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Thin Layer Drying Properties of Soybean (*Viliamz* Cultivar)

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ABSTRACT

This paper peresents a mathematical model for the thin layer drying of the *Viliamz* cultivar of soybean. The thin layer drying behaviour of soybean was experimentally investigated and the mathematical modelling performed by using thin layer drying models provided in the literature. Experiments were conducted at inlet drying air temperatures of 30, 40, 50, 60 and 70ºC and at a fixed drying air velocity of 1 m s^{-1}. Thirteen different thin layer mathematical drying models were compared according to their r values, RMSE, χ^2 and EF by non-linear regression analysis. The effect of drying air temperature on the model constants and coefficients was predicted using multiple regression analysis. According to the results, the Midilli *et al*. model was found to be the best mathematical equation for modelling thin layer drying of soybean.

Keywords: Drying kinetics, Effective diffusivity, Modeling, Soybean, Thin Layer.

INTRODUCTION

Soybean is the most important oilseed in the world market (Duarte *et al*., 2004). Its importance in grain production has been increasing due to its high yield capacity and lower harvest cost in comparison with other grains (Felipe and Barrozo, 2003). Soybean has long been used as a primary protein source in human and animal diets. Soybean proteins are used as human foods in a variety of forms, such as infant formulas, flour, protein isolates and concentrates, and textured fibers.

Therefore, the moisture in grains after harvest must be reduced to a level acceptable for marketing, storage or processing. Soybean is usually harvested with moisture content above the safe storage value. Knowledge of the drying kinetics of soybean is essential for grain quality control during the drying process.

The study of the drying behaviour of different products has recently been a subject of interest for various investigators. For example, green alfalfa (Sokhansanj and Patil, 1996), green bean (Yaldız and Ertekin, 2001), hazelnut (Lopez *et al*., 1998), lentil (Karatas, 1997), onion (Yaldız and Ertekin, 2001), parboiled rice (Bakshi and Singh, 1980), pistachio (Ghazanfari *et al*., 2003; Kashaninejad *et al*., 2003), rough rice (Basunia and Abe, 1998), soybean (Gely and Santalla, 2000), stuffed pepper (Yaldız and Ertekin, 2001), Tomato (Kross *et al*., 2004) and young coconut (Madamba, 2003).

Analysis of the drying kinetics of grains using the diffusion model is given in several publications, for example Jayas *et al*. (1991), Rafiee and Kashaninejad (2005) and Rafiee (2005). Usually, many simplified assumptions are made such as regarding the effective diffusivity as a constant with the moisture content and a negligible external mass transfer resistance, i.e. the moisture on the surface of the solid instantaneously attains the equilibrium grain moisture value.

Morey *et al*. (2003) have summarized existing models that have been used in soybean drying simulation. The more comprehensive

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of these simulation models include a thin layer equation to predict local drying rates within a deep bed. In general, the parameters of the thin layer equation depend on the material being dried and the drying conditions, and must be experimentally determined.

Freire *et al*. (2005) investigated drying kinetics of soybean seeds in the fixed bed and in the moving bed with cross flow, both being run under thin-layer conditions. Analysis of the available data followed the diffusive model approach with re-parameterization. The results showed that the effective diffusivity of the moving bed is 24 to 44% higher than that of the fixed bed.

Drying of foods depends on the heat and mass transfer characteristics of the product being dried. Knowledge of the temperature and moisture distributions throughout the product is vital for equipment and process design, quality control, and choice of appropriate storage and handling practices. Mathematical models that describe drying mechanisms of foods can provide the required temperature and moisture information (Parti, 1990).

In this study, the thin layer drying behavior of soybean in a convective type dryer was investigated and mathematical modelling using thin layer drying models provided in the literature performed.

MATERIALS AND METHODS

The Drying Model

The moisture ratio of soybean cv *Viliamz* during the thin layer drying experiments was calculated using the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad (1$$

where MR, M, Me and M0 are moisture ratio, moisture content (dry bases), equilibrium moisture and initial moisture. For mathematical modelling, the thin layer drying equations in Table 1 were tested to select the best model for describing the drying curve of the thin layer soybean.

Thin-layer Drying Equipment

The dryer consisted of a fan, a heater, a drying chamber and instruments for measurement. The dryer was bulit in Gorgan City, Iran. The airflow rate was adjusted by the fan speed control. The heating system consisted of an electric 4,000 W heater placed inside the duct. The drying chamber

Table 1. Mathematical models applied to drying curve.

