Mathematical modeling of drying characteristics of chilli in hot air oven and fluidized bed dryers

S. D. F. Mihindukulasuriya[1], H. P. W. Jayasuriya[2*]

(1. *Dept. of Food Science, University of Guelph, Guelph, Ontario, Canada*;
2. *Dept. of Soils, Water and Agricultural Engineering, Sultan Qaboos University, Oman*)

Abstract: The thin layer drying kinetics of chilli is experimentally investigated in hot air oven and fluidized bed dryers. Experiments were conducted at inlet air temperatures of 45℃, 50℃, 55℃, 60℃ and 65℃. The power consumption and quality parameters (color and capsaicin content) were measured in each experiment. Thirteen different thin layer mathematical drying models were compared by using their regression coefficient, chi square value and RMSE (root mean square error). The Midilli model was found to be the best mathematical model which could use to satisfactorily predict the moisture ratio of chilli at different drying air temperatures in each type of dryers used. Surface colour chromaticity parameter a* changed from 32.5 at 45℃ to 25.8 at 65℃ temperature in hot air dryer whereas it was changed from 29.3 at 45℃ to 23.8 at 65℃. When temperature increases from 50℃ to 65℃, there is a considerable reduction in the colour of chilli in both dryers. Capsaicin concentration was inversely related with the air temperature and there was a sharp reduction of capsaicin concentration when increasing the temperature from 60℃ to 65℃. The energy consumption was higher in fluidized bed dryer than the hot air oven dryer when moisture content of chilli reduced from 280% to 9% (d.b) during drying process. The retention time of the fluidized bed dryer in all operating temperatures was nearly three times less that of hot-air oven dryer due to higher air flow characteristics. Lowest power consumption occurred at 65℃ temperature setting in both dryers while the fluidized bed dryer consumed nearly 75% more power.

Keywords: mathematical modeling, drying kinetics, capsaicin, fluidized bed, regression

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1 Introduction

Chilli plays a vital role in the food habits in almost every Asian country as an essential ingredient in meals while giving some precious health benefits and also as one of the most important cash crops grown in those countries. Traditional and inefficient drying methods such as sun drying are commonly practiced in developing countries for chilli drying and these methods are time consuming, weather dependent and can lead to lower quality, higher waste due to capsaicin losses, contamination and spoilage, thus quality might be low when comparing to the other methods. Sun drying of chillies remains the most widely practice method throughout the Asia, Africa, Central and South America (Kaleemullah and Kailappan, 2005).

Food drying is complex process involving simultaneous mass and energy transport phenomena (Crapiste, 2000). Some research works have been done to reduce the drying time or improve the quality of chillies using mechanical drying methods (Dhanegopal et al., 1988). But the mathematical models related to drying of chillies are scanty (Kaleemullah and Kailappan, 2005). Since sun drying depends on uncontrolled factors, production of uniform and standard products is not expected. Hot air drying is the most commonly employed commercial technique for drying of biological products (Mazza and LeMaguer, 1980). The major

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*** Corresponding author: H. P. W. Jayasuriya,** Dept. of Soils, Water and Agricultural Engineering, Sultan Qaboos University, PO Box 34, PC 123, Al-Khod, Oman. Email: hemanthaj@hotmail.com; suramya2k4@gmail.com.

limitation of the hot air drying is that it takes longer for drying, resulting in product quality degradation. Fluidized bed drying is an efficient drying method due to good mixing, high heat and mass transfer coefficients and also it exhibits shorter drying time. A major disadvantage of fluidized bed is possibility of size reduction of the particles due to attrition and collision between them.

The drying kinetics of the red bell pepper (var. Lamuyo) have been studied and modeled by Vega et al. (2007) reported that Page modified model (Diamante and Munro, 1991) able to use as the best fit for every drying curve, representing an excellent tool for estimation of the drying time. Akpinar et al. (2003) has evaluated the suitability of eleven models and the best model was selected based on the highest regression with lowest RMSE and χ^2. According to his findings, the diffusion model could adequately describe the thin layer drying behavior of red peppers among the 11 thin layer-drying models. According to the Kaleemullah and Kailappan (2005), Page and Kaaleemullah models gave the best prediction for moisture removal of chilli.

The objectives of this study are: (1) to investigate and model the drying kinetics of red chilli in hot air and fluidized bed dryers; (2) to compare the quality parameters of chilli in each dryer; and (3) to evaluate the power consumption in each dryer during chilli drying.

2 Materials and methods

2.1 Equipment and instrumentation

The main equipment and the instrumentation used in the experiment were as follows;

Hot air dryer: This bench-top hot-air dryer was developed at Asian Institute of Technology (AIT) and it consists of a fin coil heater (2 kW), drying chamber with tray feeder, temperature controller, weight measuring sensor and other measuring instruments with interface facility to record data in the computer.

Fluidized bed dryer: A laboratory-scale fluidized bed dryer (Sherwood Scientific Ltd., Cambridge, England) which consists of compact bench top unit (with heater and blower), filter bag, temperature controller, centrifuge with sealed tub assembly. This compact bench-top unit uses a powerful air delivery system and heater to rapidly remove the moisture.

