International Journal of Ambient Energy

ISSN: 0143-0750 (Print) 2162-8246 (Online) Journal homepage: https://www.tandfonline.com/loi/taen20

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To cite this article: Ankur Gupta, Biplab Das & Jayanta Deb Mondol (2020): Experimental and theoretical performance analysis of a hybrid photovoltaic-thermal (PVT) solar air dryer for green chilis, International Journal of Ambient Energy, DOI: 10.1080/01430750.2020.1734658

To link to this article: https://doi.org/10.1080/01430750.2020.1734658

Accepted author version posted online: 26 Feb 2020.

Publisher: Taylor & Francis & Informa UK Limited, trading as Taylor & Francis Group

Journal: *International Journal of Ambient Energy*

DOI: 10.1080/01430750.2020.1734658

Experimental and theoretical performance analysis of a hybrid photovoltaic-thermal (PVT) solar air dryer for green chilis

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Abstract:

A hybrid photovoltaic-thermal (PVT) solar dryer for drying green chilis is developed to investigate the performance parameters at North East Indian climatic conditions. Drying kinetics of green chilis has also been studied to compare the results theoretically and experimentally. The statistical analysis showed that the Modified Henderson and Pabis model is the most suitable model for predicting the moisture ratio for the solar drying process whereas the Two-term exponential model found to be the best for the open sun drying conditions. The initial moisture content of 4.0 (g water/g dry matter) of green chilis was dried to the moisture content of 0.45 (g water/g dry matter) and 1.15 (g water/g dry matter) in the solar dryer and open sun drying, respectively, during 8 hrs of the experiment. Results indicated that the solar drying process removes moisture at a 130% higher rate compared to the natural open sun drying process.

Keywords: *PVT solar collector; solar dryer; thin-layer drying; moisture ratio; electrical efficiency; overall thermal efficiency*

1. Introduction

Green chili (capsicum annum) belongs to the category of Solanaceae [1-4]. Its main source of cultivation is in South and Central America for last many years. Green chilis are used as vegetable cum spice in the cooking foods to increase the flavor and taste. Post-harvest deterioration occurs easily in the green chili and thus increases the losses of the crop. During the harvest green chili contains high moisture content (60-85%) which affects the green chili in the form of fungal attack, quality degradation, weight loss and color change [1]. Total 38 species of Capsicum are identified and 5 common species of Capsicum are used in domestic purpose. India is the largest dry chili producer in the world which is as high as 43% of the total world production [2]. Green chili can be stored up to 3 years after removing the moisture content without any losses in the test and flavor [3]. North Eastern states (NES) of India produces 51.72% of annual green chili production of the country and used only 8% of the land for chili cultivation [4]. In most of these places, the open sun drying method is the most common process to preserve the food. However, in open sun drying, the dried product can be stored up to the certain time period without any deterioration [5]. Solar drying is mainly used to avoid the post-harvest losses of the crops due to deterioration plus to improve the quality, to increase the storage period, for natural drying and to keep safe the crops from rain, insect, dust, etc. [6].

Kaleemullah and Kailappan [7] reported the drying kinetics of red chilis at different temperatures 50, 55, 60, and 65°C in a rotary dryer. Results indicated that the overall performance was good at 55°C in terms of drying time, product quality, capsaicin content and color. Hossain and Bala [8] dried hot chili by using mixed mode open sun and tunnel based solar dryer. The drying times reduced from 22h to 20h for green chili, and 35h to 32h for red chili in tunnel based dryer than that under open sun. Chauhan et al. [9] performed the experimental analysis in the modified greenhouse dryer for the drying the bitter gourd flakes and compared the thermal models in various modes of the drying. The results of thin-layer drying showed that there was a fair agreement between the theoretical and experimental values. Further study conducted by Chauhan et al. [10] showed the importance of the thermal modelling for optimizing various parameters of the drying system. Tunde-Akintunde [11] conducted an experiment on chili pepper with and without pretreatment in open sun drying and solar tunnel drying. Experimental results indicated that the drying curves of the product were more suitable in falling-rate drying period and the pretreated green chili dried easily than the untreated green chili. Artnaseaw et al. [12] investigated the various parameters of vacuum heat pump dryer by changing the drying temperature and drying pressure in terms of the drying time, change in color, shrinkage percentage, rehydration, and microstructure of the drying chilies. Banout et al. [13] evaluated the final product (red chili) moisture content in double-pass solar dryer, cabinet dryer and natural sun drying, the drying time was taken as 32h, 73h, and 93h, respectively. The drying efficiency of the double-pass solar dryer and the color value obtained from the double-pass solar dryer dried products were higher than the cabinet dryer and open sun drying. El-sabaii and Shalaby [14] evaluated the performance of the indirect mode v-corrugated plate solar dryer for drying mint and thymus. Results indicated that it took 5h to reach it's final moisture content from the initial value (85% w.b) for mint and 34h for thymus. Chauhan et al. [15] discussed applications of software in various types of solar dryer to optimize the design parameters, simulation of solar drying systems, predicting the values of performance parameters and for reducing the cost of solar drying system. Software simulation provides the behavior of the drying system before designing for drying of specified crop. Chauhan and Kumar [16] studied the drying kinetics of gooseberry under natural convection, forced convection and open sun drying conditions. The passive mode was found to be more effective and faster than the other drying modes of gooseberry in this dryer.

Akpinar et al. [17] developed a convective cyclone dryer for drying potato slices. The dried potato slices were more uniformly dried, more hygienic, high quality and had no color loss. Sackilic et al. [18] have done an experimental study on solar tunnel dryer to dry organic tomato. A comparison of open sun drying and solar drying data was done to investigate the drying behavior of the product. Midilli and Kucuk [19] dried shelled and unshelled pistachio and developed a mathematical model for both natural and forced mode solar drying process. Togrul and Pehlivan [20] performed the solar dryer based experimentation on thin layer of apricots and regression analyses were carried out to unveil the best fit in the different mathematical models. Logarithmic model showed the best thin layer drying behavior of apricots. Ertekin and Yaldiz [21] studied the thin layer drying kinetics of eggplants at the laboratory conditions. In order to understand the drying behavior of the eggplant, the drying experiment was carried out in the temperature range between 30 °C to 70 °C and air velocity between between 0.5 to 2.0 m/s. Midilli et. al model was selected as the best model to described the moisture ratio behavior between fourteen models compared with the experimental data. Hossain and Bala [22] carried out the experiments on thin layer drying of green chili under different flow conditions. The Page equation showed better agreement between the correlated and experimental value of moisture ratio.

