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Thin-layer Drying Characteristics of Rapeseed

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Abstract

Purpose: The aims of this study were to define the drying characteristics of rapeseed and to determine the optimum thin-layer drying model for rapeseed by considering the effects of drying temperature and relative humidity. **Methods:** The thin-layer drying experiments were conducted at different combinations of drying air temperature levels of 40, 50, and 60°C and relative humidity levels of 30, 45, and 60%, on both of which drying rate depends. The drying rate increased with increasing air temperature as well as decreasing relative humidity. The 13 models were fitted to the experimental data. **Results:** From the results of the regression analysis for empirical constants of the Page model, the values of R^2 were the highest (ranging from 0.9924 to 0.9966) and the values of RMSE were the lowest (ranging from 0.0169 to 0.0296). **Conclusions:** For all drying conditions considered, the Page model was determined to be the most suitable model for describing the thin-layer drying of rapeseed (P-value < 0.01). The moisture diffusion coefficients were calculated using the moisture diffusion equation for a spherical shape, based on Fick's second law.

Keywords: Deep-bed drying, Drying rate, Moisture diffusion, Rapeseed, Thin-layer drying

Introduction

Drying is a process comprising simultaneous heat and mass transfer within a material and between the surface of a material and its surrounding environment (Akpinar et al., 2004). Many drying models have been developed to define optimal drying conditions, of which semi-empirical and empirical thin-layer drying models are the most widely used (Basunia and Abe, 1998; Kameoka, 1988; Keum and Park, 1997a; Keum, Kim, and N. U. Hong, 2002; Kim et al., 2004; Wang and Singh, 1978). A considerable amount of experiment of thin-layer drying has been done for different agricultural products, mostly corn, rice, soybeans, peanuts, and sunflower seeds. However, rarely have studies concerning the drying of rapeseed been carried out. Ghaly and Sutherland (1984) determined a maximum permissible air temperature of 60°C for drying rapeseed safely with an initial moisture content from 12% to 16% wet basis (w.b.).

The drying process causes moisture to move from the inside of the grain kernel to the exposed surface of the kernel, where it evaporates. The moisture flow within a grain kernel takes place via diffusion of liquid and/or vapor during drying (Brooker et al., 1974).

The prediction of drying rates for thin-layer drying and moisture diffusion parameters of grains are important factors of deep-bed drying models and are essential for an efficient moisture transfer analysis. Therefore, validation of a deep-bed drying model is directly dependent on how accurate the thin-layer drying equation is (Basunia and Abe, 2005). These predictions lead to optimized energy use and operating conditions as well as efficient drying.

In spite of numerous experimental and theoretical studies on the determination of drying profiles, only a small number of modeling studies exist that have analyzed

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water diffusivity in grains during drying. To analyze the falling-rate period of drying, a moisture diffusion model based on Fick's second law of diffusion is used most often to predict moisture transport. The drying of many grain products, such as rice, sunflower (Danae et al., 2000), peanuts (Palacios et al., 2004), and green beans, have been predicted successfully using Fick's second law.

Various studies to secure sources of new and renewable energy have been performed since 2007. In particular, large scale (1,500 ha) demonstration projects to produce rapeseed oil for bio diesel are planned (Kim et al., 2008). However, deterioration during storage occurs unless the rapeseed is dried, because the harvest moisture content of rapeseed is high (greater than 20%) (Han et al., 2010).

In this study, thin-layer drying experiments were performed to define the drying characteristics of rapeseed and the optimum thin-layer drying model was determined, considering the effects of drying temperature and relative humidity.