Model no.	Model name	Model	References
1	Newton	$MR= exp(-kt)$	Westerman, *et al*., 1973
2	Page	$MR= exp(-kt^n)$	Guarte, 1996
3	Modified page	$MR= exp[-(kt)^n]$	Yaldız *et al*., 2001
4	Henderson and Pabis	$MR= a\ exp(-kt)$	Yagcioglu *et al*., 1999
5	Logarithmic	$MR= a\ exp(-kt)+c$	Yaldız and Ertekin, 2001
6	Two term	$MR= a\ exp(-k_0t)+b\ exp(-k_1t)$	Rahman *et al*., 1998
7	Exponential two term	$MR= a\ exp(-kt)+(1-a)\ exp(-kat)$	Yaldız *et al*., 2001
8	Wang and Singh	$MR= 1+at+bt^2$	Ozdemir and Devres, 1999
9	Thompson	$t= a\ ln(MR)+b[ln(MR)]^2$	Yaldız and Ertekin, 2001
10	Approximation of diffusion	$MR= a\ exp(-kt)+(1-a)\ exp(-kbt)$	Yaldız and Ertekin, 2001
11	Verma *et al*.	$MR= a\ exp(-kt)+(1-a)\ exp(-gt)$	Verma *et al*., 1985
12	Modified Henderson and Pabis	$MR= a\ exp(-kt)+b\ exp(-gt)+c\ exp(-ht)$	Karathanos, 1999
13	Midilli *et al*.	$MR= a\ exp(-kt^n)+bt$	Sacilik *et al*., 2006

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temperature was adjusted using the heater power control. Two drying trays were placed inside the drying chamber. For temperature measurement, a manual digital thermometer (Testo 925, Germany) with a reading accuracy of 0.1ºC was used. A thermo hygrometer (Loutron HT-3005) was used to measure the humidity levels at various locations of the system. The velocity of air passing through the system was measured by a hot wire anemometer (Testo, 405 V1, Germany). Any change in the weight of the drying materials was determined using an electric balance with an accuracy of 0.01 g.

Sample Preparation

The '*Viliamz*' variety of soybean was used in this study. Before conducting the experiment, the moisture content of the soybean was raised by intermittently adding a calculated amount of distilled water. Moistened samples were placed in sealed plastic containers and kept for at least 72 hours in a cold store at 10ºC to allow moisture to distribute evenly inside the kernels (Giner and Mascheroni, 2002).

Experimental Procedure

The experiments were performed to determine the effect of air temperature on the thin layer drying characteristics of soybean. A series of experiments was designed to cover the commercial drying of kernels in Iran. The experiments were conducted at five air temperatures (30, 40, 50, 60 and 70ºC), the air velocitiy was fixed at 1 m s^{-1}. To decrease experimental error, each drying test was performed in triplicate. Hence, 15 drying runs were carried out in a systematic manner.

Before the start of each drying run, soybean samples were removed from the refrigerator and placed in a plastic bag in the laboratory to bring the temperature up to the room temperature. Then, the soybeans were spread in a thin layer on drying trays and placed in drying chamber and the test was started. The sample weight was continuously measured and recorded every 10 minutes. Drying continued until the moisture content (d.b.%) of the samples reached the equiliberium moisture content. The average moisture content of the samples for each weighing period was calculated based on their initial and final moisture contents. After each drying experiment, samples were oven-dried for 19 hours at 130ºC to determine their moisture contents (Giner and Mascheroni, 2002).

The equilibrium moisture contents of soybean at different temperatures used in the drying experiments were obtained using the dynamic method. Seventy grams of soybean were exposed to different air temperatures (30, 40, 50, 60 and 70ºC) in the thin layer dryer until the mass loss of the sample was ceased. After drying, the moisture content of the samples were determined and used to calculate the moisture ratio.

The Statistical Modelling Procedure

The different drying models namely, the (Newton model, Page model, Modified Page model, Henderson and Pabis model, Logaritmic model, Two term model, Two term exponential model, Wang and Singh model, Thompson model, Diffusion aproximation model, Verma *et al*. model, Modified Henderson and Pabis model and Midilli *et al*. model) were fitted to the drying data.

