MATHEMATICAL MODELLING AND EXPERIMENTAL INVESTIGATION ON SOLAR DRYER WITH REFLECTOR FOR DRYING RED CHILLY

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Abstract
The drying kinetics of chillies (red) are studied in a two-pass solar crop dryer with forced convection and in open sunlight for free convection. It is observed in drying process that the rate of drying varies during day time and in deceleration. Based on this study dry data fit altered mathematical models are developed. The performance of each model was examined by comparing the coefficient of determination (R), reduced chi-square (χ^2) and root mean square error (RMSE) of observed and predicted humidity. The drying model based on logarithmic model among these models is in harmony with the data obtained in the solar energy dryer experiment in forced convection drying. Page model is suitable for testing sun-dried chillies data in free convection mode and effective moisture diffusion was estimated by Fick's diffusion model.

Keywords: solar collector, dryer, solar reversed absorber, reflectors, chilli

Nomenclature

DM Drying Model
DSD Direct Solar dryer
ISD Indirect solar dryer
MC Moisture Content
SCD Solar crop dryer
SD Multi-Pass SCD with reversed absorber and reflector

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1. Introduction

Drying is the method to remove moisture from contains. Drying is very important process for preserving an agricultural product for a long time because of which an agricultural product may be available in all the season. Open sun drying method is always used by a farmer to dry all agricultural products. Due to limitations such as no uniform drying of agricultural product and longer time required for drying and uncleanness during drying process, this method is not suitable for mass production. Conventional dryers can be used to dry an agricultural product. In conventional dryer, hygienic condition can be maintained but it is costly due to utilization of fuel as source of energy. Solar dryers are an emerging technique which has overcome these limitations. Solar dryer technology has various advantages like simple in design, low-cost energy source and maintain hygienic condition. The critical study of solar drying processes has great practical and economic importance. In designing the process, study of fundamentals and mechanisms, level of moisture in the product and temperature required to dry-out the product are critical factors [1]. Many researchers have presented theoretical models of drying process in which heat as well as mass transfer are studied. Thin layer models and simulations help for designing new dryer with improving its usefulness in existing applications [2]. In thin layer model the moisture in agriculture product can be measured at any time and correlation can be developed with drying period. Most of the Researchers have developed a specific type of solar dryer and conducted experimentation for specific type of agriculture product. Analysis has been done without putting any evidence that this dryer can be used for other agricultural product. Many researchers have proposed a different type of solar dryer, that are categorized into direct, indirect and hybrid solar dryer [3, 4]. SCD is an example of domestic and DSD where solar radiation direct falls on the food product [5]. In a direct solar dryer, the food product placed in the thin layer on perforated trays and opened to the direct solar emission. In ISD, the air gets heated initially in the collector and then it has passes through the product. Indirect solar dyer functions more effectively and can control the drying process. Shell dryer is an example of ISD present in the literature [6]. Indirect solar dryer with natural air circulation has been specially designed for particular type of agricultural product and may be used with additional source of energy to improve its performance. Singh et al. [7] has developed an efficient solar dryer specially to dry Fruits, Spices and vegetables and has a drying capacity of about 1kg per day. The solar dryer is featured by direct, indirect and hybrid with forced or natural circulation of air. For collecting maximum energy, the solar air collector is always inclined due south so that sun rays strike perpendicular throughout the day on collector. Manual tracking may be alternative but it is not a practical. Solar air heater integrated with tracking system can be used to collect maximum heat energy but it is very expensive. The solar air heater is designed to absorb the maximum solar radiation on a sunny day. Many researchers have proposed a new type solar dryer model and present a nature of drying behaviour of agricultural product [8–11]. Thin layer drying model can be used easily as well as it gives accurate results. However, the rate of drying depends on the temperature of air and drying rate can be kept constant if temperature of air is maintained. The mathematical model [12] is used to study the effect of different air passes within the SAC on the thermal efficiency and the temperature upswing at diverse air mass flow rates. The result shows that the thermal efficiency of SAC increases rapidly as the mass flow rate is increased. But it is not possible to maintain the temperature constant all through the day. Mwithiga and Kigo [13] has noted the effectiveness of solar tracking on cumulative the drying rate, but it is a costly affaire. Fatouh et al. [14] observed the effect of air temperature and velocity upon drying characteristics of the agricultural product. The drying rate can be achieved if considered parameters are within the limits. Singh et al. [15] noted that the leafy vegetables are dried in a short period than other vegetables. Abhay Bhanudas Lingayata, V. P. Chandramohana et al. [16] had designed a new indirect type of SD. From experimentation, it is interpreted that the drying rate are dependent on air temperature and speed. Lopez Vidhana, Eric Cesar et al. [17] had designed and fabricated a mixed type of SCD and studied its performance by using a tomato. S. Nabnean, P. Nimnuan et al. [18] had used a parabolic shaped polycarbonate plate cover over a flat plate collector and noticed that the drying time is reduced significantly. Saloni Spall, V.P. Sethi et al. [19] presented an innovative SD Integrated with inclined reflective north wall (RNW). Result shows reduced drying time up to 15% and 20% underneath forced and free convection modes resp.