Tiwari et al. [23] evaluated the photovoltaic-thermal (PVT) mixed mode solar greenhouse dryer and validated the theoretical thermal energy and exergy values with the experimental data. Dorouzi et al. [24] developed PVT based liquid desiccant-assisted solar dryer for drying of tomato slice. It was found that the drying time reduced by 27% when the relative humidity level decreased from 28% to 18% and dropped by 10% when the temperature increased from 60°C to 70°C. Tiwari and Tiwari [25] evaluated the partially covered greenhouse solar dryer by varying the no. of collectors from 1 to 5 which resulted in the variation of equivalent thermal energy from 3.24 to 10.75 kWh/day, equivalent thermal efficiency from 61.56% to 42.22%, and equivalent exergy efficiency from 28.96% to 19.11%. Eltawil et al. [26] developed a PV system hybrid dryer for mint drying. Results of daily average PV efficiency, dryer efficiency, overall efficiency, energy payback time and net CO_2 mitigation were highlighted. Shyam and Tiwari [27] performed experimentation on partially covered PVT air collectors. The performance of the air collector indicated that the presence of PV module near inlet provided better results, especially at higher mass flow rate. A comparison of open sun drying and evacuated tube collector based solar drying had been performed by Singh et al. [28].

Pertinent literature reveals that the performance of the PVT based dryer has not been much attention. In addition, the performance of any solar thermal system depends on the weather conditions, but much work on the solar based drying has not been reported for the North East Indian climatic conditions. Therefore the aim of this study is to investigate the performance of a PVT based dryer at North East Indian climatic conditions. The obtained results are then compared with the existing drying kinetic models of the literature.

2. Experimental methods

2.1. Experimental set-up

The hybrid PVT solar air dryer was fabricated and installed in the National Institute of Technology, Silchar, India: latitude 24°83'N and longitude 92°77'E. The experimental setup mainly consisted of dryer cabin, PVT solar air collector, blower as shown in **Fig.1 (a)**. PVT solar air collector was made of a PV panel, glass cover, absorber plate and insulator. The length, width, and height of the solar air collector were 1.1 m, 0.55 m, and 0.2 m, respectively. A 100 W_p PV panel was installed at the top of the solar air collector with dimensions of 1.061 m × 0.67 m. A 4 mm thickness glass cover was used as a cover plate placed 0.1m above the absorber plate.

A painted black galvanized iron sheet was used as absorber plate with the thickness of 0.55 mm and area of 0.605 m^2. The collector box walls and back surface were insulated with 0.1 m polyurethane foam. To move the fluid, two air gaps were created between the glass cover and absorber plate in the upper and lower side of the solar air collector. The orientation of the solar air collector kept towards south facing and inclined at local latitude of 25°. A 40W blower was connected to the lower side of the collector to supply air to the collector box.

The dryer cabin was constructed with mild steel sheet as a rectangular box having dimensions of 0.47 × 0.47 × 0.96 m and the cabin walls were insulated with 100 mm thick polyurethane foam. The drying cabin was consisted of 5 trays to keep the products and the spacing between the trays was 150 mm. Drying trays can be easily loaded and unloaded with the help of a door and the hot air moves over and under the product surface. Drying trays were made by using aluminum meshes with the dimensions of 0.4 × 0.4 m. The schematic diagram of the hybrid PVT system is shown in **Fig.1 (b)**.

2.2. Experimental procedure

Drying experiments were conducted in the solar air dryer and in the open sun from 9:00 AM to 5:00 PM. Fresh green chilis were purchased from the local market of Silchar. Green chilis were cleaned with the water to remove dusts and the stems were plucked before the experiment starts. Drying chamber was loaded with 1 kg of green chilis distributed into 5 trays and each tray contained 200 gm of green chilis. Experiments were carried out to compare the sample in the drying cabin with the sample placed outside the drying cabin. The solar radiation, ambient air temperature, solar cell temperature, inlet and outlet temperatures of dryer, relative humidity, wind speed, mass flow rate and moisture removal rate were recorded every 1 hr interval.

2.3. Instrumentation

A pyranometer (Kipp & Zonen model CMP3) was used to measure the horizontal solar radiation with a measuring range 0-2000 W/m^2 and the accuracy of ±1%. The temperatures were measured by K-type thermocouples with an accuracy of ± 2.2%. A thermo-hygrometer (Testo model 605i) was used for relative humidity measurement having an accuracy of ±1.8%. Air velocity to and from the solar collector and dryer cabin, and wind velocity were measured by a anemometer (Lutron model AM-4224SD) with the range between 0.2-25.0 m/s and the accuracy of ±5%. Moisture loss from the products was measured by using a digital balance (Wensar model TTB 3) that can measure up to 3 kg with accuracy ±0.01 g. The experimental readings were stored in a data acquisition system (DataTaker model DT85).

2.4. Experimental uncertainty

The experimental data of solar dryer and open sun were measured with the appropriate instruments. Experimental uncertainty of temperatures, relative humidity, air velocity, moisture loss and solar radiation were used in planning and designing of drying experiments.

Let different independent variables $a_1, a_2, \dots\dots\dots a_n$ effect the any output R, and W_R is the involved uncertainty, and W_1, W_2.. W_n be the uncertainty in the independent variables. The total uncertainty in the result R is calculated by [30].

$$W_R = \left[\left(\frac{\partial R}{\partial a_1} W_1\right)^2 + \left(\frac{\partial R}{\partial a_2} W_2\right)^2 + \dots\dots\dots + \left(\frac{\partial R}{\partial a_n} W_n\right)^2\right]^{0.5} \qquad (1)$$

The measurement uncertainty involved in the temperature (W_T) can be written as:

$$W_T = \left[\left(W_{thermocouple}\right)^2 + \left(W_{connection\ point}\right)^2 + \left(W_{reading}\right)^2\right]^{0.5} = [(0.1)^2 + (0.1)^2 + (0.1)^2]^{0.5} = 0.17 \qquad (2)$$

The magnitude of measurement uncertainty involved in relative humidity (W_{RH}) can be expressed as:

$$W_{RH} = \left[\left(W_{thermo-hygrometer}\right)^2 + \left(W_{reading}\right)^2\right]^{0.5} = [(0.1)^2 + (0.1)^2]^{0.5} = 0.14 \quad (3)$$

The measurement uncertainty involved in air velocity (W_V) can be written as:

$$W_V = \left[(W_{anemometer})^2 + \left(W_{reading}\right)^2\right]^{0.5} = [(0.1)^2 + (0.1)^2]^{0.5} = 0.14 \quad (4)$$

The measurement uncertainty in moisture loss (W_{ML}) can be written as:

$$W_{ML} = \left[\left(W_{digital\ balance}\right)^2 + \left(W_{reading}\right)^2\right]^{0.5} = [(0.01)^2 + (0.01)^2]^{0.5} = 0.014 \quad (5)$$

The measurement uncertainty in solar radiation (W_{SR}) can be written as:

$$W_{SR} = \left[\left(W_{pyranometer}\right)^2 + \left(W_{reading}\right)^2\right]^{0.5} = [(1)^2 + (1)^2]^{0.5} = 1.14 \quad (6)$$

Total uncertainty in the experimental procedure can be written as:

$$\mathrm{W_{EXP}} = [(\mathrm{W_T})^2 + (\mathrm{W_{RH}})^2 + (\mathrm{W_V})^2 + (\mathrm{W_{ML}})^2 + (\mathrm{W_{SR}})^2]^{0.5} = \pm 1.17 \quad (7)$$

The error analysis shows that all calculated uncertainties are in the acceptable range. Uncertainties may be changed according to the experiment procedure.