The goodness of fit of each model was evaluated using the reduced chi-square (Martin *et al*., 2001), root mean square error (RMSE) and modelling efficiency (EF) (Ertekin and Yaldiz, 2004). The reduced chi-square is the mean square of the deviations between the experimental and calculated values for the models and was used to determine the goodness of the fit (Lahsasni *et al*., 2004). The lower the values of the reduced chi-square (χ^2), the better was the goodness of fit. The root mean square error (RMSE) gives the deviation between the predicted and experimental values and it

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must reach zero. The higher the value of the EF (EF is equal determination coefficient, R^2).

These parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad (15$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)\right]^{1/2} \quad (16$$

$$EF = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{\exp_{mean},i})^2 - \sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{\exp_{mean},i})^2} \quad (17$$

Where, $MR_{\exp,i}$ is the ith experimentally observed moisture ratio, $MR_{pre,i}$ the ith predicted moisture ratio, N the number of observations, n is the number constants and $MR_{\exp_{mean},i}$ is the mean value of experimental moisture ratio (Akpinar *et al*., 2003; Midilli and Kucuk, 2003).

The effects of initial and final moisture contents, drying air temperature, relative humidity and velocity on the drying constants have already been were investigated by many researchers (Sacilik and Elicin, 2006).

In this study, the relationships between the constants of the best suitable models with the drying air temperature were determined by multiple regression technique using linear, logarithmic, Arrhenius, exponential and power regression models which are the most common mathematical expressions. The best model for describing the thin layer drying characteristics of soybeans was chosen as the one with the highest modelling efficiency (EF) and the least reduced chi-square (χ^2) and root mean square error (RMSE). The effects of temperature on the constants and coefficient of the better mathematical model were investigated using different equations as the linear, logarithmic, inverse, quadratic, power, S-curve, exponential and logistic (Table 2).

RESULTS AND DISCUSSION

Drying rate is defined as the amount of water removed and time is shown in Figure 1 for soybean samples during thin layer drying at 30, 40, 50, 60 and 70ºC. It is apparent that the drying rate decreases continuously with improved drying time. In this curve, there was no constant-rate period but the falling-rate period is seen to occur. The results indicated that diffusion is the most likely physical mechanism governing moisture movement in the bean samples. The results were generally in agreement with some of the literature on the drying of vari-

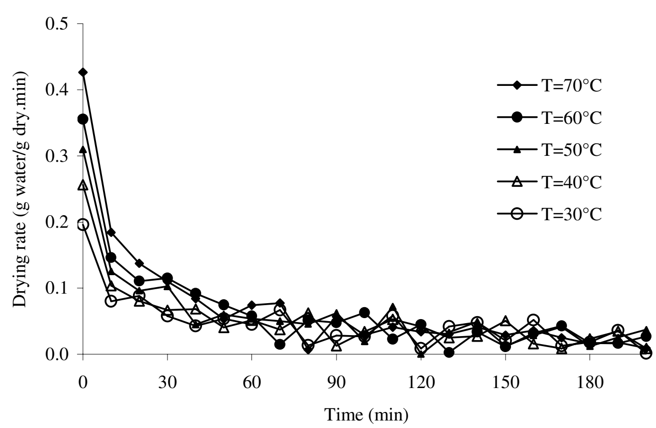

Figure 1. Drying rate curves for soybean at selected temperatures with a 1.0 m s^{-1} air velocity.

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Table 2. The mathematical model used for multiple regression.

Model name	Model
Linear	$y = b_0 + b_1 T$
Logarithmic	$y = b_0 + b_1 \ln(T)$
Inverse	$y = b_0 + b_1 / T$
Quadratic	$y = b_0 + b_1 T + b_2 T^2$
Power	$y = b_0 * T^{b_1}$
S-curve	$y = e^{b_0 + b_1 / T}$
Exponential	$y = b_0 \left(e^{b_1 T}\right)$
Logistic	$y = 1 / \left(1/u + \left(b_0 \left(b_1^{\,t}\right)\right)\right)$

ous food products (Akpinar *et al.*, 2003; Yaldiz and Ertekin, 2001).

