Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000000

Research Article

Thermal performance of drying mango slices using a baffled-type hybrid solar dryer with exhaust hot air recirculation

Debashree Debadatta BEHERA[1], Shiv Sankar DAS[2], Ramesh CHANDRA MOHANTY[1,*], Raj Kumar SATANKAR[3]

[1]Department of Mechanical Engineering, Centurion University of Technology and Management, Odisha 752050, India
[2]School of Management, Centurion University of Technology and Management, Odisha 752050, India
[3]Department of Mechanical Engineering, Poornima College of Engineering, Jaipur, Rajasthan 302022, India

ARTICLE INFO

Article history
Received: 01 June 2024
Revised: 18 September2024
Accepted: 21 September 2024

Keywords:
Solar Drying, Forced Convection, Development of Hybrid Solar Dryer, Experimental Investigation, Performance Analysis, Uncertainty Analysis

ABSTRACT

In this research, a hybrid solar dryer has been designed for day and night operation through forced convection for drying mango slices and preparation of bread toast. As studied from the literature, enough research is not done on the use of recirculation of exhaust hot air and baffle in a solar dryer. The thermal and economic performance of the dryer has been assessed by calculating collector efficiency, drying efficiency, drying rate, payback period and cost-benefit ratio. It is found that the maximum collector efficiency is 74.1% and 66.96% with and without the use of exhaust hot air recirculation. Performance parameters such as drying rate (0.95 kg/hr), drying efficiency (32.89%), payback period (1.4394 years), and cost-benefit ratio (2.08) have been evaluated. An effective drying effect is produced by using an electric coil for night operation of dryer. An increase in the solar radiation increases the temperature of air inside the collector, thereby increasing the collector efficiency, drying efficiency and drying rate. The coefficient of determination for outlet collector temperature during consecutive three days is estimated above 95%, thus signifying a higher order of fit. Performing an uncertainty analysis of measurement, the uncertainty error is calculated below 10% exhibiting a reliable experimental result. Solar drying is considered as a sustainable food preservation method without negatively impacting the environment and finds wide applications in the fruit and food processing industries, domestic purposes etc.

Cite this article as: Behera DD, Das SS, CHANDRA MOHANTY R, Satankar RK. Thermal performance of drying mango slices using a baffled-type hybrid solar dryer with exhaust hot air recirculation. J Ther Eng 2025;11(5):1−14.

INTRODUCTION

Since ancient times, firewood, fossil fuels, open solar drying, and carbon-releasing coals have been used to dry and preserve food grains. These techniques are unhealthy, expensive, and unreliable. Solar drying technology is a sustainable way to preserve food by harnessing solar energy. A

***Corresponding author.**
*E-mail address: rcmohanty@cutm.ac.in

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç good alternative for operating in all weather conditions and at night is a hybrid solar dryer.

Şirin et al. [1] used an indirect photovoltaic dryer to test its performance with and without aluminium oxide nano-particles. Using nano-particles in thermal energy storage units reduced the drying period by 15 to 22%. The energy and exergy efficiency of collector was increased by 7% and 9%, respectively. A study on drying of cassava slices using a hybrid solar dryer that included six different types of evacuated tube collectors and a centrifugal pump driven by solar PV panel was carried out by Veeramanipriya and Sundari [2]. It required 8 hours to reduce the moisture content from 91.5 to 10.67%, whereas open sun drying took 13 hours to reduce the moisture content to 22.5%. The temperature within the drying chamber is between 30 and 40°C higher than that of the surrounding air. Singh and Gaur [3] studied on a hybrid greenhouse solar dryer using a heat exchanger as the drying bed. They found that the maximum drying period of food products was reduced by 61.9%, and the maximum payback time was determined as 2.87 years. Singh and Gaur [4] investigated drying tomato, ginger, and bottle guards using a hybrid solar dryer with and without an evacuated tube collector. For the crops mentioned above, the drying efficiency with an evacuated collector ranged from 14.22 to 27.99%, whereas the drying efficiency without one ranged from 9.63 to 24.88%.

In an experiment on a hybrid solar dryer, Nwakuba et al. [5] used an electric heater to dry the red pepper. Their observations showed that energy and collector efficiency varied from 13.2 to 35.6% and 23.7 to 72.4%, respectively by using a 1500W electric heating wire. The use of a hybrid solar dryer to dry vermicelli was investigated by Suherman et al. [6]. According to the study, the dryer efficiency, energy ratio for utilization, and ultimate energy efficiency increased to 17.02%, 0.32, and 83.6%, respectively. In order to improve heat transfer, Srithanyakorn et al. [7] conducted research on a mixed-type forced convection solar dryer employing a stainless steel wire mesh collector. The drying efficiency and drying chamber temperature were increased by 23.07% and 9.57°C, respectively. Deef et al. [8] developed a novel hybrid solar dryer to dry fish waste. For three samples of fish waste, the moisture content reduced from 75.2% to 24.8% throughout 10, 7, and 5 hours of drying. Maximum drying rates were recorded as 1.1, 1.22, and 1.41 kg/h at 45, 50, and 55°C. Salve and Fulambarka [9] have developed a solar collector for drying green chillies using an aluminium can and selective coating material. The maximum moisture removal rate and collector efficiency at the maximum mass flow rate have been calculated to be 88% and 50.27%, respectively. Srimanickam and Sunil [10] investigated a photovoltaic thermal collector with a solar dryer for drying 4 kg of coriander seeds. The moisture content has been reduced by weight from 68 to 9% within six days. For the purpose of drying mango leather, Shrivastava et al. [11] evaluated the efficiency of a hybrid greenhouse solar dryer integrated with an evacuated tube collector. Compared to open sun drying (OSD), the drying time was reduced by 7 hours. The average convective heat transfer coefficient in OSD was 0.07 W/m^2°C, but in the solar dryer, it was 0.11 W/m^2°C and 0.08 W/m^2°C, respectively. In order to dry vegetables, Behera et al. [12] conducted an experimental investigation on a hybrid solar dryer with and without phase change material. The maximum collector efficiency, drying efficiency, and drying rate were increased to 64.23%, 33.16%, and 1.351 kg/hr, respectively, through the use of the turbulence method. Heydari et al. [13] performed a study on the exergy and energy efficiency of a hybrid air heater integrated to a solar dryer. By adding auxiliary thermal element to solar air heater, temperature, thermal efficiency and second law efficiency was increased.