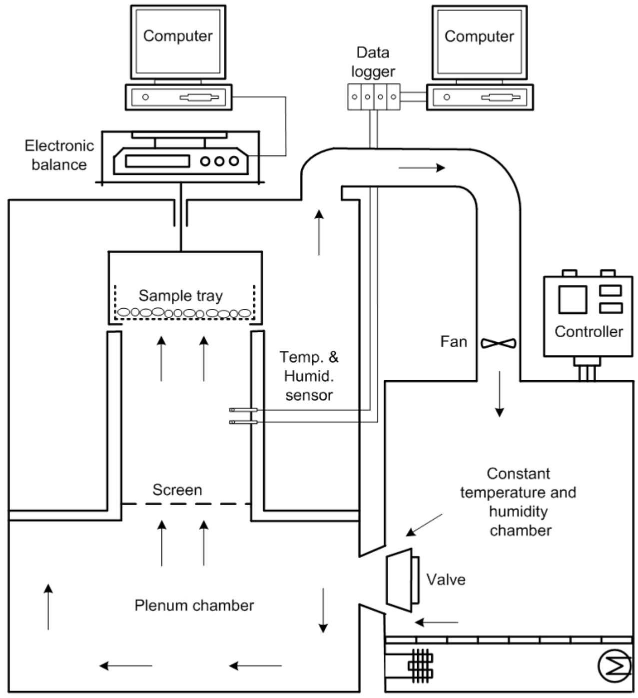

Figure 1. Schematic of the thin-layer drying apparatus and instrumentation.

Materials and Methods

Samples

Spring rapeseed (*Brassica napus Linnaeus*) samples, variety Sunmang F1-hybrid, were harvested in June in Jeonnam-do, Yeonggwang-gun. Freshly harvested samples were cleaned, then sealed in two layers of polythene bags, and finally stored in a refrigerator at 4°C (Cassells et al., 2003). Before the experiments began, the samples were taken from the refrigerator and kept at ambient air temperature for approximately 24 h, so that the samples were at room temperature (Sokhansanj et al., 1986; ANSI/ASAE S448.1, 2004).

Thin-layer drying apparatus

Thin-layer drying must be conducted under controlled air temperature and relative humidity conditions (ANSI/ASAE S448.1, 2004). Therefore, an apparatus is needed to generate drying air at constant temperature and relative humidity for thin-layer drying tests. In this work, laboratory air-conditioning equipment (MTH4100, Sanyo, UK) with ranges of operation for temperature of 20-70°C (± 0.1°C) and relative humidity of 30-98% (± 1%) was used in the drying tests. A diagram of the thin-layer drying apparatus and instrumentation is shown in Figure 1.

An insulated steel drying chamber, 280 mm in diameter and 400 mm in height, was connected to the 500 × 500 × 400 (L × W × H) mm plenum chamber. The sample tray, shaped like a shallow dish (240 mm diameter mild steel) with a 1 mm screen bottom, was placed on top of the drying chamber and was suspended from an electric balance (LC4200, Sartorius, Germany) that was accurate to ± 0.001 g. During drying, all experimental data was collected by a data logger (7327, DATASCAN, UK) and recorded by a computer.

Thin-layer drying conditions and procedure

Nine experiments were performed in total, using all permutations of temperature (40, 50, and 60°C) and relative humidity (30, 45, and 60%) values. Each experiment was performed in triplicate (ASAE S352.2, 2004).

The experiments were conducted after the system reached steady state, which took about 2 h.

Each experimental replication occurred with a sample of approximately 200 g of rapeseed. The seed sample was distributed uniformly on the drying tray surface, to a thickness of approximately 5 mm, to expose it fully to the stream of drying air. The stream of air approaching the sample must be as even as possible in temperature and humidity at any given cross section parallel to the thin layer, so that the air has uniform contact with the sample seeds.

When the samples reached the predetermined moisture content, the experiment was stopped. We selected a final moisture content of 8% as being ideal for safe rapeseed storage (Crisp and Woods, 1994; Corrêa et al., 1999).

Moisture content measurement

The moisture content of the samples was determined using the drying oven method: 10 g in a drying oven at 130°C for 4 h (ASAE S352.2, 2004).

Moisture diffusion

In thin-layer drying of agricultural products, analysis of the drying process that takes place during the falling-rate period of drying is calculated by using a simple diffusion model based on Fick's second law. Evaluation of the moisture diffusion mechanism in spherical bodies can be represented by the following equation (Brooker et al., 1974):

$$\frac{\partial M}{\partial t} = D_{eff}\left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right) \quad (1)$$

where M is moisture content (%, dry basis), t is drying time (h), D_{eff} is moisture diffusion coefficient within a particle ($m^2 \cdot s^{-1}$), and r is radius of seed (m).