In the analysis of thin layer drying data, the moisture ratio (MR) is essential to describe different thin layer the drying models. The moisture ratio was fitted to the selected thin layer drying models in order to be able to describe the drying characteristics of soybean in a thin layer convective-type dryer. The 13 models were evaluated based on the reduced chi-square (χ^2), root mean square error (RMSE) and modelling efficiency (EF). The results of statistical analysis applied to the 13 drying models at 50ºC are given in Table 3. The best model describing the thin layer drying characteristics of soybean was chosen as that with the highest EF and the lowest RMSE and χ^2.

Acceptable modelling efficiency (EF) of greater than 0.90 was obtained for all models (except the Newton model) fitted to all drying runs.

For investigating air temperature effects on constants and coefficients of drying expressions by multiple regression, the models describing the thin layer drying charactiristic were selected with EF> 0.99. As a result, Page model, Two term model, Diffusion approximation model, Verma *et al*. model, Modified Henderson and Pabis model and Midilli *et al*. model were chosen. Results for the Page model and the modified Page model were similar. Therefore, the Page model was chosen due to it is more classic format.

Inspite of the highest r and EF values calculated for the modified Page model, the constants and coefficient of the model did not show a good correllation with temperatures. Hence, a multiple regression analysis could not be carried out. The variation of moisture ratios with time for each

Table 3. The results of statistical analysis applied to the 13 drying models at 50 ºC.

T= 50ºC, V= 1 m s^{-1}, Model name	RMSE	χ^2	EF
Newton	0.113371	0.014170	0.592119
Page	0.016620	0.000343	0.990299
Modified Page	0.016620	0.000343	0.990299
Henderson and Pabis	0.054576	0.003345	0.903972
Logarithmic	0.038710	0.001778	0.949241
Two term	0.014565	0.000230	0.993428
Two term exponential	0.070417	0.005439	0.843245
Wang and Singh	0.136508	0.023415	0.334288
Thompson	0.027000	0.000914	0.974091
Diffusion approximation	0.015393	0.000255	0.992705
Verma *et al*.	0.015393	0.000255	0.992705
Modified Henderson and Pabis	0.010300	0.000120	0.996592
Midilli *et al*.	0.010807	0.000135	0.996179

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Table 4. Values of the drying constants and coefficients of selected models through the regression method for each temperature.

Drying air temperature (ºC) Model name		30	40	50	60	70
Page	k	0.02685	0.02728	0.02960	0.03262	0.03168
	n	0.61322	0.61836	0.62786	0.63182	0.68265
	RMSE	0.01083	0.01105	0.01328	0.01905	0.02889
		0.00012	0.00013	0.00018	0.00038	0.00090
	EF	0.99678	0.99635	0.99446	0.98873	0.97518
Two term	a	0.71972	0.70512	0.69622	0.68615	0.70136
	k_0	0.00177	0.00184	0.00222	0.00259	0.00385
	b	0.25231	0.26359	0.27478	0.29304	0.28581
	k_1	0.02471	0.02273	0.02724	0.03320	0.04560
	RMSE	0.01206	0.01204	0.01390	0.01615	0.01867
		0.00015	0.00015	0.00020	0.00028	0.00038
	EF	0.99601	0.99566	0.99393	0.99191	0.98964
Diffusion approximation	a	0.27043	0.28360	0.29402	0.30837	0.29568
	k	0.03043	0.02812	0.03293	0.03729	0.04884
	b	0.05900	0.06672	0.06835	0.07007	0.07916
	RMSE	0.01256	0.01339	0.01508	0.01692	0.01902
	χ^2	0.00016	0.00018	0.00024	0.00030	0.00039
	EF	0.99567	0.99464	0.99286	0.99112	0.98924
Verma *et al*.	a	0.27043	0.28360	0.29402	0.30837	0.29568
	k	0.03043	0.02812	0.03293	0.03729	0.0488
	g	0.00180	0.00188	0.00225	0.00261	0.00387
	RMSE	0.01256	0.01339	0.01508	0.01692	0.01902
		0.00016	0.00018	0.00024	0.00030	0.00039
	EF	0.99567	0.99464	0.99286	0.99112	0.98924
Modified Henderson and Pabis	a	0.168779	0.224245	0.137873	0.623908	0.200039
	k	0.066456	0.013186	0.113698	0.002391	0.023041
	b	0.280694	0.106004	0.639824	0.199961	0.130584
	g	0.005759	0.145422	0.002046	0.012303	0.142655
	c	0.548075	0.66954	0.221609	0.173637	0.669067
	h	0.001342	0.001739	0.012219	0.082141	0.00372
	RMSE	0.009219	0.007680	0.008028	0.011238	0.015337
	χ^2	8.62×10^{-5}	6.07×10^{-5}	6.68×10^{-5}	0.000133	0.000255
	EF	0.99767	0.99824	0.99797	0.99608	0.99300
Midilli *et al*.	a	0.99579	0.99902	0.99596	0.99768	0.99310
	k	0.03206	0.03409	0.03646	0.04166	0.04016
	n	0.56930	0.56589	0.57760	0.57430	0.62550
	b	6.53×10^{-5}	-7.2×10^{-5}	-6.9×10^{-5}	-7.3×10^{-5}	-6.5×10^{-5}
	RMSE	0.00957	0.00768	0.00826	0.01166	0.01687
	χ^2	9.28×10^{-5}	6.06×10^{-5}	7.07×10^{-5}	0.00014	0.00031
	EF	0.99749	0.99824	0.99786	0.99578	0.99153