In previous studies, researchers have developed a hybrid type of solar dryer with a heat exchanger using an evacuated tube collector, flat plate collector, and phase change material. Their results did not show an appreciable rise in the drying rate and collector efficiency. Further, there has been no significant work on solar collectors using a baffle, recirculation of exhaust hot air, or electric heating coils during night operation. The authors are motivated to do further experimental study in order to improve the thermal performance of a hybrid solar dryer by these research gaps or limitations in the literature. The novelty of this study is the recirculation of hot exhaust air and addition of baffle for generation of turbulence effect. Because of these provisions, the drying parameters can be improved. As hot air generated inside the collector strikes the baffles, more fluid friction inside the collector randomly increases due to the turbulence effect and increasing the collector's outlet temperature. As a result, drying efficiency and drying rate are increased. Hot exhaust air is circulated by means of a pipe that connects the inlet of collector and the outlet of drying chamber. With an electric coil, the drying chamber temperature is raised to achieve the required drying effect for use at night. In the current research, drying of mango and preparation of bread toast have been experimentally studied. Various performance parameters including payback period, and the cost-benefit ratio have been evaluated. Finally, the current experimental results have been compared with the previous literature. Solar drying is a sustainable method that produces products of appropriate quality with minimal negative environmental impact. Solar dryers can be utilized for various applications in the fruit and food processing industries, agro-based industries, domestic purposes etc.

MATERIALS AND METHODS

Working Principle of Hybrid Solar Dryer

The hybrid solar dryer consists of major components such as a blower, drying chamber, solar photovoltaic system, flat plate collector, and electric heating coil. The heated air produced by the solar collector is circulated to the drying chamber by blowers during the drying process. It is based on forced convection mode. Two forms of energy are required for drying, i.e. solar energy and electrical energy. The dryer needs solar energy during the day and electricity for night operation. Finally, the moisture found in food products is allowed to escape into the atmosphere. The flow diagram of the hybrid solar dryer operating in the day time is shown in Fig. 1.

Fabrication Process

The dimensions of each component of the solar dryer are first calculated before fabrication. The specifications of the main components are presented in Table 1. Using these dimensions of each component, a digital model of the front and rear sides of the dryer and its schematic diagram is developed using CATIA software, as displayed in Fig. 2.

The experimental set-up is constructed after the completion of the 3D model design. The material required for constructing a solar dryer has been procured from a local store. The components are manufactured, assembled, and installed in the University Mechanical Workshop. A 2.5 mm aluminium sheet has been used to fabricate the dryer. Because of the excellent heat conductivity and resistance to corrosion, aluminium sheet is selected for fabrication. Initially, aluminium sheets are cut as per the given size through a pipe cutter and sheet bending operation. Mild steel angle frames are used to join all the sheets, and finally, the sheets are riveted using a riveter. The drying chamber constructed as a rectangular stainless steel box and is capable of carrying 15 kg of fresh food products for drying. The drying chamber is structured with hinges for opening and closing the door. Three L-shaped mild steel frames are riveted inside the drying chamber to each side of the vertical walls to support three horizontal trays. Within the drying chamber, three vertical stainless steel wire mesh trays are placed uniformly at 110 mm spacing to provide a uniform air heating.

An inclined mounting structure is fabricated to support and position the solar panel using a mild steel angle frame. To maximize the solar energy incident on the collector, the solar panel and collector are oriented 20° to the south as per the latitude of the location (20.2961°N, 85.8245°E) [14]. An angle protractor is used to measure the angle of the tilted structure. The collector glass plate experiences an increase in the incident solar radiation from 9:00 AM to 1:00 PM, followed by a decrease from 1:00 PM and 4:00 PM. The collector receives a maximum solar radiation of 670 W/m^2. The charge controller and battery are placed in the basement of the drying chamber so that it will not be exposed directly to solar radiation.