The Hybrid Indirect Passive (HIP) Solar Dryer [20] is designed for large-scale drying using active solar photovoltaic and electric (SPE) dryers with thermal backup and open sun drying (OSD). Mixed Mode

Forced Convection (MFSCD) [21] has a shorter drying time, higher drying efficiency, better product quality and a payback period of 0.65 years compared to OSD. [22] FPSAC studied different weather conditions and found that solar radiation has a positive effect on the temperature of electrical equipment, glass covers and electrical equipment. Solar cookers with inner reflector and pallet lower parabolic reflector (TBPR) [23] can reach an average temperature of 140°C to 150°C. Dimple plate solar heating heat (SDPSAH) [24] Dhanbad, India showed the highest temperature variation, which was approximately 1.51 to 1.64 times higher than the corresponding FPSAH. Subarna Maiti, Pankaj Patel, Kairavi Vyas and others. [25] designed a natural convection intermittent solar dryer equipped with north-south reflectors. Compared to high solar radiation, energy consumption increased by 18.5% and MC decreased from 83% to 12% (w.b.) in 5 hrs. A single reflector north-facing condensing mirror (NFCM) is integrated into the multi-rack side-loading inclined solar cooker-dryer (ISCCD) [26]; winter.

Although this solar dryer is designed to dry a variety of agricultural products, it is still necessary to conduct drying experiments on specific agricultural products to learn about its performance and usability. In addition, solar drying can be considered as an improvement of solar drying and is a good solar energy device. Efficiency can also be increased by using single glazing, double glazing and multi-channel solar wind harvesting. Glass dryers and solar air heaters are one solution.

The objective of this work is to recommend a SCD with two pass with rock bed collector and reflector to collect the maximum possible solar radiation. A novel SD has been projected by taking a reference of reported solar dryer in literature [27, 28] and introduces some new features which help to maximize the solar energy absorption. The principal modification was that; it includes indirect type of solar dryer using forced convection heat transfer with two pass arrangement Firstly it was very important to reduce the variation in air temperature throughout the day. Secondly the drying period was long because drying started from 8 am to 5 pm for using the whole sunny day. The dryer was constructed, performed the experiment and compared with other solar dryers' performance. The drying characteristic was investigated by performing an experiment by using red chilli.

2. Mathematical model of Drying curves

Moisture ratio (MR) is calculated with following equation

MR = (Mt-Me) / (Mo-Me);

Some researchers simply calculate it as Mt / Mo [29-31] due to the constant moisture change in dry air. [29-31] outdoors during drying and sunlight. Mathematically, the drying bed equation in Table 1 was tried to be selected as the best model to explain the stability of dried pepper during sun drying and outdoor drying [29-30, 32, 33-36, 37-38]. Regression analysis was performed on a computer using excel. The correlation coefficient (R) is important to choose the best equation describing the drying equation. Root mean squares error analysis (RMSE), which is the reduction of the mean square of the R, $\chi 2$and the variance of the experiment and calculating the significance of the model, was used to determine the quality of the fit. The higher the R value, the lower the $\chi 2$ and RMSE values and the better the fit [29-30, 32, 33-36, 37-38]. These can be listed as follows:

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre\,i}) \cdot \sum_{i=1}^{n}(MR_i - MR_{\exp i})}{\sqrt{\left[\sum_{i=1}^{n}(ME_i - MR_{pre\,i})^2\right]\left[\sum_{i=1}^{n}(MR_i - MR_{pre\,i})^2\right]}} \quad (1)$$

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

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

where,

MRexp,i - *ith* experimentally observed moisture ratio,

MRpre,i – *ith* predicted moisture ratio, *N* - number of observations and *n* - number constants