drying condition was used for calculating the constants and coefficients of the chosen drying models (Table 4).

From Table 4, it is clear that changes of temperature have affected the constants and coefficient values of all models. For example, the Page model coefficients (k and n) for each drying air temperature were calculated. An increase in air temperature resulted in an increase in the constants and coefficients of the Page model. For example, when air temperature was 30 and 70ºC, k was 0.026845 and 0.031679 and n was 0.613222 and 0.682654, respectively, the constants and coefficients of Modified Handerson and Pabis model oscillated then could be regressed against the drying air temperature.

To take into account the effect of the drying variables on the chosen models (Table 3), the constants and coefficient were regressed against the drying air temperature

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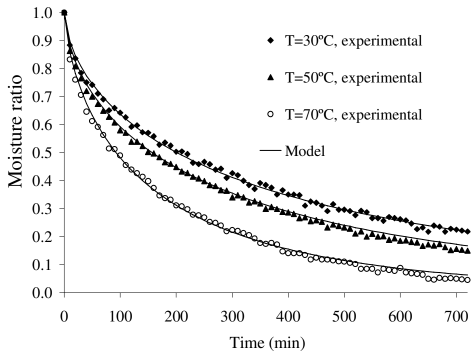

Figure 2. Variation of experimental and predicted moisture ratio by the Page model with drying time.

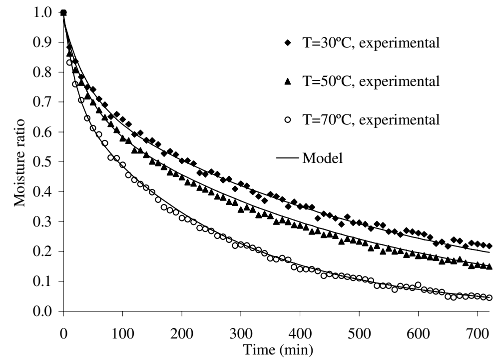

Figure 3. Variation of experimental and predicted moisture ratio by the Two term model with drying time.

using multiple regression analysis. All possible combinations of the different drying variables were tested and included in the regression. Based on the multiple regression analysis for constants and coefficients, the chosen models were shown in Table 5.

It can be seen that the Page model, the two term model, the Diffusion approximation model, Verma *et al*. model and Midilli *et al* model were in good agreement with the experimental results. Comparison of the experimental and predicted moisture ratio values with the drying time are given in Figures 2, 3, 4, 5 and 6.

Wiriyaumpaiwong *et al*. (2003) fitted the experimental results for soybean moisture rations with drying time and drying air temperature to semi-theoretical models, namely the Newton, Page and Two term models. The values of the correlation coefficient (r) for the Newton, Page and Two term models were 0.9931, 0.9934 and 0.9931, respectively.

The best model describing the thin layer drying characteristic was chosen as the one

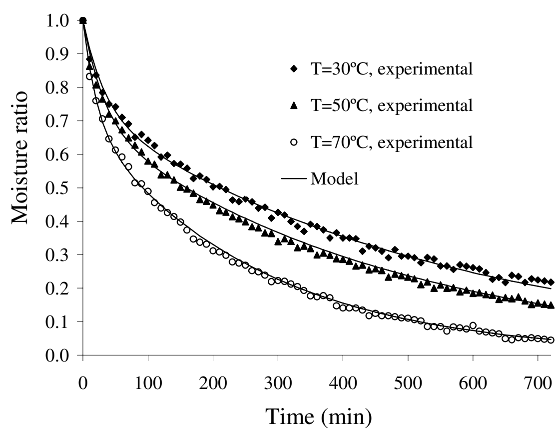

Figure 4. Variation of experimental and predicted moisture ratio by the Diffusion approximation model with drying time.