2.2 Experimental procedure

The fresh chilli (pickino variety) sample batches of 100 g were used in the experiments. Chillies were neither treated with any chemical nor sliced before conducting the experiments. Chillies were dried from 280% to 9% (d.b) moisture content in hot air and fluid bed dryers. The initial and final moisture content of the chilli samples were determined by drying duplicate samples in an oven at 105℃ for 6 hours. After dryers were reached at steady state conditions for operation temperatures, 100 g samples were put on the tray in hot air oven dryer, and correspondingly it was put in to the glass container in fluid bed dryer. Drying experiments with three replications in each case were conducted at 45℃, 50℃, 55℃, 60℃, 65℃. During the experiments dry bulb and wet bulb temperature in the drying air were recorded. In the fluid bed dryer a 2.4 m^3 min^{-1} air velocity was maintained. Power consumption of the each dryer was measured by using Fluke power meter. Surface colour of dried chilli was measured by using colorimeter (Colour flex of hunter associated laboratory) and the capsaicin content of the dried chilli in each temperature in each type of dryer was measured by using colorimetric method procedure given by Sadasivam and Munickam (1997).

2.3 Mathematical modeling

Thirteen different thin layer mathematical models were evaluated given in Table 1.

Many thin layer drying models of agricultural products are mainly empirical in nature, because of non-isotropic and non-homogenous nature of the agricultural products along with the irregular shape and the changes in their shape during drying (Togrul and Dursun, 2003). Frequently, authors propose quite simple models to simulate the drying curves of food that can provide adequate representation of experimental results although the parameters of these models lack of physical sense. The most simplified model was found to be fitted to exponential characteristics (Senadeera et al., 2003).

Table 1 Mathematical models applied to the drying curves

No	Model name	References	Model
1	Lewis	Akpinar et al. (2003)	$MR = \exp(-kt)$
2	Page	Diamante and Munro (1991)	$MR = \exp(-kt^n)$
3	Modified Page (I)	White et al. (1981).	$MR = \exp[-(kt)^n]$
4	Henderson and Pabis	Zhang and Litchfield (1991)	$MR = a.\exp(-kt)$
5	Logarithmic	Akpinar et al. (2003)	$MR = a.\exp(-kt) + c$
6	Two term	Henderson (1974)	$MR = a.\exp(-k_o t) + b.\exp(-k_1 t)$
7	Two-term exponential	Akpinar et al. (2003)	$MR = a.\exp(-kt) + (1-a)\exp(-kat)$
8	Wang and Singh	Wang and Singh (1978)	$MR = 1 + at + bt^2$
9	Diffusion approach	Yaldiz and Ertekin (2001)	$MR = a.\exp(-kt) + (1-a)\exp(-kbt)$
10	Verma *et al*.	Akpinar et al. (2003)	$MR = a.\exp(-kt) + (1-a)\exp(-gt)$
11	Modified Henderson and Pabis	Karathanos and Vasilios (1999)	$MR = a.\exp(-kt) + b.\exp(-gt) + c.\exp(-ht)$
12	Modified Page equation-II	Diamante and Munro (1991)	$MR = \exp\left(-k\left(\frac{t}{L^2}\right)^n\right)$
13	Midilli model	Ertekin and Yaldiz (2004); Midilli and Kucuk (2003)	$MR = a.\exp(-kt^n) + bt$

There are adequate literature to prove that suitability of the Page model (Diamante and Munro, 1993) for describing the drying behavior of some vegetables and fruits. Demir et al. (2004) reported that Page model was the best fitted with the drying kinetics of bay leaves. Ibrahim and Pala (2002) found that the Page equation represents drying characteristics of red pepper better than the exponential equation. Simal et al. (2005) evaluated drying kinetics of kiwi fruits where the Page model provided the best simulation of the drying kinetics of kiwi (average of 99.6±0.2%). Karathano and Vasilios (1999) reported the suitability of a thin-layer model, the Page equation, which was applied to air drying data of high sugar-containing agricultural plant products, such as currants, sultanas, and plums.

Some researches reported that the Diffusion model (Yaldiz and Ertekin, 2001) could be used to sufficiently describe the drying behavior of food materials. Queiroz and Nebra (2001) reported the best fitting was obtained in the diffusion model with diffusion coefficient on the study of drying kinetic of bananas. According to findings of the Togrul and Pehlivan (2002), the approximation of the diffusion model for apricots (non-pre-treated or SO_2-sulphured) was found to be the best explanation for one layer open sun drying behavior of the fruits. Pinedo and Murr (2006) studied the drying kinetics of pumpkin by using a vacuum dryer. The diffusion model, with and without considering the shrinkage, and with three terms of the Fourier series proved to offer an excellent fit for the drying kinetics of pumpkin.

In thin layer drying, drying kinetics of various food materials can be explained by different empirical models, as illustrated in Table 1. Lewis model describes the drying kinetic of black tea (Panchariya et al., 2002), logarithmic model for the drying of plum (Goyal et al., 2007), Modified Page model for kale (Mwithiga and Olwal, 2005), Midilli model for the apples (Menges and Ertekin, 2006). Togrul and Pehlivan (2002) has studied the drying behavior of single apricots experimentally with the help of a laboratory tray drying apparatus; among the 14 models, the logarithmic drying model described the best drying behavior of single apricots (within 99.9% correlation coefficient). Based on the available literature, any singular model was not capable of describing the drying kinetics of all agricultural products.