Table 1: Various mathematical models for solar drying

Model No.	Name of Mathematical Model	Mathematical Model
1	Newton	$MR = exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp[(-kt)^n]$
4	Henderson and Pabis	$MR = a.exp(-kt)$
5	Logarithmic	$MR = a.exp(-kt) + c$

6	Two term	$MR = a\exp(-K_0 t) + b\exp(-K_1 t)$
7	Two-term exponential	$MR = a\exp(-k t) + (1-a)\exp(-k a t)$
8	Wang and Singh	$MR = 1 + at + bt^2$
9	Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-k b t)$
10	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-g t) + c\exp(-ht)$
11	Verma *et al.*	$MR = a\exp(-kt) + (1-a)\exp(-g t)$
12	Midilli and Kucuk	$MR = a.\exp(-kt^n) + bt$
13	hompson	$t = a\ln(MR) + b((\ln(MR))^2$

3. Methods and Materials

3.1 Experimental test rig

The size of solar air collector was 2 x 1 x 0.10 meter. Two black painted absorber plates of aluminium were used. First absorber plate was inclined at 30^0 to earth in south direction. Second absorber plate was horizontal and parallel with earth which was used as a bottom of collector and surrounded by a reflector. 4mm thin clear glass had been used as a glazing over top of solar collector. The solar collector integrated with a drying box of size 1 x 1 x 1meter.All sides of box were insulated because of wood material. Two perforated trays of 5 kg capacity were used to store the chilli. Air fan were provided at the top side of dryer to control the air flow. This model was made adjustable in such a way that it could work as single pass, double pass as well as and triple pass as well as with reflector and without reflector solar dryer. Reflector was of aluminium material. The solar heater is just south, tilted 30 degrees to the earth.

3.2 Experimental procedure

During the light hours, from 8 am to 6 pm experimentation was carried out on designed solar dryer by using red chilli and evaluation of the performance was noted. The two types of solar dryer were used i.e.

(1) Solar dryer without reversed absorber and reflector
(2) Solar dryer with reversed absorber and reflector.

10 kg of Red chilli were washed by potable water and then it was stored on a thin layered perforated tray. Fan was started and set such that it maintains a 1m/s velocity of air during drying process. Experimental readings were taken at an interval of 1 hour and noted solar intensity, atmospheric air temperature, air temperature at collector outlet, weight of chilli and dryer outlet air temperature. Measure ambient air and dry air relative humidity using a wet bulb hygrometer.

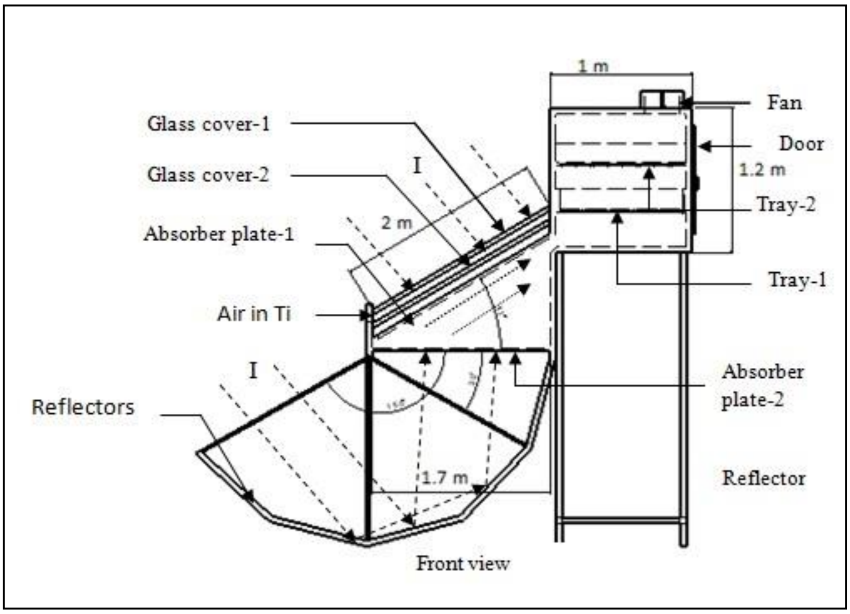

Figure1 Two pass solar dryer

3.3 Uncertainty analysis

Research Uncertainty and uncertainty in the test can result from equipment selection, conditions, measurements, environment, assessment, reading and test preparation. Temperature, drying air velocity, relative humidity of dry air, moisture content of the first and last peppers, weight loss and solar radiation were measured using appropriate equipment in the drying of red peppers in and out of the sun. The uncertainty created during the measurement process is shown in Table 2. Taking into account the relative uncertainty of individual factors caused by a_n, the estimation uncertainty is made by the following equation [39]:

$$W = [(a_1)^2 + (a_2)^2 + \cdots \ldots \ldots \ldots . (a_n)^2]^{\frac{1}{2}} \quad (4)$$