3. Drying kinetics

To evaluate the drying behavior of green chilis drying kinetics was used during experimental conditions. Moisture contents of the green chilis were obtained at the beginning and end, by using hot air oven method. The experimental moisture content (dry basis) and moisture ratio of the products were calculated by using Eqs. (8) and (9).

The moisture content (m_d) of the product on dry basis can be written as [29]:

$$m_d = \frac{w_o - w_d}{w_d} \quad (8)$$

where, w_o is the weight of the substance at the starting of the experiment and w_d weight of the dry matter.

The moisture ratio (ζ) of the product can be written as [30]:

$$\zeta = \frac{m_t - m_e}{m_i - m_e} \quad (9)$$

where m_t, m_e, and m_i are moisture content at time t, equilibrium moisture content and initial moisture content, respectively, on dry basis. When the relative humidity of the drying air fluctuates during the experiment, the moisture ratio (ζ) can also be simplified as [31]:

$$\zeta = \frac{m_t}{m_i} \quad (10)$$

The drying models based on thin layer kinetics were used to predict the best model for drying behavior of green chilis in the solar dryer and open sun. Twelve thin layer drying mathematical models of moisture ratio were considered to compare the drying kinetics (see **Table 1**). To predict the moisture ratio for different drying models the regression analysis has been carried out. The chi-square (χ^2), coefficient of determination (R^2), and root mean square error (RMSE) were evaluated for all twelve models. The most suitable drying model was selected on the basis of highest value of R^2 and lowest values of χ^2, and RMSE [32].

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} \zeta_{prd,i} - \zeta_{exp,i}}{\sum_{i=1}^{N} \zeta_{prd} - \zeta_{exp,i}}\right] \quad (11)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (\zeta_{exp,i} - \zeta_{prd,i})^2}{N - n} \quad (12)$$

$$\text{RMSE} = \sqrt{\left[\frac{1}{N} \sum_{i=1}^{N} (\zeta_{prd,i} - \zeta_{exp,i})^2\right]} \quad (13)$$

Where, $\zeta_{prd,i}$, $\zeta_{exp,i}$, N and n are i^{th} predicted moisture ratio, i^{th} experimental moisture ratio, number of observations and number of constant respectively.

4. Energy analysis

Solar cell efficiency, PV module efficiency, PV electrical output, thermal energy and overall thermal energy obtained from the solar air collector and thermal efficiency and overall thermal efficiency of the collector were calculated for PVT based drying system by using Eqs. (14)-(20).

Solar cell efficiency is evaluated by [45]:

$$\eta_c = \eta_o\left(1 - \beta_c(T_c - T_o)\right) \tag{14}$$

PV module efficiency is calculated by [46]:

$$\eta_m = \tau_g \beta_c \eta_c \tag{15}$$

PV electrical output is calculated as [47]:

$$E_{el} = \eta_m A_m I(t) \tag{16}$$

Thermal energy received by the working fluid can be expressed as [48]:

$$Q_{th} = M_f C_f (T_{fo} - T_{fi}) \tag{17}$$

Overall thermal energy received from the collector can be expressed as [49]:

$$Q_{ov,th} = Q_{th} + \left(\frac{E_{el}}{0.38}\right) \tag{18}$$

Thermal efficiency of the collector can be calculated as [50]:

$$\eta_{th} = \frac{M_f C_f (T_{fo} - T_{fi})}{A_m I(t)} \tag{19}$$

Overall thermal efficiency of the collector can be calculated as [51]:

$$\eta_{ov,th} = \eta_{th} + (\frac{\eta_c}{0.38}) \quad (20)$$

The value of the plant factor is 0.38 considering the conversion efficiency of a thermal power plant [51].

5. Results & Discussions

5.1. Performance analysis of PVT dryer

The drying experiments of green chilis are carried out in the open sun and solar air dryer on 20th August 2018 from 9:00 AM to 5:00 PM. **Figure 2** shows the variation of inlet and outlet air temperatures of dryer, ambient air temperature and solar radiation during drying time of green chilis. Within the drying period, the solar radiation and ambient air temperature were varied from 224 W/m^2 to 993 W/m^2 and 31.2 to 37.9 °C, respectively. The temperature of the working fluid increases with the increase of ambient air temperature and solar radiation. Results indicate that the peak value of the solar radiation was obtained at 1:00 PM of the day. Further, the outlet air temperature from the collector is higher than that of the ambient due to absorbance of the solar radiation. However, the outlet temperature of the dryer is lower than that of inlet due to absorption of heat by green chilis. The variations of inlet and outlet air temperatures were from 35.8 to 50.6 °C and 32.7 to 41.4 °C, respectively.

The relative humidity at different locations of the dryer is depicted in **Fig. 3.** The relative humidity dropped during 9:00 AM to 2:00 PM, due to increase in inlet ambient air temperature and solar radiation. Moreover, the relative humidity at the dryer inlet is always less than that of the dryer outlet and ambient air. The minimum value of the relative humidity was achieved in the afternoon which made favorable conditions for faster drying. The relative humidity of ambient air, inlet and outlet of dryer varied from 51.7 to 74.6%, 27.2 to 49.3% and 35.4 to 59.8% respectively.

The variation of moisture content (dry basis) of green chilis is shown in **Fig. 4.** At the start of the drying process the moisture content within green chilis was recorded as 4.0 (g water/g dry matter). The drying period was considered from 9:00 AM to 5:00 PM. It can be seen from Fig. 4, the rate of reduction of moisture from green chilis was faster for the solar drying process than the open sun. The final moisture content of dried green chilis revealed that the solar dryer can remove moisture up to 130% faster than that of open sun, and was faster in the morning to noon than that in the evening.