2.4 Determination of moisture ratio

Moisture ratios (MR) of chilli samples in each dryer were calculated by using the following equation (Akpinar et al., 2003).

$$MR = \frac{W_t - W_e}{W_i - W_e} \tag{1}$$

where, W_t = Moisture content at time t (d.b.), g; W_i = Moisture content at time zero (d.b.), g; W_e = Moisture content in equilibrium state, g.

2.4.1 Statistical analysis

The regression coefficient (R^2) was computed by using SPSS 11.5 statistical package with application of non linear multiple regression analysis. The R^2 is primary criterion for selecting the best equation to describe the drying curve equation. In addition to that, the reduce χ^2 (Chi square) as the mean square of the deviations between the experimental and calculated values for the models and root mean square error analysis (*RMSE*) were used to determined the correlation fit. The higher the vales of the R^2 and lowest vales of χ^2 and RMSE, provide the better the correlation (Yaldiz and Ertekin, 2001; Akpinar et al., 2003; Gunhan et al., 2005; Doymaz, 2004; Sacilik and Elicin, 2006).

These can be calculated as:

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

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

where, χ^2 = Chi –square; $MR_{\exp}$ = experimental moisture ratio; MR_{pre} = predicted moisture ratio; N = number of observations; n = number of constant; *RMSE* = root mean square error

3 Results and Discussion

3.1 Evaluation of drying models in hot air oven dryer

Tables 1A-10A shown in Appendix provide the results of statistical analysis undertaken in each model (with time in hours) at each temperature in each dryer. The models were evaluated based on the R^2, χ^2, and *RMSE*. The Midilli model recorded the highest R^2 with lowest χ^2 and *RMSE* and it was the best descriptive model in each dryer in each temperature as shown in the tables of Appendix.

It was clear from the data that R^2, χ^2, and *RMSE* values were varied between 0.99776-0.99883, 0.0001235-0.0004753 and 0.0108331-0.0214639 respectively. Hence, the Midilli model gave better prediction than other models, and satisfactorily described drying characteristics of chilli in hot air oven dryer. Menges and Ertekin (2006) reported similar results for the drying of golden apples.

For the fluidized bed dryer the values of R^2, χ^2, and *RMSE* varied between 0.99491-0.99899, 0.000226-0.0004744, 0.013147098-0.036653524, respectively from 45℃ to 65℃. In this drying process, the Midilli model also provided the best prediction (Table 3) for moisture removal.

Table 2 Values of the drying constant and coefficient of Midilli model determined through regression method in a hot air oven

Temperature /℃	Model Coefficients			Model constants
	R^2	χ^2	*RMSE*	
45	0.99883	0.00017	0.01289	k = 0.00572 n = 1.41077 b =- 0.00067 a = 0.99201
50	0.99873	0.00048	0.02146	k = 0.01253 b = -0.00130 a = 0.95393 n = 1.36482
55	0.99776	0.00019	0.01359	k = 0.01440 b = -0.00033 a = 0.93617 n = 1.54881
60	0.9988	0.00012	0.01083	k = 0.01487 b = -0.00017 a = 1.00103 n = 1.68586
65	0.99778	0.00017	0.01292	n = 1.53161 k = 0.03365 b = 0.00031 a = 0.98670

Table 3 Values of the drying constant and coefficient of Midilli model determined through regression method in fluidized bed dryer

Temperature /℃	Model Coefficients			Model constants
	R^2	χ^2	*RMSE*	
45	0.99491	0.00047	0.02089	a = 0.92928 k = 0.01435 n = 1.56771 b = -5.78449
50	0.99652	0.00043	0.02040	k = 0.03683 n = 1.45571 b = 0.00015 a = 0.96885
55	0.99700	0.00034	0.01703	a = 0.97473 b = -0.00008 n = 1.56773 k = 0.06273
60	0.99899	0.00156	0.03665	a = 1.04022 b = -0.00008 n = 1.23654 k = 0.19250
65	0.99740	0.00022	0.01315	b = -0.00012 k = 0.42156 a = 1.00351 n = 1.00825

The variation of moisture ratio with drying time at temperatures of 45℃, 50℃, 55℃, 60℃, 65℃ in two dryers are given in Figures 1 and 2. There is an inverse relationship between air temperature and drying time; an increase in air temperature resulted in a decrease in the drying time in both hot air ovens dryer as well as in fluidized bed dryer. The times to reach 9% (d.b) moisture content from the initial moisture content at the various drying air temperature of chilli found to be varied between 15 to 67.5 hrs in hot air oven dryer and 5 to 24 hrs in fluidized bed dryer. It is clear that drying rate decreases continuously with drying time. There was no constant rate drying periods appeared in each temperature in both dryers. These results were found to be similar to research findings by Akpinar et al. (2003) and Kaleemullah and Kailappan (2005). And this is in line with the results for mint (Ibrahim, 2006), chilli (Akpinar et al., 2003), apricots (Togrul and Dursun, 2003), orange skin (Garau et al., 2006), potato and green bean (Senadeera et al., 2003), tomato seeds (Sogi et al., 2003), carrot, corn, tomato, mushroom, garlic, onion, spinach, green pepper, red pepper, pumpkin, yellow pepper, green pea, leek and celery (Krokida et al., 2003).