4. Results and discussion

The air temperature during the drying period is shown in Figure 2. It is up to 65ºC and the drying temperature at the dryer outlet is up to 26 ºC - 49 ºC. The temperature (Tci) of the air entering the solar collector is different from the temperature (Ta). At the beginning of the experiment, in the morning (8-11 hours), Tci is lower than Ta. The reason for this behaviour can be explained as follows:

1- 9:00 The fans are not working during the measurement. After measuring 9:00, the fans are started.
2- Collector entrance area is 0.025 m². The geometry of the collector is rectangular.

The size of the rectangle is 2 m X 1 m X 0.025 m. The air entering the collector is cooler between 8:00 am and 9:00 am. But in the period 11-17, Tci is slightly higher than Ta. Tci temperature is slightly higher than Ta because the fan draws air from the environment. Direct instantaneous solar radiation reaches an average of 622 W/m^{-2}. (Figure 3). During the experiment, solar radiation is maximum in the afternoon, minimum in the morning and zero at night. During a few days of experimental study, the wind speed values measured by anemometer varied between 0 ms^{-1} and 2 ms^{-1}. In addition, the wind speed determined from the cloud values is 1.2 ms^{-1} on average.

Table 2: Drying experiment parameters uncertainty analysis for red chilli.

Parameter	**Unit**	**Observations**	
Ambiguity in the temperature measurement		**Solar Dryer**	**Open sun Drying**
inlet air temperature (Collector)	°C	±0.300-±0.506	-
outlet air temperature (Collector)	°C	±0.300-±0.506	-
inlet air temperature (Drying cabinet)	°C	±0.506	-
outlet air temperature (Drying cabinet)	°C	±0.300-±0.506-	-
Ambient air temperature	°C	±0.300	±0.300
Uncertainty in the time measurement			
Mass loss values	min	±0.2	±0.2
Temperature values	min	±0.2	±0.2
Uncertainty in the mass loss measurement	g	±0.4	±0.4
Uncertainty in the air velocity measurement	ms-1	±0.10	±0.10
Uncertainty of the measurement of relative humidity of air	RH	±0.10	±0.10
Uncertainty in the measurement of moisture quantity	g	±0.002	±0.002
Uncertainty in the measurement of solar energy	W.m-2	±0.5	±0.5

4.1 Drying curves

Put 10 kg of red chilli with an initial moisture content of 8-8.2 kg in a sun-heated oven to dry to 1.91 kg, or lay flat on the ground for outdoor sunlight. The final moisture content represents the moisture balance between the sample and the drying air in the solar dryer where no change in sample quality occurs. The variation of water content per unit volume of dried red pepper over time is shown in Figure 4. The dashed line in this diagram represents the dark period of drying. Due to the thermal inertia of the object and the rocks, it continues to dry after sunset. The final stage of drying in the solar dryer is completed in 25 hours, while drying in the open sun takes approximately 45 hours. As shown in the picture. Figure 4 clearly shows that drying rates in a solar dryer operating as forced convection can be higher than in natural open sun drying. In terms of drying, this system shortened the drying time of red pepper by two days. The relationship between drying and drying time is shown in Figure 5. It is clear that the drying rate is constant with decreasing moisture content or drying time. These curves do not have a fixed drying time; the entire drying value occurs in decreasing time. During the drop, the surface of the product is not saturated with water and the rate of drying is controlled by the diffusion of moisture from the inside of the product to the surface [40]. These results are consistent with the observations of previous researchers [33, 35, 41].