An analytical solution to equation (1) can be derived by making the following assumptions (Crank, 1975):

(a) Initially, the moisture content is distributed uniformly throughout the mass of the grain.
(b) Mass transfer is symmetric with respect to the center of the sphere.
(c) When drying begins, the surface moisture content instantaneously reaches the equilibrium moisture content.
(d) Resistance to mass transfer at the surface is negligible compared to the internal resistance of the sample.
(e) Mass transfer is represented by a diffuse mechanism.
(f) The diffusion coefficient is constant and shrinkage is negligible.

With the preceding assumptions, the following initial and boundary conditions are generally used to solve equation (1):

$$M(r, 0) = M_o \quad (2)$$

$$M(r_o, 0) = M_e \quad (3)$$

The solution to equation (1) with the initial and boundary conditions from equation (2), and (3) can be obtained for the moisture diffusion model of spherical bodies (Crank, 1975):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2 D_{eff}\pi^2}{r^2}t\right) \quad (4)$$

Air velocity measurement

The air velocity was fixed at 0.56 $m \cdot s^{-1}$ to eliminate the slightest fluidization of the seed sample. The air velocity was checked with an anemometer (Velocicalc-Plus, TSI, USA) that had a resolution of 0.01 $m \cdot s^{-1}$.

Temperature measurement

A T-type thermocouple temperature sensor (T-type, OMEGA, USA) with a resolution of 0.1°C was used to measure drying temperature.

Weight loss measurement

During the drying process, the samples were weighed periodically to determine any weight loss, from which the drying curves were obtained. The gate valve was operated automatically and was set to close and open at a frequency of 10 min (Han et al., 2006). To avoid experimental error caused by air uplift of the sample tray, the weight of the tray and sample was recorded with the gate valve closed for 30 s. The change in moisture content, relative to drying time, was calculated based on the weight change.

Thin-layer drying models

Numerous models have been proposed to describe the rate of moisture loss during thin-layer drying of biological materials. In this study, 13 models were considered (Table 1).

The proposed models were fitted to the experimental drying data for rapeseed to determine the most appropriate one among them.

Statistical analysis of data

Statistical analysis was carried out by using a nonlinear regression procedure for each individual drying run. The proposed models in Table 1 were fitted to the experimental drying data and analyzed by a stepwise multiple regression method, using the Statistical Analysis System (Ver. 9.1, SAS, USA) program.

Table 1. Thin-layer drying models

No.	Model name	Equation
1	Lewis (Lewis, 1921)	MR = exp(-kt)
2	Page (Page, 1949)	MR = exp(-kt^n)
3	Modified Page (Overhults et al., 1973)	MR = exp(-kt)^n
4	Henderson and Pabis (Henderson and Pabis, 1961)	MR = A exp(-kt)
5	Modified Henderson and Pabis (Karathanos, 1999)	MR = Aexp(−kt) + Bexp(-gt) + Cexp(-ht)
6	Thompson (Thompson, 1967)	t = A ln(MR) + B ln[(MR)]^2
7	Approximation of diffusion (Sharaf-Eldeen et al., 1980)	MR = A exp(-kt) + (1-A)exp(-Bkt)
8	Logarithmic (Temple and Boxtel, 1999)	MR = A exp(-kt) + C
9	Two-term (Glenn, 1978)	MR = A exp(-k_1t) + B exp(-k_2t)
10	Two-term exponential (Sharaf-Eldeen et al., 1980)	MR = A exp(-kt) + (1−A)exp(-Akt)
11	Wang and Singh (Wang and Singh, 1978)	MR = 1 + At + Bt^2
12	Verma et al. (Verma et al., 1985)	MR = A exp(-kt) + (1-A)exp(-gt)
13	Moisture diffusion (Crank, 1975)	$MR = (6/\pi^2)\sum_{n=1}^{\infty}(1/n^2)\exp(-n^2 D_{eff}\pi^2 t/r^2)$

MR: moisture ratio (dimensionless),
M: moisture content (%, dry basis)
M_e: equilibrium moisture content (%, dry basis)
M_o: initial moisture content (%, dry basis)
t: drying time (s or h)
A, B, C, g, h, n: empirical constants in the drying models
k, k_1, k_2: empirical coefficients in the drying models
D_{eff}: moisture diffusion coefficient within a particle ($m^2 \cdot s^{-1}$)
n: number of terms of the infinite series
r: radius of seed (m)