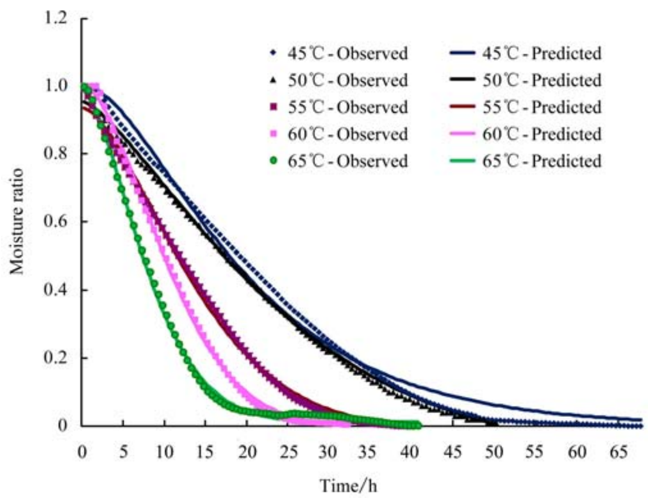

Figure 1 Variation of experimental and predicted moisture ratios by the Midilli model at 45℃, 50℃, 55℃, 60℃, 65℃ with drying time in hot air oven dryer

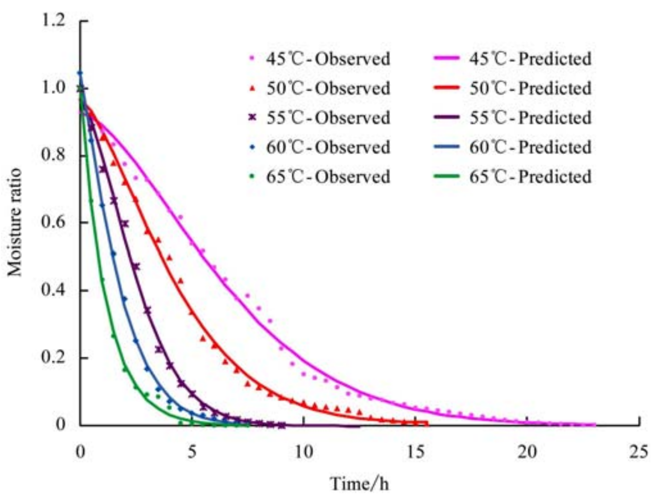

Figure 2 Variation of experimental and predicted moisture ratios by the Midilli model at 45℃, 50℃, 55℃, 60℃, 65℃ with drying time in fluid bed dryer

Drying rate is the rate of change of moisture content in the food material during drying. It is proportional to the difference in moisture content of the food at given time during drying and the equilibrium moisture content at the drying air (Sarsavadia et al., 1999). Drying rate increases with increasing temperature and there was an exponential relationship between drying rate and temperature. Obtained models are given in Figures 3-4 with their relationship.

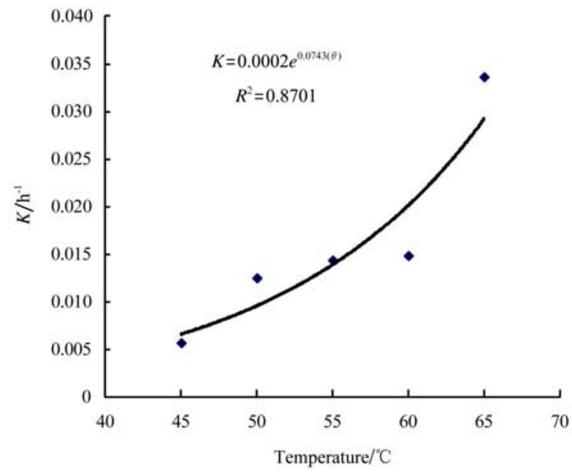

Figure 3 Variation of drying rate with drying air temperature in a hot air oven

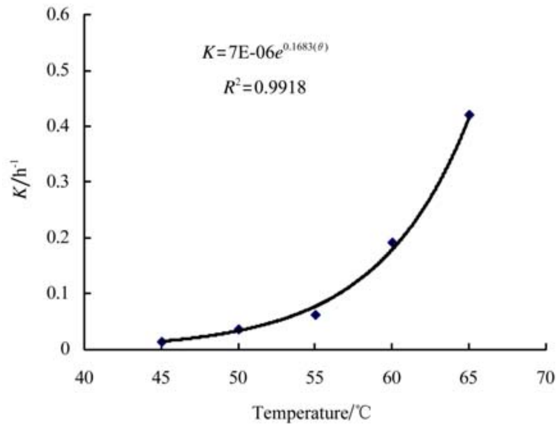

Figure 4 Variation of drying rate with drying air temperature in a fluidized bed dryer

In a hot air oven the accepted model as follows with a R^2 of 0.8701,

$$K = 0.0002e^{0.0743\theta} \tag{4}$$

where, K = drying rate, h^{-1}; θ = temperature, ℃.

In a fluidized bed dryer, the developed model is given as follows with a very strong R^2 of 0.9918,

$$K = 7\times10^{-6}e^{0.1683\theta} \tag{5}$$

where, K = drying rate, h^{-1}; θ = temperature, ℃.