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Table 5. Effects of drying air temperature on the chosen model constants and coefficients and its results for soybean.

Model No.	Model name	Model	RMSE	χ^2	EF
18	Page	$MR = \exp(-(0.0116T^{.2413})t^{(0.6997-0.0046T+0.000061T^2)})$	0.0189	0.00044	0.988
19	Two term	$MR = (0.82560 - 0.00470T + 0.00004T^2)\exp[(0.00388 - 0.00012T + 0.000002T^2)] (-k_0t) +$ $(0.14080T^{0.17150})\exp[(0.05421 - 0.00164T + 0.00002T^2))t]$	0.0196	0.00044	0.987
20	Diffusio approximation	$MR = (0.17429 + 0.004165629T - 0.000034131T^2)\exp[-(0.057345412 - 0.001488694T + 0.000019485T^2)]$ $+ (1 - (0.17429 + 0.004165629T - 0.000034131T^2))\exp[-(0.04683 + 0.00044T)t]$	0.0189	0.00041	0.988
21	Verma *et al.*	$MR = (0.17428 + 0.00417T - 0.00003T^2)\exp[-(0.05735 - 0.00149T + 0.00002T^2)t]$ $+ (1 - (0.17428 + 0.00417T - 0.00003T^2))\exp[-(0.00387 - 0.00012T + 0.000002T^2)t]$	0.0199	0.00045	0.987
22	Midilli *et al.*	$MR(a,k,b) = (0.98190 + 0.00071T - 0.000008T^2)\exp[-(0.01103T^{0.31093})t^{(0.67687-0.00552T+0.00007T^2)}]$ $+ (-0.00003 - 0.000002T + 0.00000002T^2)t$	0.0139	0.00022	0.997

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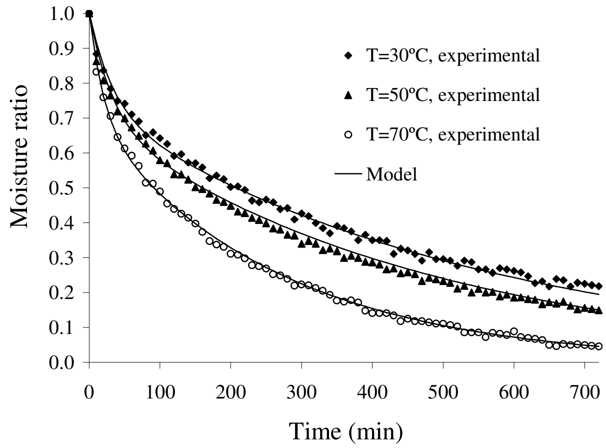

Figure 5. Variation of experimental and predicted moisture ratio by the Verma *et al*. model with drying time.

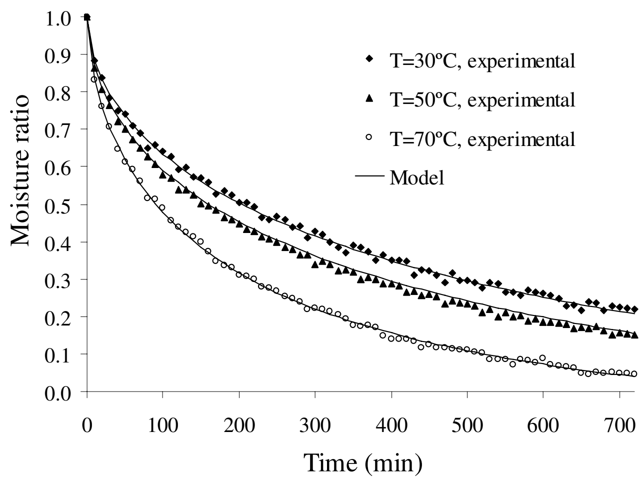

Figure 6. Variation of experimental and predicted moisture ratio by the Midilli *et al*. model with drying time.

with the highest EF and the lowest RMSE and χ^2 values. The Midilli *et al*. model was found to be the best model due to the highest EF= 0.99677 and the lowest RMSE= 0.01398 and χ^2= 0.00022.