A rectangular box-type solar flat plate collector is fabricated using a 2.5 mm thickness aluminium sheet. The sides and bottom of the collector are insulated with glass wool of 75 mm thickness. Two glass plates of varying thickness are fixed to the top of the solar collector. A gap of 38 mm is provided between two glass plates to transfer enough solar energy to the absorbing plate. The upper

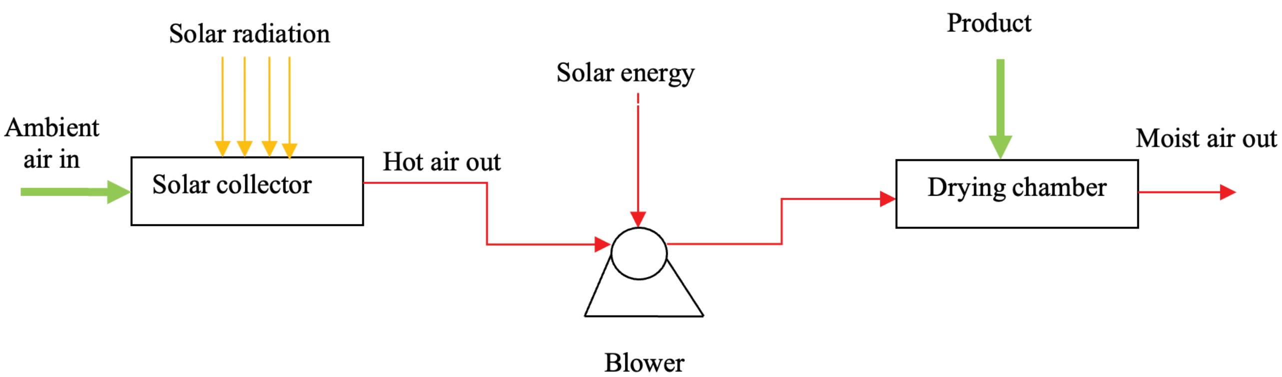
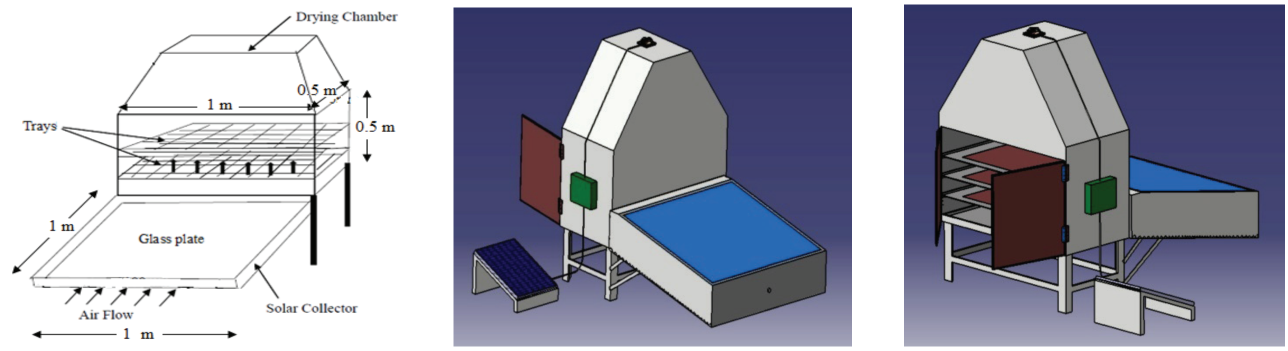


Figure 1. Flow diagram of hybrid solar dryer during day time.

Table 1. Design specifications of main components of solar dryer

Sl. No	Parameter	Specifications
1	Solar flat plate collector	1 m × 1 m × 0.22 m
2	Drying chamber	1 m × 0.5 m × 0.5 m
3	Two glass plates	0.98 m × 0.98 m of varying thicknesses of 5 mm and 4 mm
4	Glass wool	75 mm thickness



A) B) C)

Figure 2. A. Schematic diagram; B. CATIA model of front side; C. Rear side.

glass plate is movable while the lower glass plate is fixed for ease of maintenance. Using two glass plates makes it possible to enhance solar radiation transmissivity and reduce the amount of heat dissipated from the absorbing plate as a result of reradiation. The absorbing plate is constructed from a 1.5 mm thick aluminium sheet and is made of a V-shaped wavy structure by bending operation. It is a wavy structure having a larger surface area, which enhances the rate of heat transfer. A baffle provided over the absorbing plate enhances turbulence and hot air flow into the drying chamber. To maximize its ability to absorb solar energy, the dryer's outside and interior surfaces have been painted in black. By adequately sealing with glass wool, the heat losses from the side walls of the collector and drying chamber have been minimized. The escaped hot exhaust air from the drying chamber can be further recycled into the collector inlet through a pipe connection. The front and rear sides of the experimental setup for the hybrid solar dryer have been illustrated in Fig. 3.

Proper sizing and capacity of solar panel, battery, and charge controller is required to run four DC blowers. (i) The solar panel sizing is calculated for four blowers @3W, considering five sunshine hours per day that produce a 60Wh load. For climate conditions, the total load will be double, i.e., 120Wh. Considering five sunshine hours, a 120Wh/5=24W solar panel is needed. As per availability in the market, 20W capacity solar panel has been used. (ii) 12V battery is generally used for 3-100W solar panel. The Ampere hour of the battery is calculated as 120Wh/12=10Ah. Therefore, a lead acid battery with a capacity of 12V and 10Ah was used. (iii) The sizing of the charge controller is calculated as 24W/12V=2A. However, as per the market's availability, a 12V and 10A capacity MPPT charge controller has been taken. Therefore, a solar panel (20W), a battery (12V, 10Ah), and a charge controller