3.2 Determination of color in different temperature in each dryer

Figure 5 provides the information on surface colour of red chilli in hot air oven and fluid bed dryers in terms of colour parameter a^* (red/geen). According to Figure 5, the color of fresh chilli (a^*= 38) was higher than its dried state. A 25% color reduction was occurred at lowest operating temperature of 45℃ in both dryers, and was gradually decreased from 32.5 to 25.8 with the increase of temperature from 45℃ to 65℃ respectively in hot air oven. The corresponding reduction in fluidized bed dryer was from 29.3 to 23.8. At 65℃, the colour value reduction with respect to fresh chilli was nearly 33% in hot air dryer and 39% in fluidized bed dryer. There was a significant difference of colour change between temperatures 60℃ and 65℃ in both dryers. The fluidized bed dryer had a slightly higher colour value reduction when compared the hot air oven dryer.

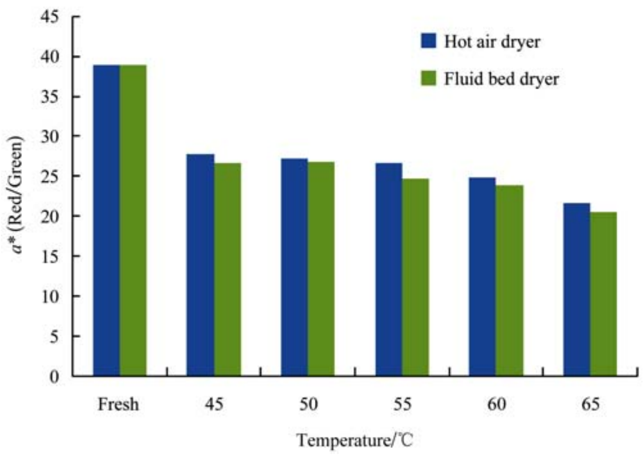

Figure 5 Surface color a^*(red/green) variation of chilli during drying at 45℃, 50℃, 55℃, 60℃, 65℃ temperature in each dryers

3.3 Determination of capsaicin content in different temperature

Capsaicin concentration was gradually decreased when increasing temperature from 45℃ to 60℃, since then it has fallen down sharply from 60℃ to 65℃ in both hot air dryer and fluidized bed dryer (Figure 6). Similar results were reported by Kaleemullah and Kailappan (2005). The polynomial equations were fitted between capsaicin content (C_{ap}, mg mL^{-1}) and temperature in a hot air oven dryer and fluidized bed dryer as Equations (6)-(7), with a value of R^2 of 0.9385 in a hot air oven dryer.

$$C_{ap} = -0.0003\theta^2 + 0.0333\theta - 0.1163 \quad (6)$$

Fitted model for capsaicin changes in the fluidized bed dryer as follows, with a value of R^2 of 0.9451.

$$C_{ap} = -0.0003\theta^2 + 0.0276\theta + 0.1012 \quad (7)$$

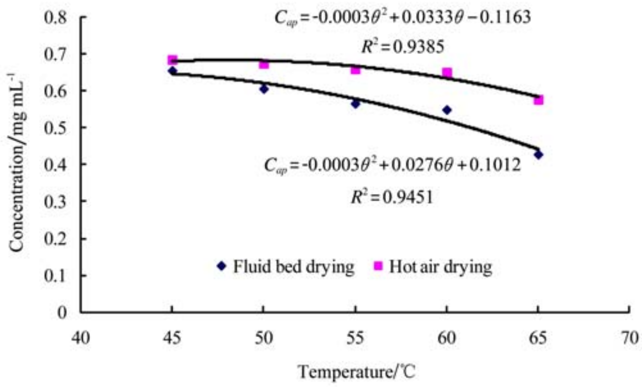

Figure 6 Variation of capsaicin content in different air temperatures during hot air drying and fluidized bed drying

3.4 Determination of power consumption by each dryer in each temperature

Table 4 shows the operating powers and power consumption rates by each dryer at different temperature settings. The operating power of the fluidized bed dryer varied between 0.45 and 1.02 kW corresponding to temperature range between 45℃ and 65℃ while the power consumption rate varied between 8.20 and 10.92 kWh, lowest retention time of 8 hrs at 65°C consuming the minimum power.

Table 4 Power consumption in both dryer at different operating temperature

Operating temperature /℃	Fluid bed dryer			Hot air oven dryer		
	Operating power /kW	Retention time /hrs	Power consumption /kWh	Operating power /kW	Retention time /hrs	Power consumption /kWh
45	0.45	24.00	10.80	0.19	75.00	12.82
50	0.63	17.00	10.71	0.19	60.50	9.97
55	0.78	14.00	10.92	0.19	53.00	7.60
60	0.95	11.00	10.45	0.19	32.00	6.08
65	1.02	8.00	8.20	0.19	24.50	4.66

The hot air oven dryer also showed the similar trend however, the dryer seemed to running under capacity operating at 0.19 kW. The power consumption rate varied between 4.66 and 12.82 kWh corresponding to temperature range between 45℃ and 65℃, lowest retention time of 24.5 hrs at 65℃ consuming the minimum power. Both dryers showed minimum power consumptions at 65℃ and corresponding to minimum retention times. However, the retention time of the fluidized bed dryer at this temperature was three times less than the hot air oven dryer due to higher air flow characteristics but consumed 76% more power.

4 Conclusions

Thirteen different thin layer drying models were compared according to their RMSE, chi-square and R^2 values in order to explain the drying behavior of chilli. According to the results of thin layer drying of chilli, Midilli model could be used to precisely predict the moisture content of product in both type of dryers at 45℃, 50℃, 55℃, 60℃, 65℃ and in fluid bed dryer with air velocity of 2.4 $m^3 min^{-1}$.

