Experimental study and comparison of integrated solar dryer with and without reversed absorber and reflector

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Abstract: The aim of this manuscript is to recommend a solar crop dryer with reversed absorber and reflector which collects the maximum possible solar emission. For experimentation, the model was made adjustable such that it can satisfy the required conditions. Two types of solar dryers are used: 1) solar dryer without reversed absorber and reflector; 2) solar dryer with reversed absorber and reflector. The average collector efficiency (η_c), drying efficiency (η_d) and the picking efficiency (η_p) of multi-pass SCD with reversed absorber and reflector (SD6) values were 34%, 49% and 64% respectively. Excel software was used to find the changes in moisture content with the time and constants by graphical method. These values show that SD6 is more effective than any other solar dryer. The experimental data is more suitable for Pages' model than other models. Pages' model gives the best results with the maximum value of R^2 and the minimum value of MBE and RMSE. It has been found that SD6 is the most effective solar dryer and can be used to dry other agriculture food products also.

Keywords: flat plate collector; solar crop dryer; reversed absorber; reflector; red chilli.

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1 Introduction

Drying is the process of removing moisture. Drying is a very important process to preserve an agricultural product for a long time because of which an agricultural product is available in all the seasons. Open sun drying method is always used by a farmer to dry all the 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 the use of fuel as an energy source. Solar dryer is an emerging technique which has overcome these limitations. Solar dryer technology has various advantages like simple design, low-cost energy source and maintenance of hygienic condition. The critical studies of solar drying processes have a great practical and economic importance. In designing the process, study of fundamentals and mechanisms, moisture level in the product and temperature required to dry the product are critical factors (McMinn, 2006). Many researchers have presented theoretical models of drying process in which heat and mass transfer are studied. Thin layer models and simulations help for designing a new dryer with improving its usefulness in existing applications (Kardum et al., 2001). In a thin layer model, the moisture in agricultural product can be measured at any time and the 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 which are classified into direct, indirect and hybrid solar dryer (Garg and Sharma, 1990; Hallak et al., 1996). SCD is an example of domestic and DSD where solar radiation directly falls on the food product (Lawand, 1966). In a direct solar dryer, the food products are 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 (Fournier and Guinebault, 1995). Indirect solar dryer with natural air circulation has been specially designed for a particular type of agricultural product and may be used with additional source of energy to improve its performance. Singh et al. (2006) has developed an efficient solar dryer especially to dry fruits, spices and vegetables and has a drying capacity of about 1 kg per day. The solar dryer is featured by direct, indirect and hybrid with a forced or natural circulation of air. For collecting maximum energy, the solar air collector is always inclined due south so that the sun rays strike perpendicular throughout the day on collector. Manual tracking may be an alternative but it is not 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 presented a nature of drying behaviour of agricultural products (Simal et al., 2005; Midilli and Kucuk, 2003; El-Beltagy et al., 2007; Akpinar et al., 2004). Thin layer drying model can be used easily as well as it gives accurate results. However, the rate of drying depending on the temperature of air and drying rate can be kept constant if the temperature of air is maintained. The mathematical model (Al Mahdi and Al Baharna, 1991) was used to examine the effect of various air passes within the SAC on the thermal efficiency and the temperature rise at different air mass flow rates. The result shows that the thermal efficiency of the SAC increases rapidly as the mass flow rate is increased but it is not possible to maintain the temperature constant throughout the day. Mwithiga and Kigo (2006) have noted the effectiveness of tracking the sun on increasing the drying rate but it is a costly affaire. Fatouh et al. (2006) observed the effect of drying air temperature and air velocity on the drying characteristics of the agricultural product. The drying rate can be achieved if the considered parameters are within the limits. Singh et al. (2005) noted that the leafy vegetables are dried in a short period than other vegetables. Lingayat et al. (2020) had designed a new indirect type of SD. From experimentation, it is interpreted that the drying rates are dependent on air temperature and velocity. López-Vidaña et al. (2020) had designed and constructed a mixed type of SCD and studied its performance by using a tomato. Nabnean and Nimnuan (2020) had used a parabolic shaped polycarbonate plate covered over a flat plate collector and noticed that the drying time is reduced significantly. Spall and Sethi (2020) presented an innovative SD integrated with inclined reflective north wall (RNW). Result shows the reduced drying time of 20% and 15% under natural and forced convection modes respectively.