The drying rate of green chilis varied continuously with time as shown in **Fig. 5.** The drying rate in solar dryer was constantly higher than the open sun and the maximum drying rate was achieved during noon mainly due to high solar energy input. The drying rate increased linearly in the initial stage and then decreased slowly in the final stage due to change of solar radiation and moisture content present in the green chilis. The change in moisture ratio of green chilis with respect to time is shown in **Fig. 6**. It is revealed that the moisture of green chilis are decreased faster in the solar dryer than in the open sun**.** Final moisture ratio of green chilis in open sun drying and solar dryer drying is found to be 0.28 and 0.11, respectively.

5.2. Drying kinetics of green chili

The regression analysis was performed to fit the experimental moisture ratio (ζ) data for the considered thin layer drying models. The best suited model for the thin layer drying kinetics of green chili was selected based on the highest values of R^2 and the lowest values of χ^2 and RMSE. The statistical results of twelve models for drying in solar dryer and in open sun drying are summarized in **Table 2** and **Table 3,** respectively. The Modified Henderson and Pabis model provided the maximum R^2 (=0.999) and the minimum values of χ^2 (=0.23×10^{-4}) and RMSE (=0.456×10^{-2}) for drying in solar dryer (see Table 2) thus the most appropriate model for this mode of drying. The Two-term exponential model gave the highest value of R^2 (=0.999) and lowest value of χ^2 (=0.19×10^{-4}) and RMSE (=0.409×$^{-2}$) for drying in open sun thus the best model for drying of green chilis in this mode. Finally, for the solar dryer drying the Modified Henderson and Pabis model can be obtained as follows.

$$\zeta = 2.24586\, e^{(-0.12878\, t)} - 0.74889\, e^{(-0.01328\, t)} - 0.49843\, e^{(-0.40439\, t)} \tag{21}$$

In addition, for the open sun drying the Two-term exponential model can be obtained as follows.

$$\zeta = 0.21904\, e^{(-1.83909\, t)} + (1-0.21904)\, e^{(-1.83909 \times 0.21904\, t)} \tag{22}$$

To validate the drying model a comparison of predicted moisture ratio with experimental moisture ratio in different drying conditions was performed. The predicted and experimental moisture ratio for the Modified Henderson and Pabis model for green chilis for drying in solar dryer is shown in **Fig. 7.** Results indicate a good agreement. Further, the Two-term exponential model is found to be more suitable for predicting the moisture ratio for the open sun drying and the predicted vs experiment results is shown in **Fig. 8.** The results are found to be in order.

5.3. Energy analysis of PVT air collector

Figure 9 portrays the variation of electrical energy, thermal energy, and overall thermal energy obtained from the PVT collector. Results reveal that the magnitudes of electrical and thermal energy vary with respect to the solar radiation. The thermal energy output of the system is higher than the electrical output due to low conversion efficiency of the PV module. The variation of electrical, thermal and overall thermal energy ranged between 0.016 and 0.064, 0.032 and 0.0146 and 0.074 and 0.314 kWh, respectively. The daily total electrical, thermal and overall thermal energy obtained from the PVT air collector are 0.409, 0.859, and 1.933 kWh, respectively.

Figure 10 portrays the variation of electrical, thermal, and overall thermal efficiency of the PVT solar dryer. It has been noted that production of thermal efficiency increases with an increase solar radiation during noon time. However, the efficiency of the PV module decreases with increase in solar radiation and ambient temperature due to higher operating temperature thus affected the overall thermal efficiency of the PVT system. Results show that the average electrical, thermal and overall thermal efficiency was found to be 12.29%, 18.81% and 51.18%, respectively.

6. Conclusion

In the present study, the performance analysis of a prototype PVT solar dryer, drying kinetics of green chili and energy analysis of PVT based solar dryer were experimentally investigated. In order to identify the best theoretical model for predicting the moisture ratio of the green chilis in the PVT solar dryer and open sun drying conditions, a statistical analysis was performed to compare twelve established mathematical models developed for drying by using experimental data. The energy analysis was also carried out to obtain the electrical and thermal performance parameters of the prototype PVT solar dryer.

The following conclusions are drawn on the basis of this study.

- The final moisture ratio of the green chilis was 0.11 for solar drying and 0.28 for open sun drying after the same experimental test period thus indicating that the hybrid solar dryer is more effective in drying compared to the open sun drying method.
- Over an 8-hour test period, the solar dryer removed moisture content of green chilis at 130% higher rate than drying in the open sun.

- The statistical analysis showed that Modified Henderson and Pabis model is more appropriate for solar drying system, whereas, Two-term exponential model is best fitted for drying in open sun.
- Electrical energy, thermal energy, and overall thermal energy for the PVT solar dryer over the experimental period were found to be 0.409, 0.859 and 1.933 kWh/day, respectively.
- Average electrical efficiency, thermal efficiency, and overall thermal efficiency of the PVT solar dryer were found to be 12.29%, 18.81%, and 51.18%, respectively..

Nomenclature

$a, b, c, g, \square, k, k_{0,} k_1, n$	Constants in drying model
A_m	Area of module (m^2)
E_{el}	Electrical energy (kWh)
C_f	Specific heat of working fluid (J/kg K)
$I(t)$	Solar intensity (W/m^2)
M_d	Moisture content of the product (db %)
M_e	Equilibrium moisture content (db %)
M_f	Mass flow rate of working fluid (kg/s)
M_i	Initial moisture content (db %)
M_t	Moisture content at time t (db %)
$MR_{exp,i}$	Experimental moisture ratio
$MR_{prd,i}$	Predicted moisture ratio
N	Number of observations
n	Number of constants
Q_{th}	Thermal energy (kWh)
$Q_{ov,th}$	Equivalent thermal energy (kWh)
RMSE	Root mean square error
R^2	Coefficient of determination

T_c	Cell temperature (°C)
T_{fi}	Fluid temperature at inlet of PVT air collector (°C)
T_{fo}	Fluid temperature at outlet of PVT air collector (°C)
T_o	Cell temperature for optimum cell efficiency (°C)
t	Time (s)
W_1, W_2, W_n	Uncertainties in independent variable
W_{EXP}	Total uncertainty in the experimental procedure
W_{ML}	Total uncertainty in the measurement of moisture loss
W_R	Total uncertainty in the result
W_{RH}	Total uncertainty in the measurement of relative humidity
W_{SR}	Total uncertainty in the measurement of solar radiation
W_T	Total uncertainty in the measurement of temperature
W_V	Total uncertainty in the measurement of air velocity
w_d	Dried weight of the product (kg)
w_o	Initial weight of the product (kg)

Greek letter

χ^2	Chi-square
β_c	Packing factor of module
η_c	Solar cell efficiency
η_m	Module efficiency
η_o	Standard efficiency at standard condition
η_{th}	Thermal efficiency
$\eta_{ov,th}$	Overall thermal efficiency
τ_g	Transmissivity of glass
ζ	Moisture ratio

Subscripts

EXP	Experimental procedure
ML	moisture loss
NES	Northern Eastern states

PV	Photovoltaic
PVT	Photovoltaic-thermal
RH	Relative humidity
SR	Solar radiation
Th	Thermal

Acknowledgement:

One of the author (Dr. Biplab Das) acknowledge the fund received from DBT, Govt. of India, as DBT Overseas Award. Authors thank DST, Govt of India for providing the fund for the research

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List of Table Captions

Table 1. Mathematical models of moisture ratio to describe the thin layer drying kinetics [33-44].