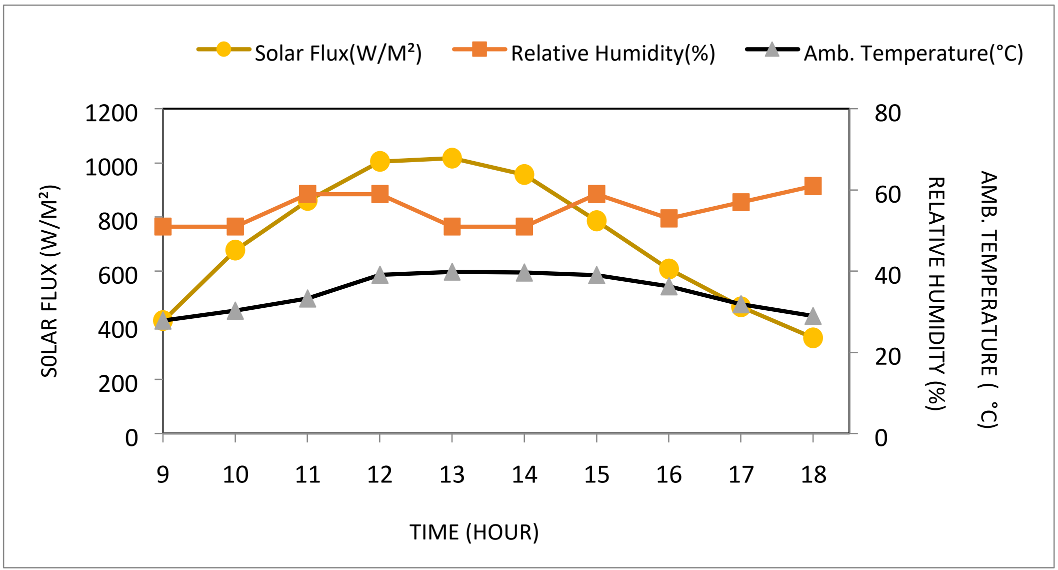

Figure 2

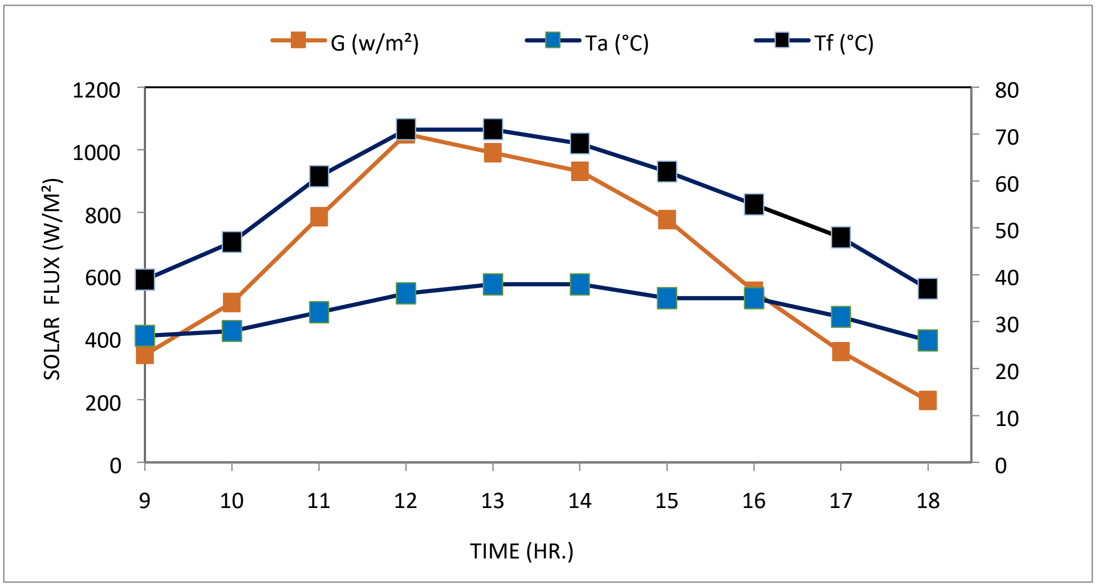

Figure 3

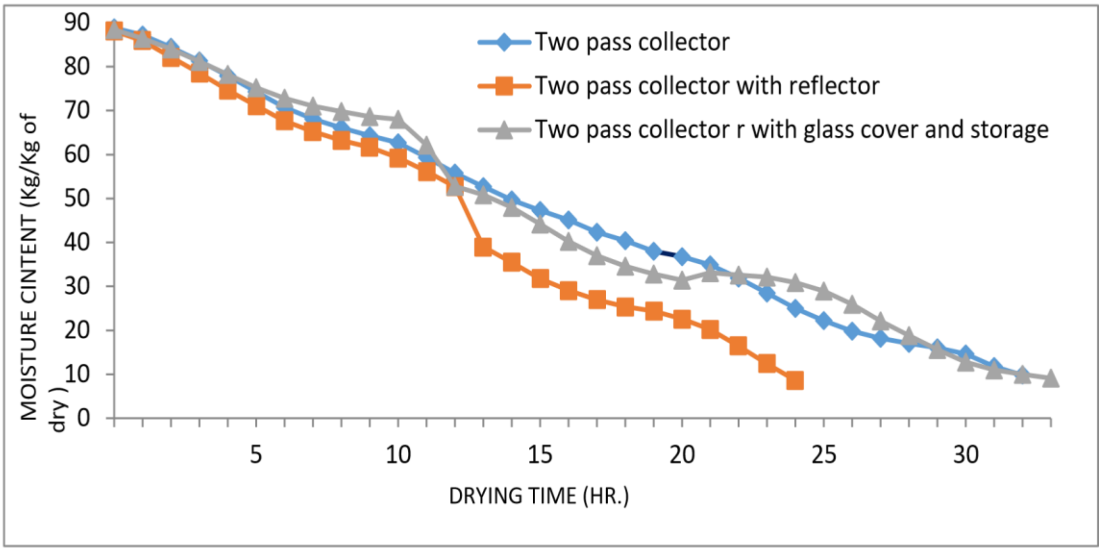

Figure 4

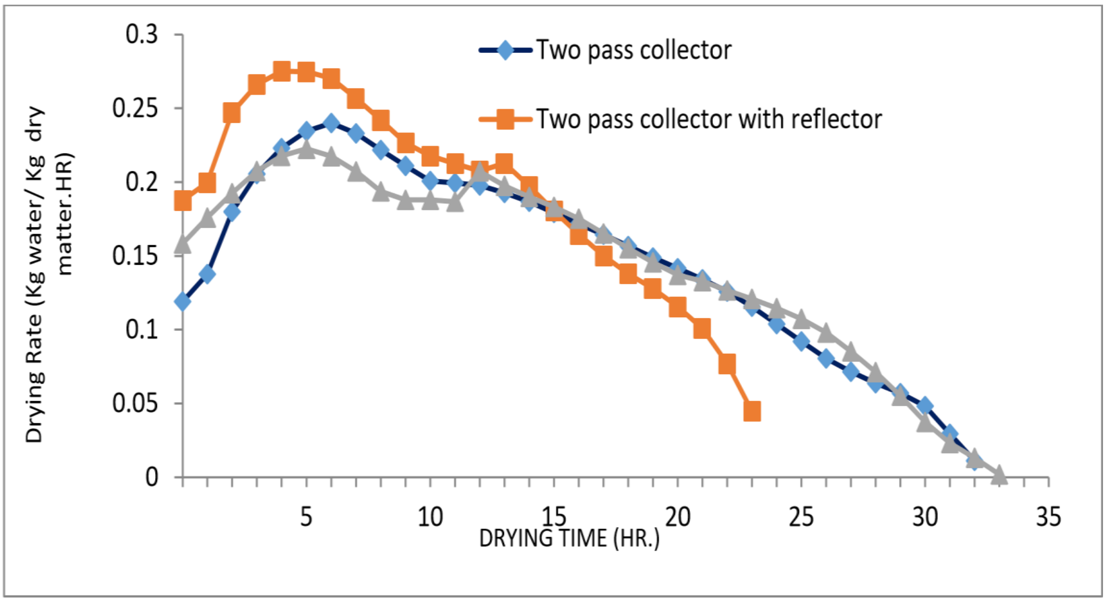

Figure 5

4.2 Mathematical model for solar and open-sun drying curves

To normalize the drying curve, information on the dry basis of moisture content versus time is converted into a space called moisture versus time (Figure 4). Moisture data on different test samples were converted to ideal moisture content and then curve fit calculated by drying time was performed on 13 models dried by previous researchers (Table 1). Tables 3 and 4 present the statistical results of these models for forced sun exposure and natural sun exposure, respectively. Models were evaluated according to R, $\chi 2$ and RMSE. The logarithmic model, as revealed in Table 3, is the best descriptive model for thin-layer forced basking of peppers. R = 0 can be determined from the logarithmic model of the chilli. ***R=98894, $\chi 2$=0.001909399, RMSE = 0.042918624*** avg. For natural sun drying of thin chilli layers, Verma et al. model is the best explanatory model as shown in Table 4. From the Verma et al. model for chilli, it was calculated that; R=**0.99535, $\chi 2$=0.00080099,** ***RMSE*****= 0.0280580 19.**

Table 3. Moisture ratio modelling based on forced sun drying time for a thin layer of red pepper.