Hybrid indirect passive (HIP) solar dryer (Ssemwanga et al., 2020) suggested that mass drying against a conventional active-mode solar photovoltaic and electric (SPE) dryer. Mixed mode forced convection type (MFSCD) (Lakshmi et al., 2019) take less drying time, has better dryer efficiency, improved quality of product than OSD and a payback period of 0.65 yrs. The FPSAC (Rani and Tripathy, 2020) examine for different air flow rates, found a strong positive effect of solar intensity on the temperature of absorber plate, glass cover and outlet air of collector. Solar cooker equipped with internal reflectors and a tracking-type bottom parabolic reflector (TBPR) (Tawfik et al., 2021) is able to attain the intermediate temperatures up to 140–150°C. The spherical dimple plate solar air heater (SDPSAH), IIT (ISM) Dhanbad, India (Perwez and Kumar, 2019) shows the highest heat transfer rate, which is about 1.51 to 1.64 times higher than the corresponding FPSAH. Maiti et al. (2011) developed a natural convection batch-type solar dryer fitted with north-south reflectors. At a high solar radiation, the collector efficiency had increased by 18.5% and MC reduced from 83% to 12% (w.b.) in 5 hrs. In a multi-shelf side loading inclined solar cooker-cum-dryer (ISCCD) (Singh and Sethi, 2018) integrated with single reflector north facing booster mirror (NFBM) shows significant improvement in performance of both cooking and drying operations particularly in winter months.

Although this solar dryer had been developed for multi-purpose agricultural food drying, drying tests are still needed for specific agricultural products in order to study its performance and viability to use. In addition, solar drying can be considered as an advancement of natural sun drying and it is an efficient technique of utilising solar energy. Use of single glazing, double glazing and multi pass solar air collector can also improve its efficiency. Glazing the dryer and solar air heater can be a practical solution.

The objective of this work is to recommend a SCD with reversed absorber 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 (Jain and Jain, 2004; Jain, 2007; Khawale and Thakare, 2018; Khawale, 2017) and introduces some new features which help to maximise the solar energy absorption. The principal modification was that, it includes indirect type of solar dryer using forced convection heat transfer with single pass, double pass and multi 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 using chilli.

2 Material and methods

2.1 Experimental apparatus

The size of solar air collector was 2 × 1 × 0.10 metre. Two black painted absorber plates of aluminium were used. First absorber plate was inclined at 30 degree 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 × 1 × 1 metre. 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 was provided at the top side of dryer to control the air flow. This model was made adjustable such that it can work as a single pass, double pass 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.

2.2 Experimental procedure

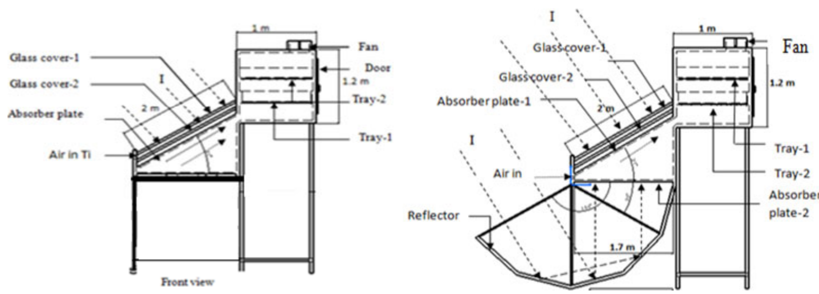
During the light hours, from 8 am to 6 pm experimentation was carried out on a designed solar dryer by using red chilli and evaluation of the performance was noted. The two types of solar dryer used were:

1 solar dryer without reversed absorber and reflector

2 solar dryer with reversed absorber and reflector.

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

Figure 1 (a) Solar dryer without reversed absorber and reflector (b) Solar dryer with reversed absorber and reflector (see online version for colours)



(a) (b)

2.3 Performance analysis

The performance of the solar dryer can be assessed from the thermal efficiency of collector or drying rate of the agricultural product (Joshi et al., 2004).

2.3.1 Drying rate

Drying rate depends on various factors which have a very monotonous and time consuming calculation. In thin layered drying, Pathak et al. (1991) noted the temperature of air, initial moisture percentage in product, velocity and relative humidity of air are various factors over which drying rate vary. For various products, drying rates have been successfully analysed by using Pages' equation (Li et al., 1987). The equation is as follows:

$$M_r = e^{-zt^n} \tag{1}$$

where Mr – moisture ratio, t – drying time in hours, z and n are drying constants.

Moisture ratio given by equation:

$$\text{Moisture ratio } M_r = \frac{M_t - M_e}{M_o - M_e} = e^{-zt} \tag{2}$$

where

M_t instantaneous moisture content (% db)

M_e equilibrium moisture content (% db)

M_o initial moisture content (% db).