Surface colour parameter a* changed from fresh fruit 38.8 to 32.5 at 45℃ and further reduced to 25.8 at 65℃ temperature in hot air oven dryer, whereas it changed from 38.8 to 29.3 from fresh to 45℃ and further reduced to 23.8 at 65℃ in the fluidized bed dryer. In both dryers 16% - 25% colour value reduction was occurred from fresh to lowest operating temperature of 45℃, while 33%-39% overall reduction was appeared between fresh and operating temperature of 65℃. When temperature increases from 60℃ to 65℃, there was a steeper colour reduction in both dryers. The reduction of colour chromaticity a* was found to be slightly higher in fluid bed dryer than hot air oven dryer.

The retention time of the fluidized bed dryer in all operating temperatures was nearly three times less than the hot air oven dryer in all operating temperatures due to higher air flow characteristics. Lowest power consumption occurred at 65℃ temperature setting while fluidized bed dryer consuming nearly 75% more power. Capsaicin content of chillies decreased with increasing temperature and it reduced sharply from 60℃ to 65℃.

When selecting the best model to describe the drying kinetics of each dryer, Midilli model gave the best correlation with comparatively similar results in both dryers, recording highest R^2 with lower chi-squire and *RMSE* values. Therefore, it can be concluded that Midilli model can be applied for finding drying kinetics for chilli in the dryers tested.

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Appendixes

Table 1A Values of the drying constant and coefficients of different models determined through regression method at 45℃ in hot air oven dryer.

Model	45℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.94874	0.00520	0.07191	k = 0.02909		
2	0.99615	0.00038	0.01946	k = 0.00438	n = 1.51494	
3	0.99615	0.00038	0.01946	k = 0.02774	n = 1.51494	
4	0.96989	0.00307	0.05514	k = 0.03324	a = 1.15080	
5	0.99539	0.00070	0.02626	k = 0 .01979	a = 1.35222	g = -0.27957
6	0.96989	0.00311	0.05514	a = 0.71385	b = 0.43694	k_0 = 0.03324
				k_1 = 0.03324		
7	0.99548	0.50532	0.22051	a = -0.02071	b = 0 .00010	
8	0.99548	0.05729	0.23747	a = -0.02071	b = 0 .00010	k = 1.00002
9	0.94931	0.00525	0.07188	a = 0.08943	g = 0.02928	k = 0.02928
10	0.96989	0.00314	0.05514	a = 0.37444	g = 0.03324	k = 0.03324
				b = 0.37262	c = 0.40373	h = 0.03324
11	0.99105	0.02032	0.14182	a = 1.99732	b = 0.04498	
12	0.99615	0.00039	0.01946	k = 0.00037	l = 0.44257	n = 1.51494
13	0.99883	0.00017	0.01290	k = 0.00572	n = 1.41077	a = 0.99200
				b = -0.00067		

Table 2A Values of the drying constant and coefficients of different models determined through regression method at 50℃ in hot air oven dryer

Model	50℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.96364	0.00341	0.05816	k = 0.04927		
2	0.99349	0.00061	0.02448	n = 1.39455	k = 0.01387	
3	0.99349	0.00061	0.02448	n = 1.39455	k = 0.04653	
4	0.97237	0.00261	0.05067	a = 1.09858	k = 0.05371	
5	0.99181	0.00077	0.02750	k = 0.03743	c = -0.15875	a = 1.19733
6	0.97237	9.19567	2.98542	k_0 = 0.05371	a = 0.24289	k_1 = 0.05371
				b = 0.85569		
7	0.99872	0.00011	0.01042	b = 0.00030	a = -0.03514	
8	0.99186	0.02952	0.16982	k = 0.09208	a = 1.00000	b = 1.00000
9	0.96364	0.00346	0.05816	a = 0.49988	k = 0 .04927	g = 0.04927
10	0.97237	0.00271	0.05081	k = 0.05371	a = 0.30954	b = 0.30954
				c = 0.47000	g = 0.05371	h = 0.05371
11	0.99007	0.00093	0.03029	k = 0.07130	a = 1.88987	
12	0.99349	0.00051	0.02234	l = 1.58035	n = 1.39456	k = 0.04971
13	0.99873	0.00048	0.02146	k = 0.01253	b = -0.00130	a = 0.95392
				n = 1.36482		

Table 3A Values of the drying constant and coefficients of different models determined through regression method at 55℃ in hot air oven dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.96463	0.06292	0.24959	k = 0.07449		
2	0.9946	0.00050	0.02211	n = 1.41879	k = 0.02290	
3	0.99464	0.05960	0.24168	n = 1.41879	k = 0.06983	
4	0.97384	0.06241	0.24731	a = 1.10651	k = 0.08153	
5	0.98849	0.05809	0.23738	k = 0.06302	c = -0.10251	a = 1.16209
6	0.97384	0.06371	0.24731	k_0= 0.08153	a = 0.10341	k_1 = 0.08153
				b = 1.00309		
7	0.99738	0.06158	0.24566	b = 0.00066	a = -0.05193	
8	0.96873	0.06828	0.25735	k = 0.06172	a = 1.00000	b = 1.00000
9	0.96463	0.06422	0.24959	a = 0.50089	k = 0.07449	g = 0.07449
10	0.97384	0.06507	0.24731	k = 0.08153	a = 0.33011	b = 0.41275
				g = 0.08154	h = 0.08153	c = 0.36364
11	0.90148	0.06866	0.25940	k = 0.10000	a = 1.00000	
12	0.99464	0.06022	0.24168	l = 1.44260	n = 1.41879	k = 0.06479
13	0.99776	0.00019	0.01360	k = 0.01440	b = -0.00032	a = 0.93616
				n = 1.54881		