Table 2. Statistical results of various thin layer drying models for moisture content and drying time of green chilis for the solar dryer drying

Table 3. Statistical results of various thin layer drying models for moisture content and drying time of green chili for the open sun drying

Lists of Figure Captions:

Fig.1. Hybrid PVT solar dryer (a) actual set up and (b) schematic diagram.

Fig. 2. Variation of inlet and outlet air temperatures of dryer, ambient air temperature and solar radiation during drying time of green chilis.

Fig. 3. Variation of relative humidity of ambient air, inlet and outlet of dryer during drying time of green chilis.

Fig. 4. Comparison of moisture content of green chilis for the solar dryer and open sun drying during drying time **Fig. 5.** Variation of drying rate for the solar dryer and open sun drying during drying time.

Fig. 6. Variation of moisture ratio for the solar dryer drying and open sun drying during drying time.

Fig. 7. Comparison of the experimental and predicted moisture ratio for the Modified Henderson and Pabis drying model of green chilis for the solar drying.

Fig. 8. Comparison of the experimental and predicted moisture ratio for the Two-term exponential drying model of green chilis for the open sun drying.

Fig. 9. Hourly variation of electrical energy, thermal energy and overall thermal energy.

Fig. 10. Hourly variation of electrical efficiency, thermal efficiency and overall thermal efficiency over a day

Table 1.

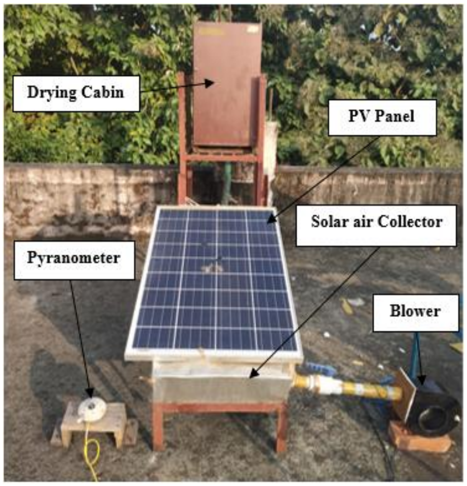
S. No.	Drying Model	Model Equation	Reference
1.	Lewis/Newton	$\zeta = e^{(-kt)}$	[33]
2.	Page	$\zeta = e(-kt^n)$	[34]
3.	Modified Page	$\zeta = \exp(-(kt)^n)$	[35]
4.	Henderson and Pabis	$\zeta = a \exp(-kt)$	[36]
5.	Modified Henderson and Pabis	$\zeta = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	[37]
6.	Two-term	$\zeta = a \exp(-k_0t) + b \exp(-k_1t)$	[38]
7.	Logarithmic	$\zeta = a \exp(-kt) + c$	[39]
8.	Wang and Singh	$\zeta = 1 + at + bt^2$	[40]
9.	Two-term exponential	$\zeta = a \exp(-kt) + (1-a) \exp(-kat)$	[41]
10.	Verma et al.	$\zeta = a \exp (-kt) + (1-a) \exp(-gt)$	[42]
11.	Diffusion approach	$\zeta = a \exp (-kt) + (1-a) \exp(-kbt)$	[43]
12.	Midilli et al.	$\zeta = a \exp(-kt^n) + bt$	[44]

Table 2.

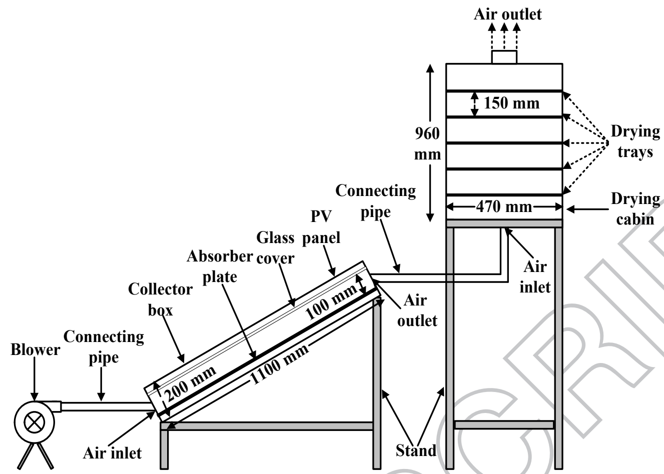
S. No.	Drying Model	Model Constants	R^2	χ^2	RMSE
1.	Lewis/Newton	k=0.182746094	0.943203	0.005617	0.070659
2.	Page	k=0.074458881, n=1.569936922	0.996218	0.000374	0.01823
3.	Modified Page	k=0.182746094, n=1	0.943203	0.005617	0.070659
4.	Henderson and Pabis	k=0.200089055, a=1.077417812	0.956240	0.004327	0.062017
5.	Modified Henderson and Pabis	k=0.128781256, a=2.245861656, b=-0.748898846, c=-0.498430577, g=0.013287903, h=0.404394427	0.999763	0.000023	0.004561
6.	Two-term	k_0=0.200089892, k_1=0.200088744, a=0.506517803, b=0.570900218	0.956240	0.004327	0.062017
7.	Logarithmic	k=0.022480466, a=5.575419288, c=-4.560045023	0.998435	0.000155	0.011724
8.	Wang and Singh	a=-0.117852271, b=0.000587847	0.998033	0.000194	0.013145
9.	Two-term exponential	a=0.305285077, k=2.003165915	0.991279	0.000862	0.027682
10.	Verma et al.	k=0.386593754, a=9.549792672, g=0.430616132	0.992951	0.000697	0.024887
11.	Diffusion approach	a=9.721059664, k=0.387025028, b=1.111687507	0.992953	0.000697	0.024884
12.	Midilli et al.	a=0.979281291, k=0.064529574, b=0, n=1.640744026	0.996925	0.000304	0.016437

Table 3.