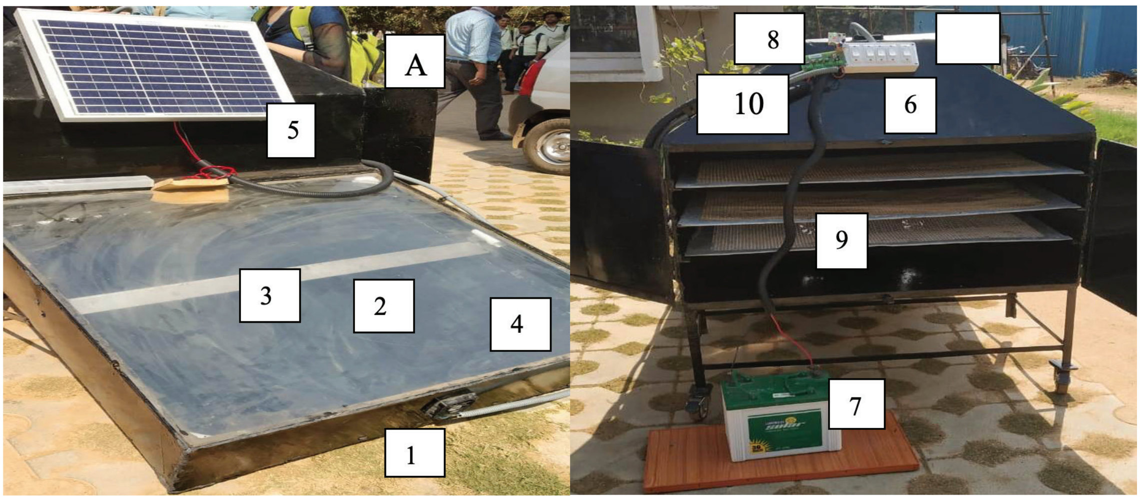


Figure 3. Experimental set-up: A; B. Front side; C. Rear side of hybrid solar dryer.

1, 8; DC blower at the inlet and outlet of the collector, 2. Absorbing plate, 3. Baffle, 4. Connecting pipe at the inlet of collector, 5. Solar panel, 6. Drying chamber, 7. Battery, 9. Tray, 10. Charge controller

Table 2. Specifications of different electrical components

Sl.No	Parameter	Specifications
1.	Polycrystaline type solar photovoltaic panel	Maximum power output =20W, Maximum voltage =17V, Maximum current =1.18A, Open circuit voltage =21.50V, Short circuit current =1.29A
2.	MPPT charge controller	12V, 10A
3.	Inverter	100W, IGBT model
4.	DC blower	3W, 12V, 0.6A
5.	Lead acid type battery	12V, 10Ah
6.	Electric heating coil	50W, 5A

(12V, 10A) have been used in the present work to power four DC blowers.

The first DC blower is placed at the collector inlet, bringing enough ambient air into the solar collector. To ensure adequate circulation of hot air within the drying chamber, the two additional DC blowers are connected electrically at the collector outlet. Moist air is released into the atmosphere by the fourth one, which is located at the drying chamber›s outlet. Table 2 presents the specifications for various electrical components.

Measuring Instruments

Various measuring devices such as infrared thermometer, hygrometer, lux meter, anemometer, and digital balance weighing machine are used to measure various parameters like temperature, relative humidity, intensity of solar radiation, air velocity, and weight of food product respectively. Different measuring devices and their specifications are presented in Table 3.

Uncertainty Analysis of Measurement

The uncertainty surrounding any measurement originates from variations in the data collected and can be caused by either random or systematic effects. Determination of measurement uncertainty is essential because it allows assessments of experimental results to be made while considering their effect. The standard deviation of the measurement is to be determined for finding the uncertainty error. The reading of the outlet collector, drying chamber temperature, and relative humidity of the drying chamber are recorded five times at regular intervals at some particular operating conditions. The final result is obtained by taking an average of all the recorded data. The standard deviation of the experimental result is obtained by using Equation (1) [15];

$$\sigma = \sqrt{\frac{\Sigma_{i=1}^{n}\left(Z_i - \bar{Z}\right)^2}{n-1}} \quad (1)$$

Where, σ = standard deviation, Z_i = recorded data in i^{th} time, $\bar{Z}$ = mean value of Z_i, n = number of recorded data.

The uncertainty error of measurement is determined by using Equation (2);

$$U_{T_{CO}} = \frac{\sigma_{T_{CO}}}{T_{CO_{MEAN}}} \times 100 \quad (2)$$

Where, $T_{CO_{MEAN}}$ is the average outlet collector temperature, $\sigma_{T_{CO}}$ is standard deviation of outlet collector temperature and $U_{T_{CO}}$ is the uncertainty error of outlet temperature in percentage.

Table 3. Specifications of measuring instruments

Measuring instruments	Measured parameters	Model of measuring instruments	Accuracy	Ranges
Infrared thermometer	Temperature	MT-5	± 2°C/±2%	40~550°C
Hygrometer	Humidity	KUSAM-MECO, KM919	Humidity: ±2.5% for 30-80%, ± 3.0% for 20-29.9% and 80.1-89.9, ± 5% for 1-19.9 and 90.1-99.9	Temperature: 20.0 ~ +60.0°C Humidity: 1.0 ~ 99.9% RH.
Lux meter	Solar radiation	KUSAM-MECO-LUX 99	± 5%	2000 to 50000 Lux
Anemometer	Velocity	KUSAM-MECO, KM-909	± 3% FS	Temperature: 20.0° ~ +60.0°C Wind velocity: 0.0-30.0 m/s

A)

B)

Figure 4. Drying of mangoes; A. Before drying; B. After drying.