The Midilli *et al*. model was validated by comparing the experimental moisture ratio values with the predicted ones in any particular drying experiment. The experimental and predicted moisture ratio values lay around the straight line (Figure 7). This clearly demonstrates that this model could be used to explain the thin layer drying behaviour of soybean.

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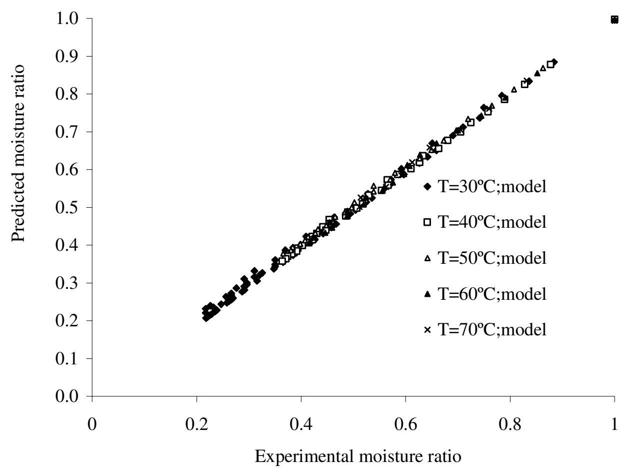

Figure 7. Experimental and predicted moisture ratio at different drying times.

CONCLUSIONS

The experimental moisture ratio was fitted to 13 thin layer drying models. Models were evaluated on the basis of root mean square error (RMSE), chi-square (χ^2) and modelling efficiency (EF). The constants and coefficients of models, except Newton model, with EF> 0.97 for each drying air temperature were calculated. Due to inconsistancies in the constants' and coefficients' values of the Henderson and Pabis model the relationships of the constants and coefficients of this model with the drying air temperature did not show good results. Therefore, it was unsuitable for multiple regression and was omitted from the final comparison.

The values of the constants of the Page model, Two term model, Diffusion aproximation model, Verma *et al*. model and Midilli *et al*. model were regressed against those of the drying air temperature using multiple regression analysis. All possible combinations of the variables were tested and included in the multiple regression analysis. According to the results for the EF, RMSE and χ^2 values of those thin layer drying models for all drying temperatures, the Midilli *et al*. model gave the lowest RMSE and χ^2 values and the highest EF values. Hence, the Midilli *et al*. model was chosen to represent the thin layer drying of soybeans.

Nomenclature

a, b, c	Empirical constants in the drying models
g, h, k, k_0, k_1	Empirical coefficient in the drying models (min^{-1})
MR	Moisture ratio
M	Moisture content, (% dry basis, d.b.)
n	Empirical constants in the drying models and number of constants
N	Number of observations
t	Time, (min)
T	Temperature, (ºC)
Subscript	
a	Absolute
e	Equilibrium
exp	Experimental data
pre	Predicted data
0	Initial moisture

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بررسی خواص خشک شدن لایه نازک سویا (رقم ویلیامز)

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چکیده

مقاله حاضر مدل ریاضی خشک شدن سویا رقم ویلیامز را ارائه می‌دهد. رفتار خشک‌شدن لایه نازک سویا به‌طور آزمایشگاهی بررسی شده و با مدلهای ریاضی لایه نازک ارائه شده توسط محققان، انطباق داده شده است. آزمایشات با دمای هوای ورودی ۳۰ ، ۴۰ ، ۵۰ ، ۶۰ و۷۰ درجه سیلسیوس و با سرعت ثابت یک متر بر ثانیه انجام شد. با کمک تحلیل غیرخطی رگرسیون، نتایج با سیزده مدل ریاضی مختلف خشک‌شدن جریان نازک، متناسب با مقادیر RMSE ، χ^2 و EF مقایسه گردید. با کمک تحلیل رگرسیون چندگانه، اثر دمای هوای خشک شدن بر روی ثوابت و ضرایب مدل ، محاسبه شد. مطابق با نتایج به‌دست آمده، مدل ریاضی میدیلی و همکارانش بهترین انطباق با فرایند خشک شدن سویا را دارد.