Following equation may be used to calculate moisture content on dry basis M_t (% db) (ASHRAE, 2001):

$$M_t = \frac{(w_t - w_d)}{w_d} \tag{3}$$

And the equation used to calculate moisture content on wet basis (% wb):

$$M_t = \frac{(w_t - w_d)}{w_t} \tag{4}$$

where

W_t weight of chilli at a time (t) (kg)

M_d mass of dry chilli (kg).

From exponential and Newtonian model (Sun and Woods, 1994), Page introduced an equation as:

$$\text{Drying rate}\left(\frac{dm}{dt}\right) = -z(M_t - M_e) \tag{5}$$

z is drying rate constant, per hour.

By distinguishing, the drying model can be explained as follows:

$$M_z = e^{-zt^n} \tag{6}$$

In deriving this equation, the resistance of water movement and gradient in the material is ignored. If the drying rate decreases at a constant temperature, pressure and humidity of the air, this equation is valid (Nellist, 1976), which is characteristic of products with low moisture content (e.g., grains], Negative sign is important which shows the characteristics of drying process (Fatouh et al., 2006).

$$\text{Moisture ratio } M_r = \frac{M_t - M_e}{M_o - M_e} = e^{-zt} \tag{7}$$

2.3.2 Collector efficiency

By using formula:

$$\eta_c = \frac{\dot{m}aC_{pa}(T_o - T_i)}{[(I * Ac1) + (Ieff * Ac2)]} \tag{8}$$

where

$\dot{m}a$ mass of air flowing in collector and dryer per unit time

C_{pa} specific heat of air at constant pressure

T_o air temperature at collector exit

T_i inlet temp. of air at collector entrance

I	solar emission on absorber plate 1 (hourly)
A_{C1}	area of absorber plate 1
I_{eff}	actual solar emission on reversed absorber plate 2 (hourly) ($I_{eff} = \rho * I * A_R$)
ρ	reflectivity of reflector
A_R	area of reflector
A_{C2}	area of absorber plate 2.

2.3.3 Dryer thermal efficiency

$$\eta_d = \frac{M_w H_{fg}}{\dot{m}a C_{pa} (T_d - T_i)} \tag{9}$$

where

$\dot{m}a$	mass of air flowing per unit in the dryer
C_{pa}	specific heat of air at constant presssure
T_d	temperature of air in dryer
T_i	inlet air temperature at collector equal to ambient temp.
H_{fg}	latent heat of water (evaporation)
M_w	mass of evaporated water.

2.3.4 Dryer pick-up efficiency

$$\eta_p = \frac{M_w}{\dot{m}a \Delta_t (W_{ce} - W_{ci})} \tag{10}$$

where

M_w	mass of evaporated water in time Δ_t
$\dot{m}a$	air mass flow rate
W_{ce}	humidity of air at dryer exit (absolute)
W_{pa}	humidity of air at dryer inlet (absolute).

2.3.5 Drying model

Use the following model to find the best model described the characteristics of drying curves for drying of chilli in solar dryer (Cakmak and Yıldız, 2011; Midilli and Kucuk, 2003; Ong, 1995; Doymaz, 2005).

Following equations were used to evaluate MBE and RMSE.

$$MBE = \frac{1}{N} \sum_{i=1}^{N} \left(M_{rpre}, i - M_{r\exp}, i \right)^2 \tag{11}$$

$$\text{RMSE} = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{rpre}, i - M_{r\exp}, i\right)^2\right]} \tag{12}$$

The best model is selected from the mean deviation error and the root mean square error of the determination coefficient R^2. The higher R^2 value and the lower MBE and RMSE values are used to select the best model (Günhan et al., 2005).

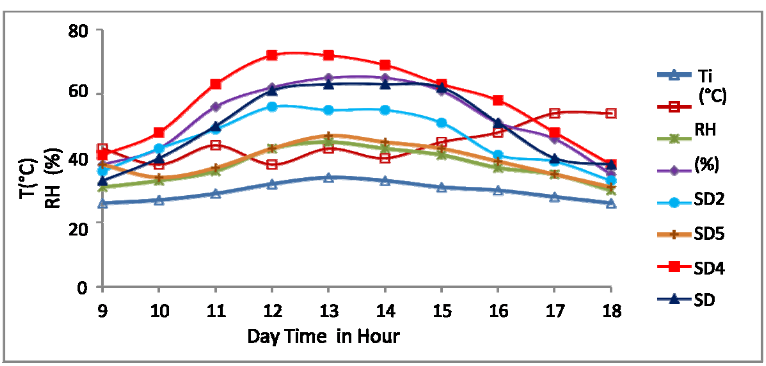
Table 1 Drying models

SN	*Model*	*Equation*
1	NEWTON	$M_r = e^{-zt}$
2	PAGE	$M_r = e^{-zt^n}$
3	HENDERSON and PABIS	$M_r = a * e^{-zt^n}$

3 Results and discussion

Six different types of solar dryers were used to dry the red chilli. The test was conducted on a sunny day. In a typical experimental run the deviation in ambient temperature, relative humidity and air temperature at collector outlet of different types of solar dryer are shown in Figure 2. Graphical presentation shows that the temperature of air rise in SD6 is more reducing the drying period of agricultural product.