Experimental Procedure for Drying Mangoes

The portable solar dryer is initially placed in an area that would provide for maximum exposure to solar radiation. The experiments were carried out during June to test five kilograms of green mangoes for pickle preparation. The mango slices are placed inside the drying chamber after it has been preheated for thirty minutes. Three days are required to complete the tests considering 6 hours of drying time per day. After the experiment is completed, the food product›s initial and final weights are determined for each day. To compare the results, an additional tray of mango slices is set outside the dryer for open sun drying. The drying of mangoes before and after drying is shown in Fig. 4. When comparing the hybrid type to other traditional solar drying techniques, the quality parameters, including taste, aroma, colour, and nutritional content, are higher. By reducing the moisture content in fruits and vegetables, solar drying improves their nutrient content by preventing microbe growth and deterioration. Dried food products therefore can be preserved fresher for a longer period in a hybrid solar dryer.

Performance Analysis of Solar Dryer

The dryer performance depends on the parameters such as inside temperatures of the dryer, relative humidity, solar radiation, and hot air velocity. The parameters such as payback period, cost-benefit ratio, moisture content on a dry basis, drying efficiency, drying rate, and collector efficiency are to be determined to assess the performance of the solar dryer by using Equations (3-5) [16] and Equation (6) [17].

The efficiency of the collector,

$$\eta_c = \dot{m}_a C_p \left(\frac{T_{co} - T_{ci}}{A_c \times I_T} \right) \tag{3}$$

Where, $\dot{m}_a$ is mass flow rate of air, C_P is specific heat at constant pressure, T_{co} and T_{ci} are collector outlet and inlet temperature. Maximum value of $\dot{m}_a$ is calculated at 1:00 PM as 0.0272kg/s and C_P is taken as 1007 J/kgK.

The drying efficiency of a system determines its overall efficiency, which is measured based on the instantaneous flux incidence (I_T), collector surface area (A_C), moisture removal (m_{wt}), and latent heat of evaporation (L_V). It is the energy required to use heated air to remove moisture from food products.

$$\text{Drying efficiency} = \eta_{drying} = \frac{m_{wt} \times L_V}{A_c \times I_T} \tag{4}$$

As evident from the Equation 4, the drying efficiency depends on many parameters such as quantity of moisture removal, latent heat of evaporation, collector surface area and instantaneous flux incidence. It can be improved with the higher moisture removal and latent heat of evaporation of moisture. It is calculated by taking collector surface area and latent heat of evaporation as 1 m^2 and 2260 kJ/kg respectively.

The ratio of the time interval and the difference between two successive moisture contents is known as the food product's drying rate (DR).

$$DR = \frac{MC_{db(t+dt)} - MC_{db(t)}}{dt} \tag{5}$$

Where, $MC_{db(t+dt)}$ is moisture content of food products at time $t + dt$ and $MC_{db(t)}$ moisture content of food products at time period t

The initial and final moisture contents are used to determine the moisture content ratio on a dry basis (m_{dr}) using Equation 6. The initial and final moisture content are taken as 74% and 10% respectively for inlet and outlet of collector [18].

$$m_{dr} = \frac{MC_{dbi} - MC_{dbf}}{MC_{dbf}} \tag{6}$$

Performance indices such as payback period and cost-benefit ratio have been discussed below using Equations (7-8) [17]. A solar drying system's payback period (PBP) is a significant economic factor. It is the amount of time required to recover the savings from the project's total investment during that time. It is calculated as explained below.

$$\text{Payback period} = \frac{C}{M_{dryproduct}P_{dryproduct} - M_{freshproduct}P_{freshproduct} - M_{dryproduct}X} \qquad (7)$$

Where, C = Dryer's total capital cost, which is the sum of its labour and material costs.

X = Drying cost = Total capital cost per year / total amount of dried products produced annually

$M_{dry\ product}$= Production of dry products annually

$M_{fresh\ product}$ = Amount of fresh products

As seen from Equation (7), the payback period depends on the drying cost, total capital cost and annual amount of fresh and dry product. Its value can be improved with the increase in the drying cost and amount of annual fresh and dry products. Less payback period is desired because the total investment cost on a solar dryer will be recovered during less period of time.

The cost-benefit ratio of a developed system is the ratio of its total annual benefit to its total capital cost. And is given as;

$$Cost-benefit\ ratio = \frac{\text{Annual benefit received}}{\text{Entire capital cost of the developed system}} \qquad (8)$$

Using the above equations, the different performance indicators have been calculated and presented in Table 4.

Any system must be economically viable for the successful adoption by the market. The hybrid solar dryers are evaluated economically using various economic indicators.