The measured and predicted values were compared and statistically analyzed to determine the best-fit equations. The coefficient of determination (R^2) and the root mean square error (RMSE) were used to determine the quality of the fit (Akpinar et al., 2004; Sacilik et al., 2006).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{mea,i} - MR_{pred,i})^2} \quad (5)$$

Results and discussion

Thin-layer drying models

Figure 2 shows the typical characteristic drying curves of rapeseed via thin-layer drying operation for the nine different drying conditions. It is easy to recognize that drying rate depends on both drying temperature and relative humidity. The drying rate increased with increasing drying temperature as well as decreasing relative humidity. The changes in the moisture content of rapeseed with time were also revealed; it decreased continuously as drying time increased.

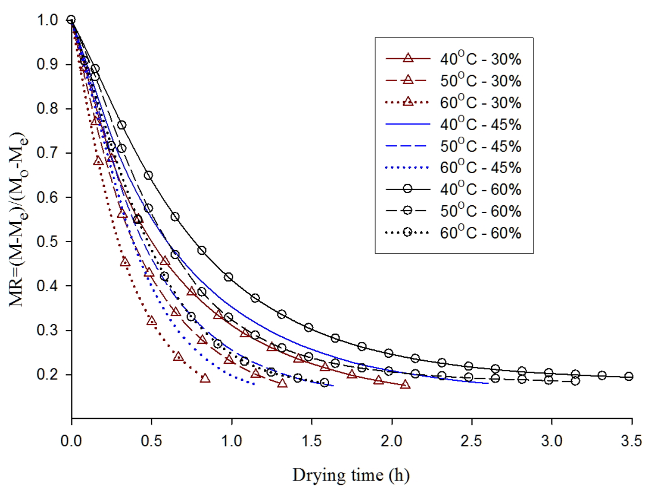

Figure 2. Drying curves of rapeseed at various air temperature and relative humidity values.

The variation in drying rate with time for each run was used to calculate the drying constants of the models using a nonlinear regression method. Then, the drying data were fitted to the 13 models. The drying constants and

Table 2. Statistical analysis results obtained for the Lewis, Page, modified Page, Henderson and Pabis, modified Henderson and Pabis, Thompson, approximation of diffusion, and logarithmic models

Drying condition*	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
	Lewis		Modified Page		Page		Henderson and Pabis	
T1-RH1	0.9807	0.0503	0.9821	0.0511	0.9930	0.0219	0.9758	0.0449
T1-RH2	0.9696	0.0565	0.9713	0.0548	0.9932	0.0201	0.9613	0.0481
T1-RH3	0.9299	0.0828	0.9610	0.0895	0.9966	0.0227	0.9076	0.0729
T2-RH1	0.9917	0.0319	0.9922	0.0324	0.9962	0.0169	0.9887	0.0294
T2-RH2	0.9832	0.0408	0.9833	0.0406	0.9924	0.0239	0.9775	0.0426
T2-RH3	0.9504	0.0776	0.9765	0.0984	0.9927	0.0232	0.9332	0.0718
T3-RH1	0.9932	0.0263	0.9928	0.0274	0.9963	0.0186	0.9934	0.0255
T3-RH2	0.9937	0.0226	0.9928	0.0249	0.9943	0.0296	0.9938	0.0229
T3-RH3	0.9939	0.0258	0.9965	0.0608	0.9945	0.0222	0.9939	0.0290
Drying condition*	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
	Modified Henderson and Pabis		Approximation of diffusion		Thompson		Logarithmic	
T1-RH1	0.9954	0.0383	0.9981	0.0168	0.9975	0.0152	0.9917	0.0390
T1-RH2	0.9958	0.0875	0.9974	0.0244	0.9769	0.0464	0.9968	0.0194
T1-RH3	0.9684	0.0911	0.9931	0.0213	0.9471	0.1184	0.9961	0.0246
T2-RH1	0.9994	0.0962	0.9970	0.0687	0.9958	0.0211	0.9966	0.0327
T2-RH2	0.9981	0.0898	0.9971	0.0791	0.9926	0.0274	0.9971	0.0149
T2-RH3	0.9437	0.0675	0.9755	0.0839	0.9570	0.0971	0.9935	0.0244
T3-RH1	0.9976	0.1010	0.9916	0.0311	0.9923	0.0281	0.9980	0.0291
T3-RH2	0.9941	0.0856	0.9910	0.0346	0.9915	0.0407	0.9879	0.0421
T3-RH3	0.9931	0.1415	0.9884	0.0479	0.9726	0.0629	0.9857	0.0599