Figure 2 Deviation of relative humidity, ambient temperature and Final temperature with day time (hr) (see online version for colours)



The average temperature of drying air was recorded about 57°C and 50°C for SD6 and SD5 respectively at the inlet of the drier. During peak daylight hours maximum temperature of drying air was recorded about 71°C at the drier inlet. From the air temperature curves it can be observed that the invented dryer can be used to dry a variety of farming products.

During the peak light hours maximum intensity of solar energy was recorded about 905 W/m². The average dry and wet bulb temperature recorded were 32°C and 25.8°C correspondingly. The recorded relative humidity of air was about 32% at inlet and 70% at the exit of solar dryer chamber. Figures 3 to 5 shows a variation in collector, drying and pick-up efficiency with a solar flux for all the dryers.

Figure 3 Variation of collector efficiency with time (hr) (see online version for colours)

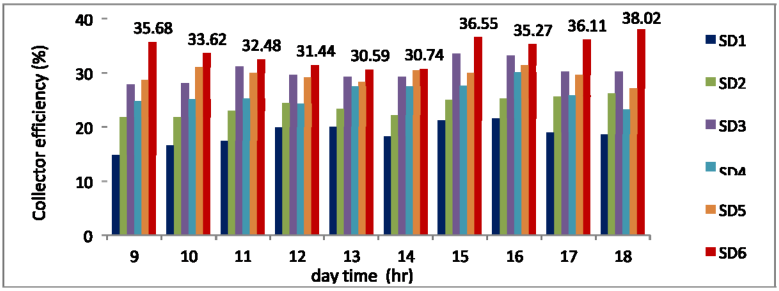


Figure 4 Variation of drying thermal efficiency with time (hr) (see online version for colours)

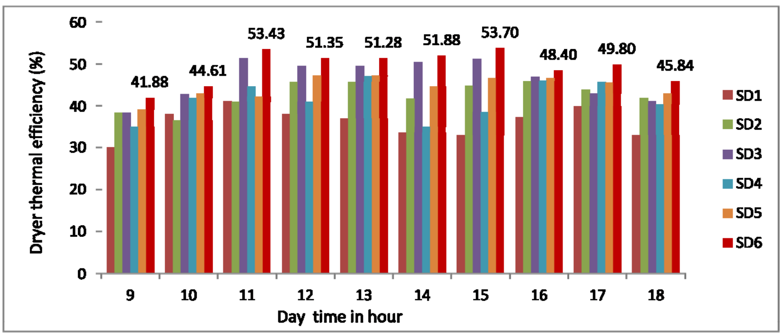
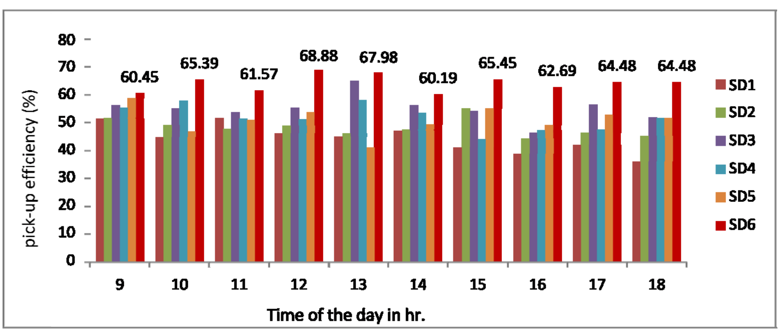


Figure 5 Variation of pickup thermal efficiency with time (hr) (see online version for colours)



From Figures 3 to 5, it was observed that at an average value of I_s = 675 w/m^2, T_a = 34°C and ma = 1.614 kg/min, collector efficiency (η_c) of SD6 and SD3 were 36% and 30%, respectively. It was noted that at an average value I_s = 427 w/m^2, Ta = 28°C and ma = 1.614 kg/min, collector efficiency (η_c) values of SD5 and SD2 were 29.7% and 25%, respectively. And the collector efficiency values of SD1 and SD4 were 19% and 26%, respectively.