Table 4. Performance parameters

Performance parameters	Values
Maximum collector efficiency with and without exhaust hot air recirculation	74.1% and 66.96%
Drying efficiency	32.89%
Drying rate	0.95 kg/hr
Moisture content on a dry basis	2.55
Payback period	1.439 years
Cost-benefit ratio	2.008

Table 5. Analysis of cost of solar dryer

Items	Cost/year (INR)	Cost/year (USD)
Material cost includes Aluminium Sheet, Glass plate, glass wool, Hinges, square bar, flat, angle, screw, drill bit, electro rod, riveting	15,736	196.977
Cost of electrical components includes solar panel, battery, charge controller, inverter, switches, wire, DC fan, electric coil	15,000	187.765
Total capital cost = material cost+cost of electrical components + labour cost	30,736	384.743
Annual cost = Total capital cost + maintenance cost (assuming 1% capital cost)	31,043	388.67
Drying cost (X)	75	0.94
Annual price of fresh product, $P_{fresh\ product}$	55000	688.55
Annual price of dry product, $P_{dry\ product}$	64,500	807.47

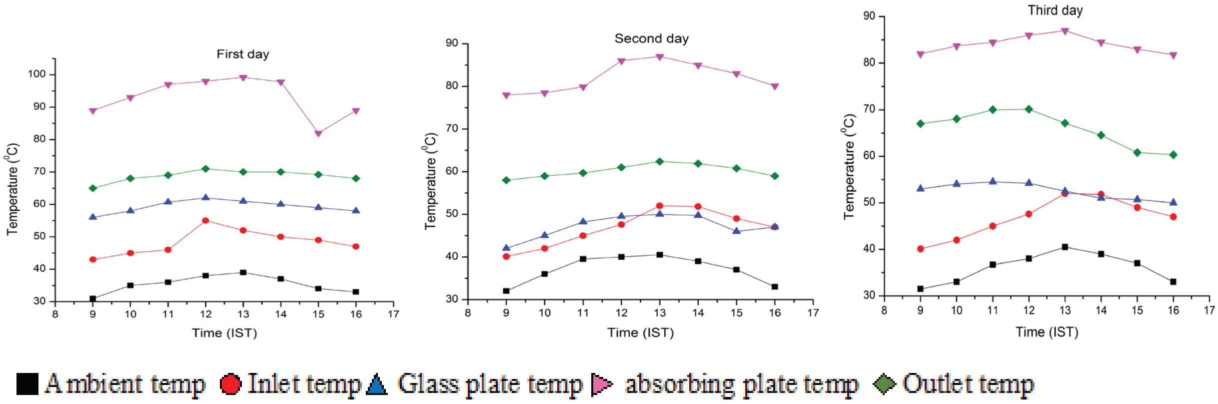


Figure 5. Temperature variations in solar collector.

The various cost parameters are presented in Table 5. The hybrid solar dryer›s total capital cost is estimated at 30,736 INR. The annual cost is calculated by adding the total capital cost and maintenance cost. As an average estimation, the present hybrid solar dryer can dry 1000 kg of fresh product annually, producing 430 kg of dry products and the drying cost per kg of dry product is calculated as 75 INR as presented in Table 5. If a conventional solar dryer is used for the same amount of fresh product, 350 kg of dry product will be produced with a drying cost of 87.81 INR per kg. It is observed that the drying cost per kg is less in case of hybrid solar dryer because of more annual production of dry product.

The PBP value of 1.439 years signifies that the total investment in the hybrid solar dryer can be recovered within 1.5 years. The cost-benefit ratio 2.008 reveals a sound investment against the total benefit received over the period. Therefore, the developed system is economically viable and feasible for drying various vegetables.

RESULTS AND DISCUSSION

Temperature Variation in Solar Collector and Drying Chamber

To investigate the drying rate and drying efficiency of the hybrid solar dryer, the temperature variation in the drying chamber and solar collector needs to be measured on regular intervals. The tests are carried out throughout three days, with a 7-hour drying period every day from 9:00 AM to 4:00 PM.

The temperatures of the glass plate, absorbing plate, collector inlet, and collector outlet are constantly monitored in order to determine the temperature variation in the solar collector. It is found that when the temperature within the collector increases and the humidity decreases so that the ability of the air to carry moisture increases. The temperatures for the atmosphere, collector inlet, glass plate, absorbing plate, and collector outlet are 39, 52, 61, 99.2, and 71°C respectively on the first day at 1:00 PM. As shown in Fig. 5, similar tests conducted on the second and third days indicate that the highest temperatures are at 40.5, 52, 50, 87, 62.4°C and 40.5, 52, 52.5, 87, and 67.1°C, respectively. It has been noted that the highest temperature occurs between 12:00 and 1:00 PM at the various above-mentioned locations**.** The standard deviation and average temperature of the outlet collector at 1.00 PM are determined by repeated measurement five times. The standard deviation and uncertainty error of collector outlet temperature are calculated as 1.2 and 1.63%, respectively, by using Equations (1-2). The experimental measurement data is considered reliable as the uncertainty error is less than 10%.

The residual plot of the outlet collector temperature during three consecutive days with respect to time as shown in Fig. 6. A nonlinear regression analysis using MATLAB R2024a has been performed on the experimental