*T1 = 40°C, T2 = 50°C, T3 = 60°C, RH1 = 30%, RH2 = 45%, RH3 = 60%

Table 3. Statistical analysis results obtained for the two-term, two-term exponential, Wang and Singh, Verma et al., and moisture diffusion models

Drying condition*	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
	Two-term		Wang and Singh		Two-term exponential		Verma et al.		Moisture diffusion	
T1-RH1	0.9995	0.0337	0.9782	0.0451	0.9942	0.0309	0.9985	0.0242	0.9942	0.0243
T1-RH2	0.9996	0.0354	0.9796	0.0657	0.9882	0.0298	0.9916	0.0489	0.9893	0.0294
T1-RH3	0.9909	0.0689	0.9420	0.0724	0.9533	0.0601	0.9855	0.0782	0.9415	0.0558
T2-RH1	0.9927	0.0618	0.9920	0.0324	0.9983	0.0185	0.9985	0.0245	0.9885	0.0362
T2-RH2	0.9901	0.0989	0.9895	0.0369	0.9929	0.0244	0.9907	0.0644	0.9833	0.0439
T2-RH3	0.9810	0.0715	0.9510	0.0828	0.9567	0.0570	0.9546	0.0592	0.9480	0.0584
T3-RH1	0.9948	0.0563	0.9943	0.0238	0.9985	0.0158	0.9978	0.0799	0.9801	0.0457
T3-RH2	0.9929	0.0638	0.9972	0.0240	0.9950	0.0212	0.9926	0.0656	0.9598	0.0663
T3-RH3	0.9883	0.0888	0.9986	0.0112	0.9944	0.0265	0.9922	0.0270	0.9647	0.0684

*T1 = 40°C, T2 = 50°C, T3 = 60°C, RH1 = 30%, RH2 = 45%, RH3 = 60%

the corresponding values of R^2 and RMSE of the 13 models are listed in Tables 2-3.

The models were evaluated based on the values of R^2 and RMSE. These statistical parameters were calculated for all conditions. Among the 13 models, the values of R^2 were the highest (ranging from 0.9924 to 0.9966) and the values of RMSE were the lowest (ranging from 0.0169 to 0.0296) for the Page model, based on all data points.

From the analysis of variance (ANOVA) using Fisher's least significant difference method, the best predictions

Table 4. Results of regression analysis for empirical constants of the Page model

MR = exp(-kt^n)			
T (°C)	RH (%)	k*	n*
40	30	1.09401	0.75798
	45	0.98914	0.71620
	60	0.79361	0.59702
50	30	1.47942	0.83385
	45	1.28340	0.83001
	60	0.99671	0.74876
60	30	1.99099	0.90972
	45	1.70381	0.94381
	60	1.32597	0.90050

*Significant at the 0.01 probability level.

of the experimental data, covering all drying runs, was obtained by the Page model. All corresponding R^2 values were consistently higher and the RMSEs were lower than they were for other models. Therefore, the Page model gave better predictions than the others did, and satisfactorily described the thin-layer drying characteristics of rapeseed.

From the results of regression analysis for the empirical constants of the Page model, (Table 4) parameters k and n were determined from the experimental coefficients for the Page model (P-value < 0.01) using equations (6) and (7).

$$k = 0.02246 + 3.2428 \cdot RH + 0.0006308 \cdot T^2 - 2.01481 \cdot RH^2 - 0.06077 \cdot T \cdot RH \quad (6)$$
$$(R^2 = 0.9949)$$

$$n = 0.60932 - 1.72018 \cdot RH^2 + 0.02529 \cdot T \cdot RH \quad (7)$$
$$(R^2 = 0.9864)$$

The drying curves obtained were fitted with the Page model. Figures 3 to 5 show the comparisons between the experimental data and the predicted drying curves from the Page model for the different test conditions. The curves showed good correlation between the measured and predicted values.