Model no	**Constant**	**Model constants**	***R***	***$\chi 2$***	***RMSE***
1	k	0.027867	0.97566	0.003699992	0.060800226
2	k	0.042010	0.97063	0.003399988	0.057971702
	n	0.872687			
3	k	0.027666	0.97662	0.003466500	0.058071704
	n	0.879586			
4	a	0.909999	0.97961	0.002493000	0.048696354
	k	0.024363			
5	a	1.019939	0.97949	0.001908388	0.043218089
	k	0.018753			
	c	-0.133075			
6	a	0.453060	0.99060	0.0026899765	0.048977248
	ko	0.025453			
	b	0.465570			
	k1	0.024353			
7	a	0.074679	0.98073	0.002605039	0.053344230
	k	0.329993			
8	a	-0.020100	0.96905	0.004420650	0.065660089
	b	0.000100			
9	a	0.114000	0.98790	0.002319783	0.048246340
	k	0.917823			
	b	0.025785			
10	a	0.302689	0.97969	0.002529598	0.048897355
	k	0.024353			

	b	0.303345			
	g	0.024353			
	c	0.303345			
	h	0.024353			
11	**a**	**0.114045**	***0.99446***	***0.001909399***	***0.042918624***
	k	**0.892000**			
	g	**0.022197**			
12	a	0.897777	0.98824	0.002002013	0.043006621
	k	0.024675			
	n	0.9430000			
	b	-0.0010000			
13	a	-38.2599	0.98021	24.00232844	4.6807000056
	b	-2.34245			

Table 4. Modeling of moisture content during outdoor drying of thin layers of red chilli moisture with measured moisture content in a drying process.

Model no	**Constant**	**Model constants**	***R***	$\chi 2$	***RMSE***
1	k	0.022041	0.98164	0.002218574	0.047999176
2	**k**	**0.04438**	**0.98222**	**0.001614172**	**0.038708560**
	n	**0.834565**			
3	k	0.023332	0.98048	0.001634181	0.038708561
	n	0.833573			
4	a	0.901144	0.98127	0.001113050	0.033080434
	k	0.019956			
5	**a**	0.922864	0.98065	0.001103165	0.033708325
	k	0.018777			
	c	-0.016417			
6	a	0.440412	0.97923	0.001142604	0.032996945
	ko	0.019875			
	b	0.461533			
	k1	0.0178944			
7	a	0.095372	0.98061	0.001233648	0.035916112
	k	0.213365			
8	a	-0.014389	0.96638	0.004758789	0.067999182
	b	0.000072			
9	a	0.1340930	0.97300	0.00102901	0.031450723
	k	0.507399			
	b	0.036987			
10	a	0.300350	0.97250	0.001160147	0.033109457
	k	0.017698			
	b	0.301460			
	g	0.0198454			
	c	0.3112449			
	h	0.02001			
11	a	0.140010	0.97535	0.00080099	0.028058019
	k	0.599001			
	g	0.017899			
12	a	0.956734	0.97300	0.00103309	0.032349920
	k	0.050017			
	n	0.700999			
	b	-0.000387			
13	a	-39.4528	0.97561	19.86461176	4.9909008
	b	-.193789			

Validation of the established model was made by comparing the computed moisture content with the measured moisture content in any particular drying run under certain conditions The performance of the thin-layer forced insolation is shown in Figure 6. Experimental data are often banded around a straight line representing the calculated data, indicating that the mathematical model was designed to explain the drying behaviour of red chilli.