S. No.	Drying Model	Model Constants	R^2	χ^2	RMSE
1.	Lewis/Newton	k=0.138050827	0.978697	0.001375	0.034963
2.	Page	k=0.0851250001, n=1.295792885	0.999660	0.000022	0.004418
3.	Modified Page	k=0.13856, n=1	0.978682	0.001377	0.03498
4.	Henderson and Pabis	k=0.147619922, a=1.044511047	0.985766	0.000918	0.028568
5.	Modified Henderson and Pabis	k=0.117852351, a=1.831356888, b=-0.443549526, c=-0.369954323, g=0.01663278, h=0.2448477	0.996985	0.000195	0.013153
6.	Two-term	k_0=0.147619294, k_1=0.147620199, a=0.494670304, b=0.549839832	0.985766	0.000918	0.028568
7.	Logarithmic	k=0.050342455, a=2.236333546, c=-1.22391676	0.998294	0.000110	0.009889
8.	Wang and Singh	a=-0.106021877, b=0.001850692	0.997977	0.000130	0.010770
9.	Two-term exponential	a=0.219046364, k=1.839092194	0.999708	0.000019	0.004094
10.	Verma et al.	k=0.196951691, a=1.429185013, g=0.518971358	0.999515	0.000031	0.005275
11.	Diffusion approach	a=1.646828823, k=0.210564455, b=2.085358243	0.999662	0.000022	0.004403
12.	Midilli et al.	a=0.996358724, k=0.083068455, b=0, n=1.306957494	0.999691	0.000020	0.004208


Drying Cabin
PV Panel
Solar air Collector
Pyranometer
Blower

(a)


Air outlet
150 mm
960 mm
Drying trays
470 mm
Drying cabin
Connecting pipe
PV panel
Glass cover
Absorber plate
Collector box
Connecting pipe
Blower
Air inlet
outlet
Air inlet
100 mm
1100 mm
200 mm
Stand

(b)

Fig.1.

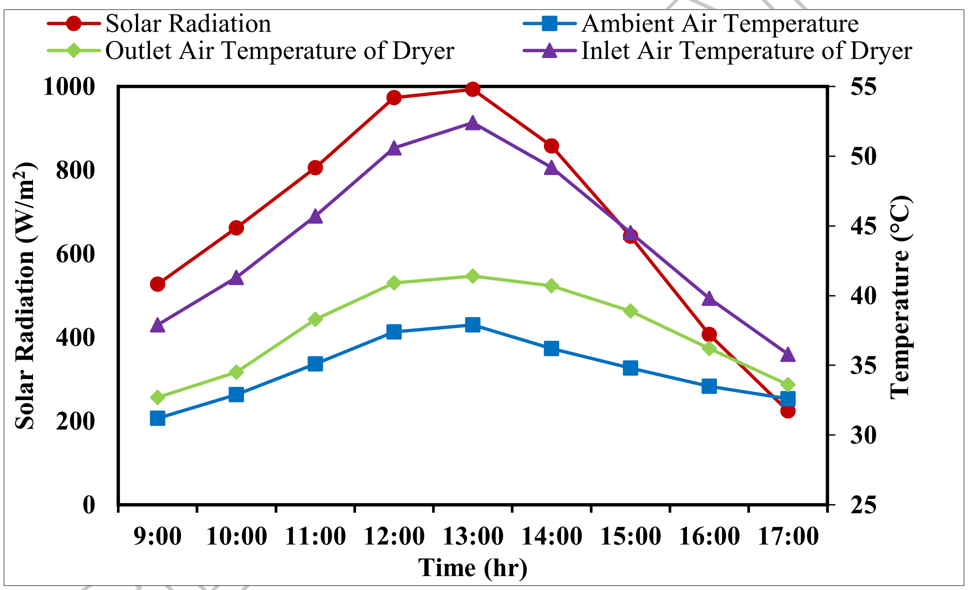

Solar Radiation
Ambient Air Temperature
Outlet Air Temperature of Dryer
Inlet Air Temperature of Dryer
Solar Radiation (W/m²)
Temperature (°C)
Time (hr)
9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00

Fig. 2.

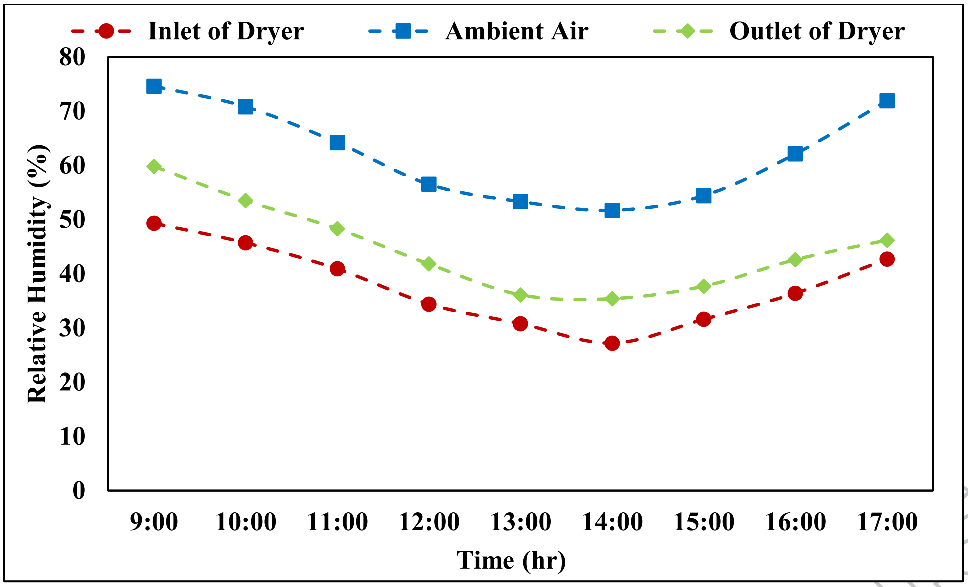

Inlet of Dryer
Ambient Air
Outlet of Dryer
Relative Humidity (%)
80
70
60
50
40
30
20
10
0
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 3.