It was observed that dryer thermal efficiency (η_d) and pick-up efficiency (η_p) at an average value I_s = 675 w/m^2, T_a = 34°C and ma = 1.614 kg/min, of SD6 and SD3 were

49% and 46%; 64% and 55% respectively. At an average value I_s = 427 w/m^2, T_a = 28°C and ma = 1.614 kg/min the dryer thermal efficiency (η_d) and pick-up efficiency (η_p) of SD5 and SD2 were 45.5% and 38%; 54% and 50% respectively. Dryer thermal efficiency (η_d) and pick-up efficiency (η_p) of SD4 and SD1 were 47.8% and 37.7%; 55% and 45% respectively. From the above experiment it was analysed that the solar air heater with reversed absorber and reflector was more efficient than conventional SCD. This observation was validate with earlier studies that the heat gain by reversed absorber plate is noteworthy (Goyal and Tiwari, 1997; Forson et al., 2007).

The change of MC in red chilli with time for SD1, SD2, SD3, SD4, SD5 and SD6 is graphically represented in Figure 6. The MC in fresh red chilli was nearly similar during all tests whereas the initial value was 4.1 kg/kg (db) and 3.9 kg/kg (db) for SD4 and SD1 respectively. From Figure 7, it is manifested that drying rate more than SD1 in SD4. These results ensure that SD4 used forced convection and attained higher air temperature which increases moisture removal rate from red chilli. From Figure 7, it is noted that drying rate continuously goes on decreasing in all the cases and drying period is less for SD4 as compare to SD1.

Figure 6 Profile of the moisture content vs. drying time (see online version for colours)

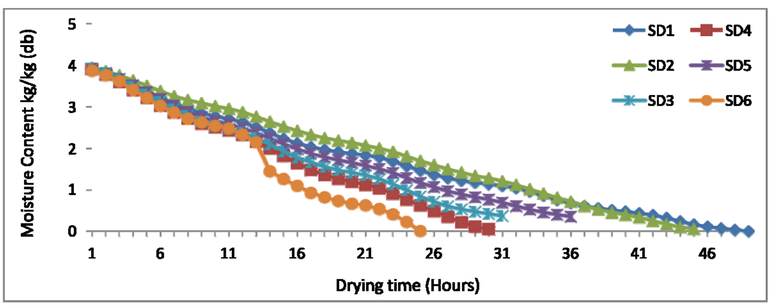


Figure 7 Profile of drying rate vs. drying time (see online version for colours)

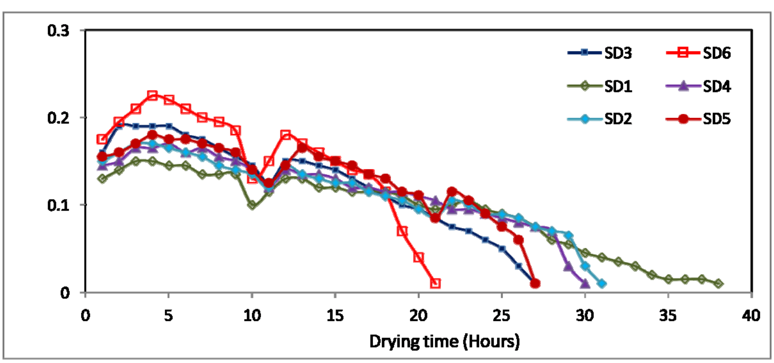


Figure 6 shows that in SD5, MC were for shorter period in the red chilli above the equilibrium MC than SD2. Figure 7 shows the contour of drying rate vs. drying time. It was observed that the drying rate in SD5 is greater than SD2 due to higher drying air temperature and increases vapour pressure in the red chilli which reduces the effect of relative humidity during sunny day (Garg et al., 1985).

From Figures 6 and 7, it is also observed that the MC in red chilli above the equilibrium MC in SD6 is reduced remarkably than SD1, SD2, SD3, SD4 and SD5. Drying rate is found to be higher in SD6 than in SD1, SD2, SD3, SD4 and SD5 because of high drying temperature and vapour pressure in the chilli which increased the rate of evaporation.