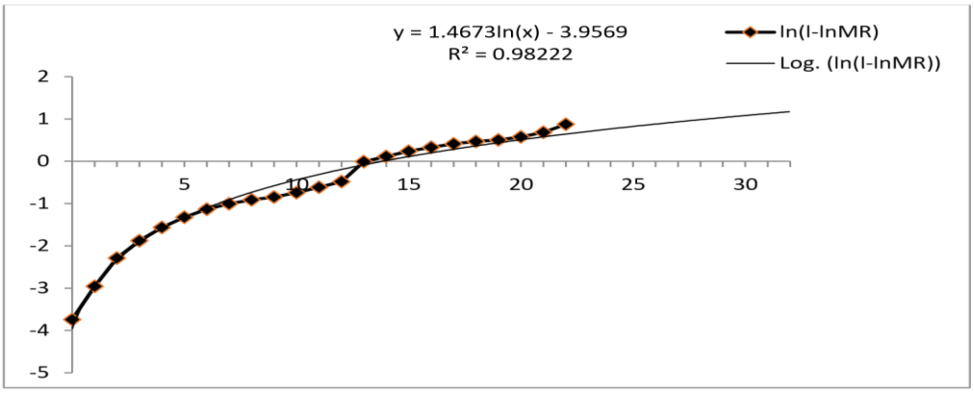

Figure 6

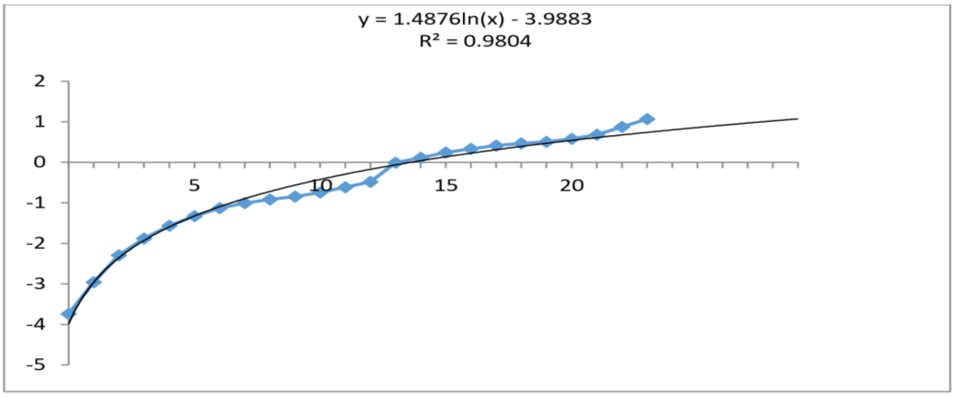

Figure 7

4.3 Optimum decision coefficient determination

Mass transfer phenomenon in case of food are difficult. Generally, the drying process during the price decline is modelled assuming that the main process is abnormal. Therefore, the diffusion coefficient estimated from the experimental results is a good factor that includes both the known theory and the influence of unknown factors [42]. Experimental drying data used to determine the diffusion coefficient were interpreted using Fick's second diffusion model.

$$\frac{dM}{dT} = D\frac{d^2\ M}{dr^2} \qquad (5)$$

solving equation (5), for example moisture migration is diffusion, temperature diffusion coefficient, negligible shrinkage and spheres [43]:

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}exp\left[-n^2\pi^2\frac{D_{eff}t}{R^2}\right] \qquad (6)$$

Eq. for long drying. (6) can only be simplified to the first term of the series [44]:

$$ln(MR) = ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2\frac{D_{eff}\,t}{R^2}\right) \qquad (7)$$

The effective water diffusion coefficient is calculated by the slope method. Diffusion coefficients are usually determined by plotting drying test data against ln (MR) versus time (as given in equation). (7)) As shown in Figure 6, 7 [45]. by balancing. (7), the plot of ln(MR) versus time gives a straight line with the following slope:

$$Slope = \left[\pi^2\ \frac{D_{eff}\ t}{R^2}\right] \qquad (8)$$

The D_{eff} value for red chilli was 3.56 X10^{-9} m^2/s and 2 for sun drying.40 X10^{-9} m^2/h for air drying. Maskan and Gogus [46] found that D_{eff} ranged from 2.32 X10^{-10} to 2.76 X10^{-9} m^2/s in hot air drying of chillis at 60°C -80°C. Try this in $D_{eff.}$ for red chilli.

Conclusion

In this study, drying behavior of red chilli in forced convection and drying behaviour in sunlight in free convection mode were investigated. The fast drying of red chilli in all varieties occurs during autumn. Drying behaviour of red chilli is well explained by 13 mathematical models which are used in both forced sun drying and outdoor sun drying process. The results show that the logarithmic model is the most suitable model to explain the drying curve of the chilli film with R value equals to **0.98222,** $\chi 2$ is **0.001614172** and RMSE **0.038708560**. However, page model satisfactorily describes the drying curve of chilli with R of **0.98222** and $\chi 2$ *of* **0.001614172** with **0.038708560** RMSE in open solar mode. Effective moisture dissipation was estimated by Fick's diffusion model.

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