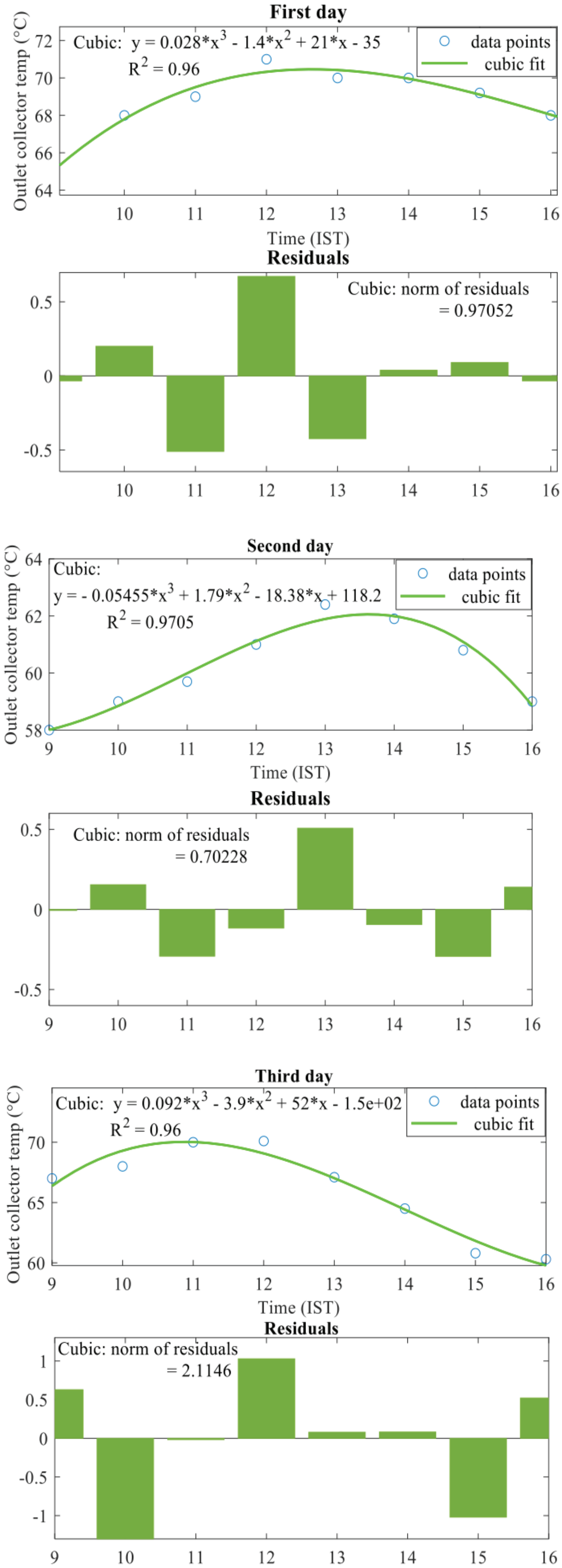


Figure 6. Error analysis plot for outlet collector temperature.

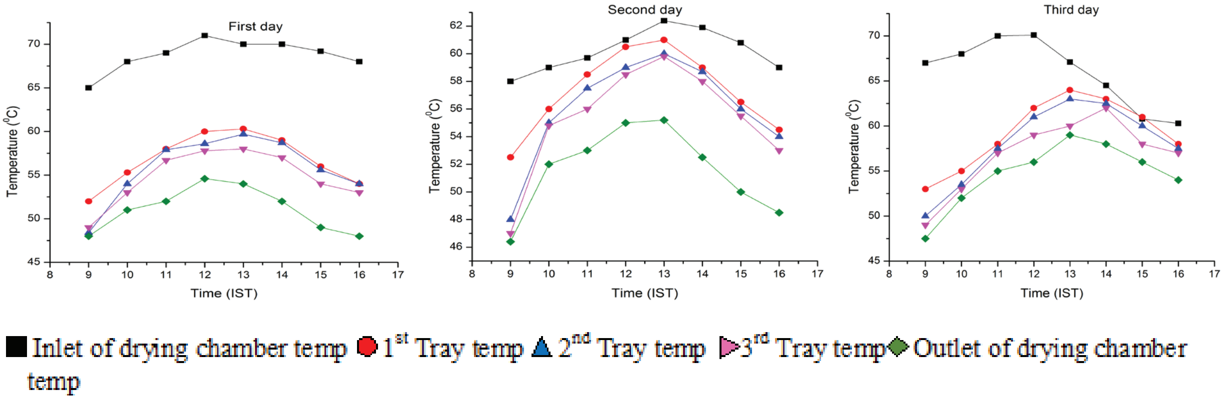


Figure 7. Temperature variation of the drying chamber.

data to provide a best-fit curve represented by a third-degree polynomial. The coefficient of determination (R^2) is used to analyze the relationship between variations of outlet collector temperature with respect to time period. The significance of the relationship between these two factors can be determined by this coefficient. The results show that there is a perfect correlation between the parameters, with R^2 values of 96%, 97%, and 96% for the first-, second-, and third-day observations, respectively. The norm of residuals for the first, second, and third day are found as 0.97, 0.7, and 2.11, respectively, representing a good relation between the parameters.

A similar procedure is used to regulate the drying chamber's temperature. The drying chamber consists of three trays, with the first tray positioned at the bottom. It is found that the temperature at the bottom tray is high and slightly decreases in trays placed above. The maximum temperatures of the drying chamber at 1:00 PM on the first day were recorded at 70°C at the inlet, 60.3, 59.7, 58, and 54°C at the first, second, and third trays, and the drying chamber outlet respectively. The maximum temperatures on the second and third days are 62.4, 61, 60, 59.8, 55.2, and 67.1, 64, 63, 60, and 59°C, respectively. From this data for three days, it is observed that the inlet drying chamber temperature shows maximum because it is almost the same at the outlet of the solar collector. This temperature gradually decreases when the hot air flows from the bottom towards the top of the tray. The heated and low-humidity air circulating in the first tray causes moisture content of the mango to evaporate and rise to the top of the drying chamber. The temperature further decreases in the second and third trays. This is because the first tray is positioned at the bottom of the drying chamber and collector outlet; the vaporized moisture will move upward from the first tray toward the outlet of the drying chamber, thus reducing the temperature in the second and third trays placed above. This results in a difference in temperature between the first tray and the drying chamber's outlet. A temperature gradient is established due to hot air flow from the bottom to the top of the drying chamber. The drying rate and food quality are uniformly maintained due to the even distribution of hot air as the perforated trays are evenly spaced inside the drying chambers. The uncertainty error of drying chamber is obtained as 3.7% using Equation (2). The temperature variations of different trays have been shown in Fig.7.