Table 2 Constants value fitting of DM

SN	*Solar dryer type*	*Thin layer DM*	*Constant*	*DM constants*	*MBE*	*RMSE*	R^2
1	SD1	NEWTON	Z	0.060	0.00132	0.036	0.990
		PAGE	Z	0.027	0.00020	0.014	0.998
			N	0.1.212			
		HENDERSON and PABIS	A	0.8547	0.0173	0.132	0.990
			Z	0.0610			
2	SD2	NEWTON	Z	0.080	0.00364	0.060	0.97
		PAGE	Z	0.0.032	0.00044	0.021	0.994
			N	1.22			
		HENDERSON and PABIS	A	1.229	0.00364	0.060	0.97
			Z	0.080			
3	SD3	NEWTON	Z	0.070	0.00194	0.044	0.99
		PAGE	Z	0.0386	0.0001	0.009	0.99
			N	1.186			
		HENDERSON and PABIS	A	1.160	0.00108	0.033	0.994
			Z	0.077			
4	SD4	NEWTON	Z	0.070	0.00382	0.062	0.974
		PAGE	Z	0.029	0.00026	0.016	0.997
			N	1.252			
		HENDERSON and PABIS	A	1.492	0.00332	0.058	0.974
			Z	0.075			
5	SD5	NEWTON	Z	0.08	0.00303	0.055	0.97
		PAGE	Z	0.038	0.00114	0.0034	0.98
			N	1.161			
		HENDERSON and PABIS	A	1.230	0.00301	0.055	0.974
			Z	0.080			
6	SD6	NEWTON	Z	0.1	0.0058	0.243	0.96
		PAGE	Z	0.0398	0.004	0.021	0.995
			N	1.267			
		HENDERSON and PABIS	A	1.276	0.00379	0.062	0.969
			Z	0.102			

Experimental data of drying chilli was used to describe the DM. Newton DM, Page DM and Henderson and Pabis DM was fitted with the experimental data of drying chilli. In the DM, the data of MC and drying time had been used. In all models, Excel software was used to find the changes in moisture content with the time as well as constants by graphical method. The best DM was decided from higher value of R^2 and lowest value of MBA and RMSE (Devahastin and Pitaksuriyarat, 2006). The best drying model were selected out of three drying models by drying red chilli, where constant mass flow rate was maintained. Table 2 shows the experimental constant values which fits in the DM. From Table 2, it has been noted that Pages' DM is the most fitted DM to describe the drying curves of red chilli. The experimental data was fit to the Page's DM than Newton's and Henderson and Pabis DM. The Page's DM gives best result with higher value of R2and lower values of MBE and RMSE.

4 Conclusions

After experimentation and comparison, it has been observed that the significant improvement found in solar dryer with reversed absorber and reflector was in thermal, drying and pick-up efficiency. Further it has been pointed out that, at constant air flow rate, the solar collector inlet and exit air temperature difference increases with the rise in solar irradiation.

The average collector efficiency (η_c) values are 26.11%, 29.56% and 34% for the SD4, SD5 and SD6 respectively. It displays that the collector efficiency (η_c) of SD6 is more than SD4 and SD5. The drying efficiency (η_d) values are 41%, 44% and 49% and Pick-up efficiency (η_p) value are 51%, 55% and 64% for the SD4, SD5 and SD6 respectively. These value shows that SD6 is more efficient than SD4 and SD5.

Experimental data of drying chilli was used to describe the drying model. In all models, Excel software was used to find the changes in MC with the time as well as constants by graphical method. The best DM was decided from the highest value of R2and lowest value of MBA and RMSE. Table 2 shows the experimental constant values which is fitting in the DM. It has been noted that Pages' DM is the most fitted DM. The experimental data was appropriate for the Page's DM than Newton's, Henderson & Pabis DM. The Page's DM gives best result with the highest value of R^2 and lowest values of MBE and RMSE.

Finally, it has been found that SD6 is the most effective solar dryer than SD1, SD2, SD3, SD4, and SD5.

Solar dryer with reversed absorber and reflector is capable of reducing drying time as compared to the other solar dryer and OSD. In addition, red chilli was completely protected from insects, dust and rain. This dryer can also be used to dry other agricultural food products and the products which are sensitive to the exposure of solar radiation.

In present study, it is difficult to cover the complete surface area of reflector by solar radiation during light hours. In future study, there is a need to develop a tracking system for a reflector to cover all the surface area of the reflector by solar radiation throughout the day.

References

Akpinar, E.K., Sarsilmaz, C. and Yildiz, C. (2004) 'Mathematical modeling of a thin layer drying of apricots in a solar energized rotary dryer', *International Journal of Energy Research*, Vol. 28, No. 8, pp.739–752.

Al Mahdi, N. and Al Baharna, N.S. (1991) 'Thermal performance of an *n*-pass solar air heater', *Renewable Energy*, Vol. 1, Nos. 3–4, pp.527–532.

ASHRAE (2001) *Fundamental Handbook*, Atlanta GA, USA.

Cakmak, G. and Yıldız, C. (2011) 'The drying kinetics of seeded grape in solar dryer with PCM-based solar integrated collector', *Food and Bioproducts Processing*, Vol. 89, No. 2, pp.103–108.

Devahastin, S. and Pitaksuriyarat, S. (2006) 'Use of latent heat storage to conserve energy during drying and its effect on drying kinetics of a food product', *Appl. Therm. Eng.*, Vol. 26, pp.1705–1713.