Table 4A Values of the drying constant and coefficients of different models determined through regression method at 60℃ in hot air oven dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.94053	0.00666	0.08108	k = 0.08881		
2	0.99871	0.00013	0.01122	n = 1.70378	k = 0.01433	
3	0.99871	0.00013	0.01122	n = 1.70378	k = 0.08277	
4	0.96820	0.00360	0.05923	a = 1.19956	k = 0.10400	
5	0.98233	0.00203	0.04423	k = 0.08218	c = -0.10083	a = 1.25464
6	0.96820	0.00369	0.05923	k_1 =0.10400	a = 0.59942	k_2 = 0.10400
				b = 0.60014		
7	0.98572	0.00050	0.02214	b = 0.00097	a = -0.06305	
8	0.94053	0.00683	0.08108	k = 0.08881	a = 1.00000	b = 1.00000
9	0.94053	0.00683	0.08108	a = 0.50018	k = 0.08881	g = 0.08881
10	0.96820	0.00379	0.05923	k = 0.10400	a = 0.69606	b = 0.32141
				c = 0.18207	g = 0.10400	h = 0.10400
11	0.99364	0.00070	0.02619	k = 0.14391	a = 2.13630	
12	0.99871	0.00013	0.01122	l = 1.25803	n = 1.70379	k = 0.03133
13	0.99880	0.00012	0.01083	k = 0.01487	b = -0.00017	a = 1.00103
				n = 1.68586		

Table 5A Values of the drying constant and coefficients of different models determined through regression method at 65℃ in hot air oven dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.97133	0.00226	0.04729	k = 0.11520		
2	0.99698	0.00024	0.01528	n = 1.46790	k = 0.03893	
3	0.99698	0.00028	0.01655	n = 1.46790	k = 0.10956	
4	0.98360	0.00130	0.03565	k = 0.12943	a = 1.13757	
5	0.98468	0.00123	0.03451	c = -0.01495	a = 1.14290	k = 0.12384
6	0.98360	0.00133	0.03565	k_1 = 0.12943	a = 0.51824	b = 0.61932
				k_2 = 0.12943		
7	0.91963	0.00652	0.07991	b = 0.00105	a = -0.06739	
8	0.97133	0.00231	0.04729	k = 0.11520	a = 1.00000	b = 1.00000
9	0.97133	0.00231	0.04729	a = 0.50131	k = 0.11520	g = 0.12943
10	0.98360	0.00423	0.06295	b = 0.38783	k = 0.12943	g = 0.12943
				c = 0.35842	a = 0.39131	h = 0.12943
11	0.99636	0.00028	0.01656	a = 1.99472	k = 0.17669	
12	0.99698	0.00024	0.01528	l = 0.98937	n = 1.46790	k = 0.03773
13	0.99778	0.00017	0.01292	b = 0.00031	a = 0.98670	n = 1.53161
				k = 0.03365		

Table 6A Values of the drying constant and coefficients of different models determined through regression method at 45℃ in fluidized bed dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.96834	0.00288	0.05315	k = 0.07575		
2	0.99216	0.00288	0.05315	k = 0.02628	n =1.37946	
3	0.99216	0.00069	0.02580	k = 0.07150	n =1.37946	
4	0.97426	0.00237	0.04765	a = 1.08306	k = 0.08139	
5	0.98436	0.00145	0.03692	a = 1.12587	k = 0.06630	c = -0.07827
6	0.97426	0.00247	0.04765	a = 0.54183	k_0 = 0.08139	b = 0.54123
				k_1 = 0.08139		
7	0.98921	0.00099	0.03079	b = 0.00067	a = -0.05231	
8	0.96834	0.00300	0.05315	a = 1.00000	k = 0.07575	b = 1.0000
9	0.96834	0.00300	0.05315	a = 0.61487	k = 0.07575	g = 0.07575
10	0.97426	0.00236	0.04559	a = 0.33085	b = 0.33084	c = 0.42136
				g = 0.08139	h = 0.08139	k = 0.08139
11	0.99002	0.00089	0.02919	a = 1.88168	k = 0.10892	
12	0.99216	0.00071	0.02580	n = 1.37946	l = 1.02210	k = 0.02791
13	0.99491	0.00047	0.02089	a = 0.92928	k = 0.01435	n = 1.56770
					b = -5.78449e-06	

