	k=0.0078	a=1.3390	c= -0.3324		0.99931	0.00615
	0.06	80	k=0.0105	a=1.0900	c= -0.0844		0.99991	0.00215
		100	k=0.0132	a=1.1750	c= -0.1734		0.99996	0.00131
		120	k=0.0137	a=1.4160	c= -0.4056		0.99952	0.00472
	0.08	80	k=0.0150	a=1.0460	c= -0.0431		0.99995	0.00147
		100	k=0.0193	a=1.0950	c= -0.0916		0.99980	0.00298
		120	k=0.0186	a=1.2640	c= -0.2560		0.99968	0.00364
7	0.04	80	k=0.0066	n=1.0320	a=0.9989	b= -0.0003	0.99969	0.00423
		100	k=0.0036	n=1.2510	a=0.9907	b=0.0004	0.99298	0.02061
		120	k=0.0077	n=1.0760	a=1.0010	b= -0.0005	0.99941	0.00567
	0.06	80	k= -0.0004	n=1.5260	a=1.0040	b= -0.0119	0.99990	0.00234
		100	k=0.0138	n=1.0250	a=1.0000	b= -0.0007	0.99998	0.00108
		120	k= -0.0220	n=0.9003	a=1.0000	b= -0.0358	0.99992	0.00187
	0.08	80	k=0.0144	n=1.0270	a=1.0010	b=0.0000	0.99998	0.00102
		100	k=0.0181	n=1.0600	a=0.9985	b=0.0002	0.99991	0.00197
		120	k=0.0183	n=1.0870	a=1.0010	b= -0.0005	0.99994	0.00161
8	0.04	80	a= -0.0074	b=0.000017			0.99964	0.00460
		100	a= -0.0079	b=0.000016			0.99182	0.02224
		120	a= -0.0098	b=0.000026			0.99916	0.00681
	0.06	80	a= -0.0107	b=0.000037			0.99988	0.00256
		100	a= -0.0148	b=0.000068			0.99995	0.00151
		120	a= -0.0179	b=0.000081			0.99914	0.00634
	0.08	80	a= -0.0147	b=0.000073			0.99988	0.00228
		100	a= -0.0200	b=0.000131			0.99989	0.00226
		120	a= -0.0219	b=0.000138			0.99961	0.00403

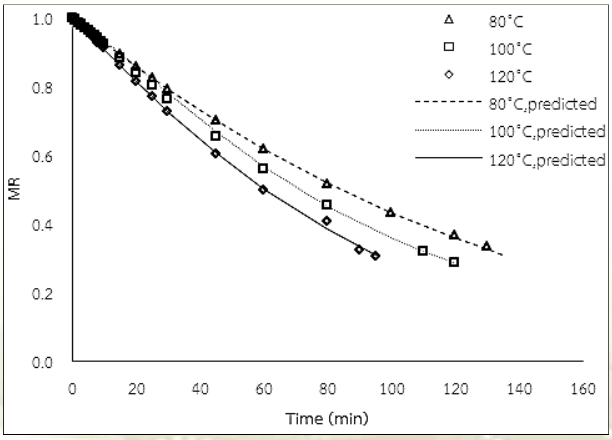

Figure 8 Experimental and predicted drying curves of HA-DW drying of GBR at 0.04 m^3/s and different drying temperatures.

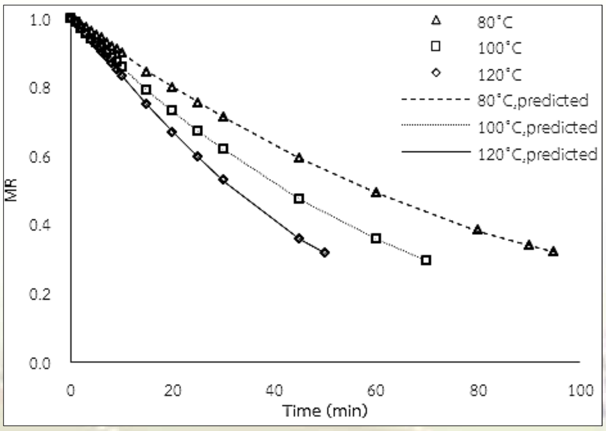

Figure 9 Experimental and predicted drying curves of HA-DW drying of GBR at 0.06 m^3/s and different drying temperatures.

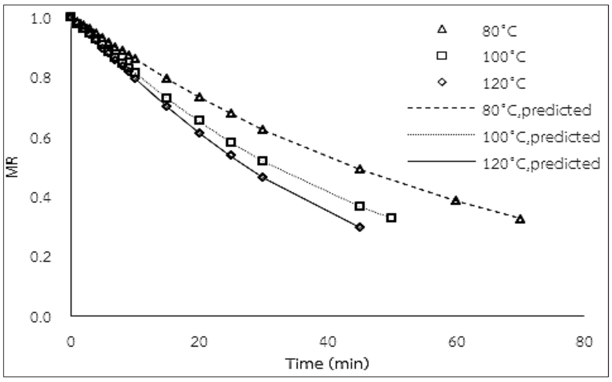

Figure 10 Experimental and predicted drying curves of HA-DW drying of GBR at 0.08 m^3/s and different drying temperatures.

4. Conclusions

Drying characteristics of HA-DW drying of GBR were provided at the air flow rates of 0.04-0.08 m^3/s and the drying temperatures of 80-120°C. Air flow rate and drying temperature had a considerable effect on drying time and drying rate. Increased air flow rate and drying temperature led to increased drying rate and short drying time. The shortest drying time of 45 min was achieved by drying GBR at the greatest air flow rate of 0.08 m^3/s and the highest drying temperature of 120°C. The best fitted drying model for HA-DW drying of GBR was the Midilli et al. model ($MR=a\exp(-kt^n)+bt$). It resulted in the highest average R^2 of 0.9991 and the lowest RMSE of 0.0045.

5. Acknowledgements

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