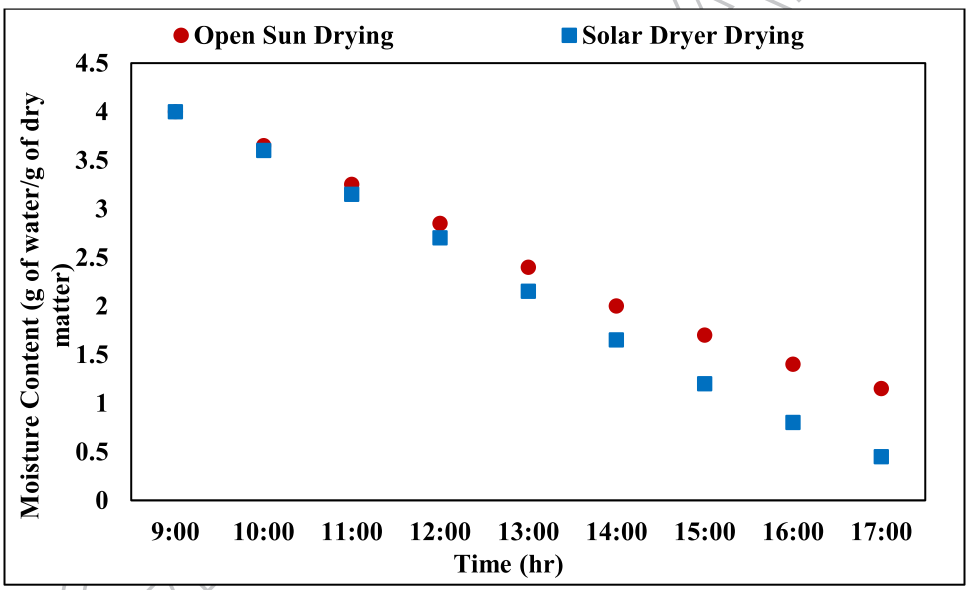

Open Sun Drying
Solar Dryer Drying
Moisture Content (g of water/g of dry matter)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 4.

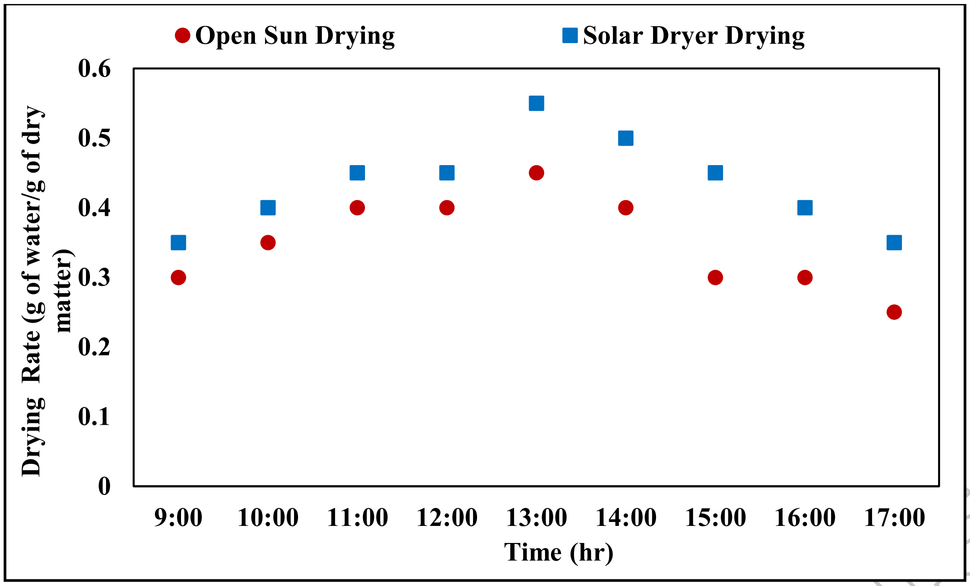

Open Sun Drying
Solar Dryer Drying
Drying Rate (g of water/g of dry matter)
0
0.1
0.2
0.3
0.4
0.5
0.6
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 5.

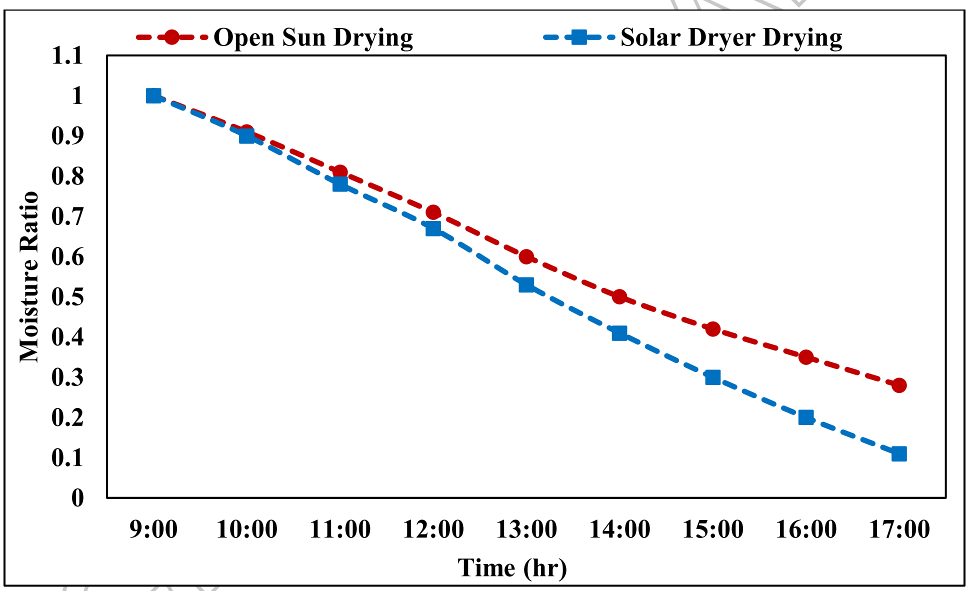

Open Sun Drying
Solar Dryer Drying
Moisture Ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 6.

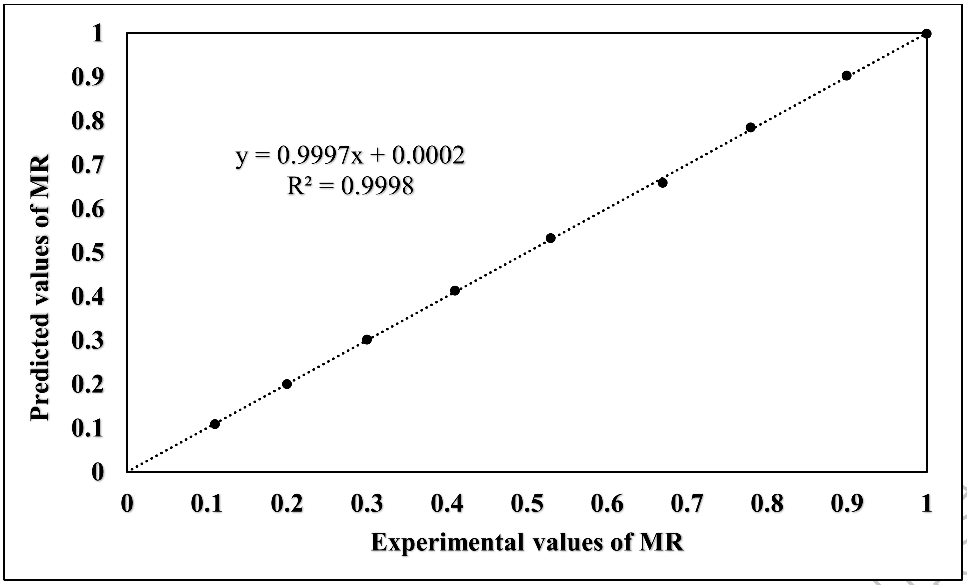

y = 0.9997x + 0.0002
R² = 0.9998
Predicted values of MR
Experimental values of MR
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Fig. 7.