Doymaz, I. (2005) 'Sun drying of figs: an experimental study', *Journal of Food Engineering*, Vol. 71, No. 4, pp.403–407.

El-Beltagy, A., Gamea, G.R. and Essa, A.H.A. (2007) 'Solar drying characteristics of strawberry', *Journal of Food Engineering*, Vol. 78, No. 2, pp.456–464.

Fatouh, M., Metwally, M.N., Helali, A.B. and Shedid, M.H. (2006) 'Herbs drying using a heat pump dryer', *Energy Conversion and Management*, Vol. 47, Nos. 15–16, pp.2629–2643.

Forson, F.K., Nazha, M.A.A., Akuffo, F.O. and Rajakaruna, H. (2007) 'Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb', *Renewable Energy*, Vol. 32, No. 14, pp.2306–2319.

Fournier, M. and Guinebault, A. (1995) 'The 'shell' dryer-modeling and experimentation', *Renew. Energy*, Vol. 6, pp.459–463.

Garg, H.P. and Sharma, S. (1990) 'Mathematical modeling and experimental evaluation of a natural convection solar dryer', *Proceedings of 1st Word Renewable Energy Congress*, Reading, UK, Vol. 2, pp.904–908.

Garg, H.P., Sharma, V.K., Mahajan, R.B. and Bhargave, A.K. (1985) 'Experimental study of an inexpensive solar collector cum storage system for agricultural uses', *Solar Energy*, Vol. 35, No. 4, pp.321–331.

Goyal, R.K. and Tiwari, G.N. (1997) 'Parametric study of a reverse flat plate absorber cabinet dryer: a new concept', *Solar Energy*, Vol. 60, No. 1, pp.41–48.

Günhan, T., Demir, V., Hancioglu, E. and Hepbasli, A. (2005) 'Mathematical modeling of drying of bay leaves', *Energy Conversion and Management*, Vol. 46, Nos. 11–12, pp.1667–1679.

Hallak, H., Hilal, J., Hilal, F. and Rahhal, R. (1996) 'The staircase solar dryer: design and characteristics', *Renew Energy*, Vol. 7, No. 2, pp.177–183.

Jain, D. (2007) 'Modeling the performance of the reversed absorber with packed bed thermal storage natural convection solar crop dryer', *J. Food Eng.*, Vol. 78, pp.637–647.

Jain, D. and Jain, R.K. (2004) 'Performance evaluation of an inclined multi-pass solar air heater with in-built thermal storage on deep-bed drying application', *J. Food Eng.*, Vol. 65, pp.497–509.

Joshi, C.B., Gewali, M.B. and Bhadari, R.C. (2004) 'Performance of solar drying systems: a case study of Nepal', *Journal of the Institution of Engineers*, Vol. 85, No. 2, pp.53–57.

Kardum, J.P., Sander, A. and Skansi, D. (2001) 'Comparison of convective, vacuum and microwave drying of chlorpropamide', *Drying Technology*, Vol. 19, No. 1, pp.167–183.

Khawale, V.R. (2017) 'Modeling the performance of multi-pass solar crop dryer with reversed absorber', *International Journal of Science and Engineering Investigations (IJSEI)*, Vol. 6, No. 61, pp.2251–8843.

Khawale, V.R. and Thakare, S.B. (2018) 'Modeling and experimental studies on solar crop dryer coupled with reversed absorber type solar air heater', *International Journal of Energy and Power Engineering, World Academy of Science Engineering and Technology (WASET)*, Vol. 12, p.3.

Lakshmi, D.V.N., Kumar, P.M., Layek, A. and Nayak, P.K. (2019) 'Performance analyses of mixed mode forced convection solar dryer for drying of stevia leaves', *Solar Energy*, August, Vol. 188, No. 1, pp.507–518.

Lawand, T.A. (1966) 'A solar cabinet dryer', *Solar Energy*, Vol. 10, No. 4, pp.158–164.

Li, R.Y., Morey, V. and Afinrud, M. (1987) 'Thin-layer drying rates of oilseed sunflower', *Transactions of the American Society of Agricultural Engineers*, Vol. 30, No. 4, pp.1172–1175.

Lingayat, A.B., Chandramohan, V.P., Rajua, V.R.K. and Meda, V. (2020) 'A review on indirect type solar dryers for agricultural crops – dryer setup, its performance, energy storage and important highlights', *Applied Energy*, 15 January, Vol. 258, p.114005.

López-Vidaña, E.C., César-Munguía, A.L., García-Valladares, O., Pilatowsky, F.I. and Brito, O.R. (2020) 'Thermal performance of a passive, mixed-type solar dryer for tomato slices (*Solanum lycopersicum*)', *Renewable Energy*, March, Vol. 147, Part 1, pp.845–855.