The drying rate at the beginning of the process was higher because water existing on the surface evaporates initially. Subsequently, the drying rate decreased because the amount of water that must move to the surface from the cells decreased. Resistance to water movement may exist due to shrinkage at the surface of the seed, which reduces the drying rate considerably. Therefore, the rate of moisture removal is limited by the diffusion of moisture from the inside to the surface of the seed.

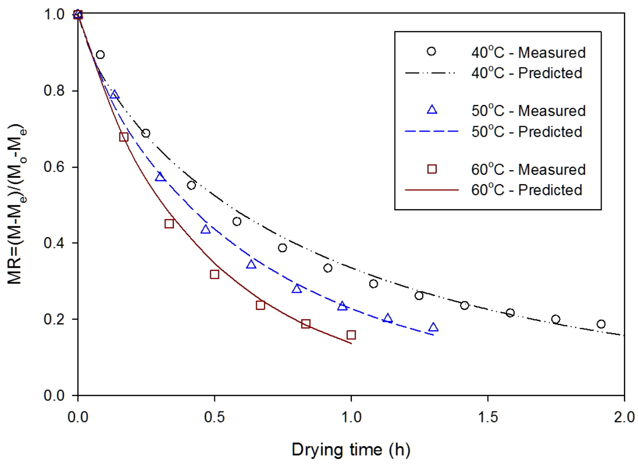

Figure 3. Measured and predicted drying rates using the Page model under drying temperatures of 40, 50, and 60°C at 30% relative humidity.

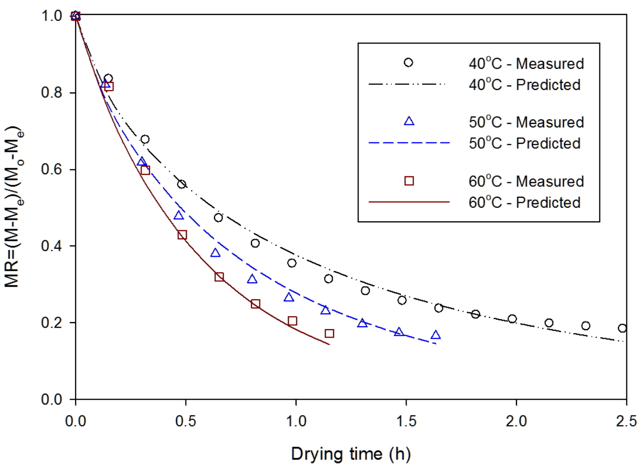

Figure 4. Measured and predicted drying rates using the Page model under drying temperatures of 40, 50, and 60°C at 45% relative humidity.

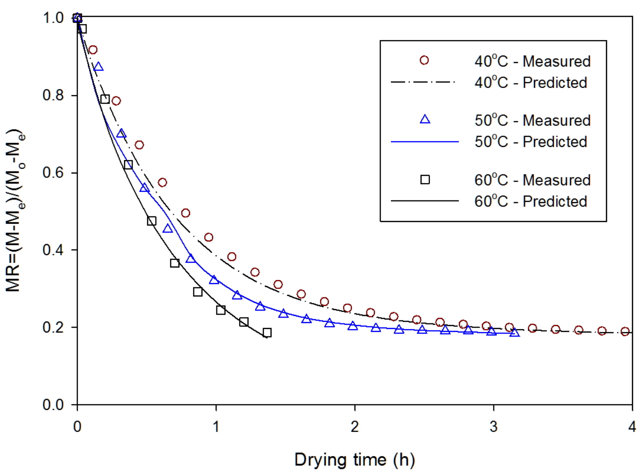

Figure 5. Measured and predicted drying rates using the Page model under drying temperatures of 40, 50, and 60°C at 60% relative humidity.

Conclusion

Thin-layer drying experiments were conducted at different combinations of drying air temperature levels of 40, 50, and 60°C and relative humidity levels of 30, 45, and 60%. The thin-layer drying characteristics of rapeseed were determined. Based on the analytic results, the following conclusions were made:

The drying rate depends on both drying temperature and relative humidity. The drying rate increased with increasing air temperature as well as decreasing relative humidity. The 13 models were fitted to the experimental data. For all drying conditions considered, the Page model was determined the most suitable model for describing the thin-layer drying of rapeseed (P-value < 0.01).

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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