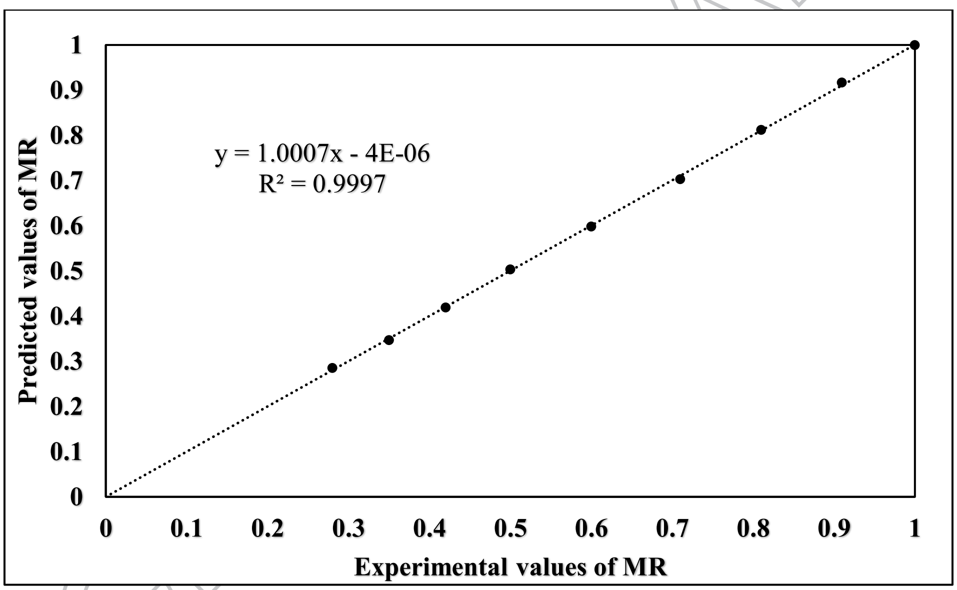
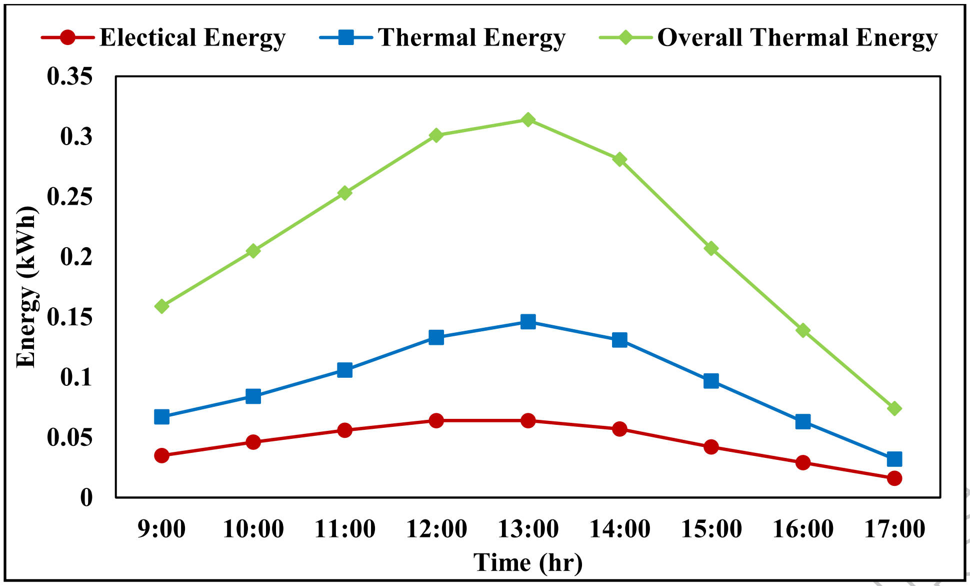
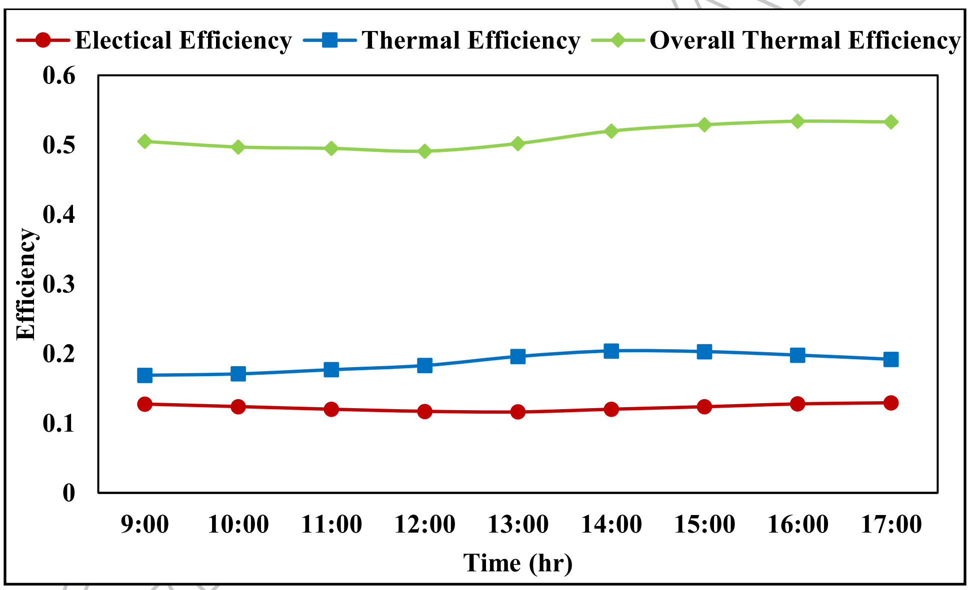

y = 1.0007x - 4E-06
R² = 0.9997
Predicted values of MR
Experimental values of MR
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Fig. 8.



Electical Energy
Thermal Energy
Overall Thermal Energy
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Energy (kWh)
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 9.



Electical Efficiency
Thermal Efficiency
Overall Thermal Efficiency
0.6
0.5
0.4
0.3
0.2
0.1
0
Efficiency
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time (hr)

Fig. 10.