Maiti, S., Patel, P., Vyas, K., Eswaran, K. and Ghosh, P.K. (2011) 'Performance evaluation of a small scale indirect solar dryer with static reflectors during non-summer months in the Saurashtra region of western India', *Solar Energy*, November, Vol. 85, No. 11, pp.2686–2696.

McMinn, W.A.M. (2006) 'Thin-layer modelling of the convective, microwave, microwave convective and microwave-vacuum drying of lactose powder', *Journal of Food Engineering*, Vol. 72, No. 2, pp.113–123.

Midilli, A. and Kucuk, H. (2003) 'Mathematical modeling of thin layer drying of pistachio by using solar energy', *Energy Conversion and Management*, Vol. 44, No. 7, pp.1111–1122.

Mwithiga, G. and Kigo, S.N. (2006) 'Performance of a solar dryer with limited sun tracking capability', *Journal of Food Engineering*, Vol. 74, pp.247–252.

Nabnean, S. and Nimnuan, P. (2020) 'Experimental performance of direct forced convection household solar dryer for drying banana', *Case Studies in Thermal Engineering*, 11 November, Vol. 22, No. 4, p.100787.

Nellist, M.E. (1976) 'Exposed layer drying of ryegrass seeds', *Journal of Agricultural Engineering Research*, Vol. 21, No. 1, pp.49–66.

Ong, K.S. (1995) 'Thermal performance of solar air heaters: mathematical model and solution procedure', *Solar Energy*, Vol. 55, No. 2, pp.93–109.

Pathak, P.K., Agrawal, Y.C. and Singh, B.P.N. (1991) 'Thin layer drying model for rapeseed', *Transactions of the American Society of Agricultural Engineers*, Vol. 34, No. 6, pp.2505–2508.

Perwez, A. and Kumar, R. (2019) 'Thermal performance investigation of the flat and spherical dimple absorber plate solar air heaters', *Solar Energy*, 15 November, Vol. 193, pp.309–323.

Rani, P. and Tripathy, P.P. (2020) 'Thermal characteristics of a flat plate solar collector: Influence of air mass flow rate and correlation analysis among process parameters', *Solar Energy*, 15 November, Vol. 211, No. 1, pp.464–477.

Simal, S., Femenia, A., Garau, M.C. and Rossello, C. (2005) 'Use of exponential, pages and diffusional models to simulate the drying kinetics of kiwi fruit', *Journal of Food Engineering*, Vol. 66, No. 3, pp.323–328.

Singh, H., Singh, A.K., Chaurasia, P.B.L. and Singh, A. (2005) 'Solar energy utilization: a key to employment generation in the Indian Thar Desert', *International Journal of Sustainable Energy*, Vol. 24, No. 3, pp.129–142.

Singh, M. and Sethi, V.P. (2018) 'On the design, modelling and analysis of multi-shelf inclined solar cooker-cum-dryer', *Solar Energy*, 1 March, Vol. 162, pp.620–636.

Singh, P.P., Singh, S. and Dhaliwal, S.S. (2006) 'Multi-shelf domestic solar dryer', *Energy Conversion and Management*, Vol. 47, pp.1799–1815.

Spall, S. and Sethi, V.P. (2020) 'Design, modeling and analysis of efficient multi-rack tray solar cabinet dryer coupled with north wall reflector', *Solar Energy*, 15 November, Vol. 211, No. 1, pp.908–919.

Ssemwanga, M., Makule, E., Kayondo, S.I. et al. (2020) 'Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits', *Solar Energy*, 1 July, Vol. 204, No. 1, pp.419–428.

Sun, D. and Woods, J.L. (1994) 'Low-temperature moisture transfer characteristics of barley: thin-layer models and equilibrium isotherms', *Journal of Agricultural Engineering Research*, Vol. 59, No. 4, pp.273–283.

Tawfik, M.A., Sagade, A.A., Palma-Behnke, R., El-Shal, H.M., Abd Allah, W.E. (2021) 'Solar cooker with tracking-type bottom reflector: an experimental thermal performance evaluation of a new design', *Solar Energy*, 15 May, Vol. 220, No. 1, pp.295–315.

Nomenclature

SD	Solar dryer
SCD	Solar crop dryer
SAC	Solar air collector
SD1	Single glazing solar dryer
SD2	Double glazing solar dryer
SD3	Multi-pass solar dryer
SD4	Single glazing SCD with reversed absorber and reflector
SD5	Double glazing SCD with reversed absorber and reflector
SD6	Multi-pass SCD with reversed absorber and reflector
DSD	Direct solar dryer
ISD	Indirect solar dryer
MC	Moisture content
DM	Drying model