Table 7A Values of the drying constant and coefficients of different models determined through regression method at 50℃ in fluidized bed dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.97516	0.00224	0.04672	k = 0.11180		
2	0.99602	0.00036	0.01857	k = 0.04657	n = 1.36759	
3	0.99602	0.00036	0.01857	k = 0.10619	n = 1.36759	
4	0.98212	0.00166	0.03960	k = 0.12101	a = 1.09164	
5	0.98729	0.00118	0.03301	k = 0.10612	a = 1.11597	c = -0.04756
				k_0 = 0.12101		
6	0.98212	0.00175	0.03960	k_0 = 0.12101	a = 0.59311	b = 0.49852
				k_1 = 0.12101		
7	0.98049	0.00181	0.04144	b = 0.00134	a = -0.07467	
8	0.97516	0.00237	0.04672	k = 0.11180	a = 1.00000	b = 1.00000
9	0.97516	0.00237	0.04672	a = 0.50007	g = 0.11180	k = 0.11180
10	0.98212	0.00186	0.03960	a = 0.49693	h = 0.12101	g = 0.12101
				b = 0.39734	c = 0.19736	k = 0.12101
11	0.99513	0.00044	0.02041	a = 1.90309	k = 0.16322	
12	0.99602	0.00044	0.02041	k = 0.09233	n = 1.36759	
13	0.99652	0.00044	0.02041	k = 0.03683	n = 1.45571	b = 0.00015
				a = 0.96885	l = 1.28431	

Table 8A Values of the drying constant and coefficients of different models determined through regression method at 55℃ in fluidized bed dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.96926	0.00307	0.05435	k = 0.18915		
2	0.99626	0.00039	0.01889	n = 1.47738	k = 0.07735	
3	0.99626	0.00039	0.01889	k = 0.17686	n = 1.47738	
4	0.97599	0.00249	0.04792	k = 0.20391	a = 1.09127	
5	0.98266	0.00189	0.04088	k = 0.17959	c = -0.04702	a = 1.11894
6	0.97599	0.00272	0.04794	k_1 = 0.203911	a = 0.54171	k_0 = 0.20391
				b = 0.54955		
7	0.97212	0.00288	0.05154	b = 0.00333	a = -0.11929	
8	0.96926	0.01278	0.10467	a = 1.00000	k = 0.18915	b = 1.00000
9	0.96926	0.00334	0.05435	a = 0.03625	k = 0.18913	g = 0.18915
10	0.97599	0.00299	0.04794	a = 0.42149	c = 0.28139	k = 0.20391
				h = 0.20390	g = 0.20391	b = 0.38837
11	0.99339	0.03138	0.17019	k = 0.28186	a = 1.96195	
12	0.99626	0.00651	0.07590	k = 0.16994	n = 1.47738	
13	0.99700	0.00034	0.01704	a = 0.96472	b = -0.00008	n = 1.56773
				k = 0.06273		

Table 9A Values of the drying constant and coefficients of different models determined through regression method at 60℃ in fluidized bed dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.98567	0.00141	0.03665	k = 0.26611		
2	0.99806	0.00016	0.01215	n = 1.30954	k = .16587	
3	0.99806	0.00016	0.01215	k = 0.25363	n = 1.30954	
4	0.99301	0.00075	0.02598	a = 1.09516	k = 0.28849	
5	0.99493	0.00058	0.02229	a = 1.10784	c = -0.02209	k = 0.27080
6	0.99301	0.00083	0.02586	a = 0.71076	b = 0.38440	k_0 = -0.28849
				k_1 = -0.28848		
7	0.94418	0.00565	0.07150	b = 0.00555	a = -0.15494	
8	0.98567	0.00157	0.03665	a = 1.00000	b = 1.00000	k = 0.26611
9	0.98567	0.00157	0.03665	a = 0.90047	k = 0.26612	g = 0.26611
10	0.99301	0.00157	0.03665	a = 0.60690	b = 0.24413	c = 0.24413
				g = 0.28849	h = 0.28849	k = 0.28849
11	0.99776	0.00157	0.03665	a = 1.86791	k = 0.38175	
12	0.99806	0.00157	0.03665	k = 0.23983	l = 1.15117	n = 1.30954
13	0.99899	0.00157	0.03665	a = 1.04022	b = -0.00008	k = 0.19250
				n =1.23654		

Table 10A Values of the drying constant and coefficients of different models determined through regression method at 65℃ in fluidized bed dryer

Model	55℃			Model constants		
	R^2	χ^2	*RMSE*			
1	0.99734	0.00018	0.01318	k = 0.99734		
2	0.99738	0.00020	0.01321	n = 1.01567	k = 0.41769	
3	0.99738	0.00020	0.01321	n = 1.01567	k = 0.42336	
4	0.99737	0.00020	0.01316	a = 1.00528	k = 0.42695	
5	0.99738	0.00021	0.01315	k = 0.42491	a = 1.00611	c = -0.00142
6	0.99740	0.00023	0.01313	a = 0.11827	b = 0.88761	k_0 = 0.34612
				k_1 = 0.44004		
7	0.83081	0.01438	0.11263	a = -0.20404	b = 0.00943	
8	0.99734	0.00021	0.01318	a = 0.99460	b = 0.79543	k = 0.42539
9	0.99734	0.00021	0.01318	a = 0.99465	g = 0.33801	k = 0.42538
10	0.99731	0.02876	0.24569	a = 0.11127	b = 0.61783	c = 0.27679
				g = 0.87981	h = 0.87990	k = 0.68379
11	0.99734	0.00020	0.01318	a = 0.99921	k = 0.42483	
12	0.99738	0.00021	0.01321	k = 0.25155	l = 0.77909	n = 1.01567
13	0.99740	0.00023	0.01315	a = 1.00350	b = -0.00011	k = 0.42155
				n =1.00825		