Variation of relative humidity inside drying chamber

The dryer›s relative humidity (RH) of air is not uniform; it varies with time during the drying period. As shown in Fig. 8, the RH of the exhaust moist air is compared for three days with that of the heated and ambient air within the drying chamber. At 1:00 PM on the first day, the heated and unsaturated air inside the drying chamber has a RH of 38%. In contrast, atmospheric air has a RH of 51%. As the temperature of the drying chamber increases, the RH gradually reduces and the amount of moisture removed from the food products increases. Drying chamber›s hot air is found to have a lower RH than the outside air, while the moist air that exits the chamber has a higher RH. At 1:00 PM on the second day, the ambient air humidity is 50% and the RH of the first, second, and third trays, as well as the drying chamber outlet, are measured to be 38.4, 38.5, 38.7, and 38.9%, respectively. Similarly, the corresponding values on the third day are 35.7, 35.6, 35.7, and 36%.

The RH of drying chamber is found to be significantly different from that of the surrounding air. This is because the drying chamber›s hot and dry air has a higher capacity to carry moisture than the surrounding air. The RH of air in the inner part of the drying chamber gradually decreases from 10:00 AM to 1:00 PM due to increased temperature. Because of the significant moisture removal of food products, there is a relatively slight difference in the humidity of the drying chamber and exhaust air during the same duration. On the second and third days, the RH of the exhaust air and the drying chamber remain unchanged and it remains constant, and the RH is gradually reduced in the inner part of the drying chamber as compared to the first day. Thus, the moisture removal rate from food products is

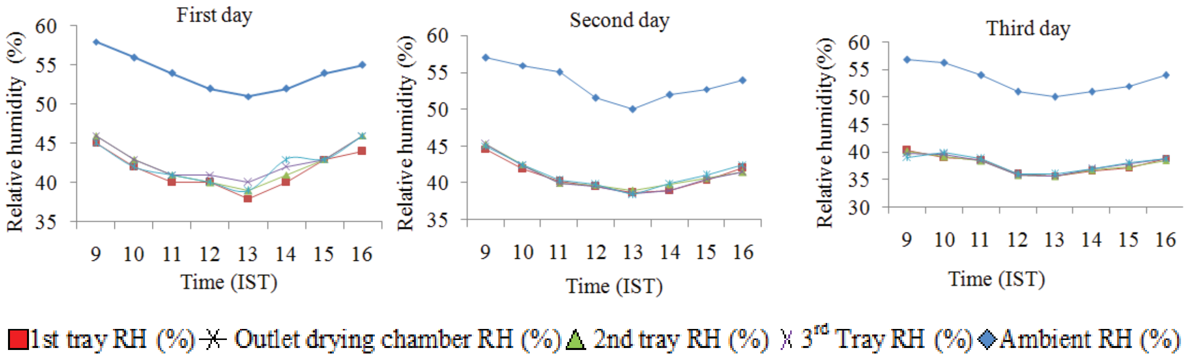


Figure 8. Variation of relative humidity of drying chamber and ambient air.

gradually reduced from the first to the third day. The uncertainty error of relative humidity is obtained as 3.147% using Equation (2).

Temperature of drying chamber during the night time

An additional heating device, such an electric heating coil, is used to dry because solar radiation is unavailable in cloudy and night conditions. The electric heater is powered by a battery that solar panel charges during the day time and provides 4 to 5 hours of backup power at night. An electric coil has been placed in the drying chamber so that it can run at night time. The electric heating coil and inverter are powered by a battery. The experimental setup for the night use is shown in Fig. 9.

The drying chamber is preheated for thirty minutes before the drying process starts. For making bread toast, the temperature is constantly monitored between 6.30 and 7:30 PM. Table 6 shows that the drying chamber›s maximum temperature is 66.7°C. The drying rate is evaluated as 0.85 kg/hr, resulting in a satisfactory drying effect and overall efficiency of the dryer.

Variation of collector outlet temperature, collector efficiency and solar radiation with time

The outlet temperature of the collector, solar radiation impacting the collector surface, and collector efficiency depend on the day time. Tests have been conducted on the variation in solar radiation for three days, considering the effect of collector efficiency and collector outlet temperature. At the maximum incident solar radiation of 670 W/m^2, the maximum collector outlet temperature, and its corresponding efficiency were determined as 72°C and 65.74%, respectively, using Equation (3) on the first day. The efficiency and collector outlet temperature gradually increases from 10:00 AM to 1:00 PM and then reduced after 1:00 PM as presented in Fig. 10. Similarly, at the maximum incident solar radiation of 657 W/m^2 and 643 W/m^2 on the second and third days, the corresponding maximum collector outlet temperature and efficiency were found as 72.5°C, 66.96%, and 72°C, 63% respectively as shown in Figs. 11 and 12, respectively.

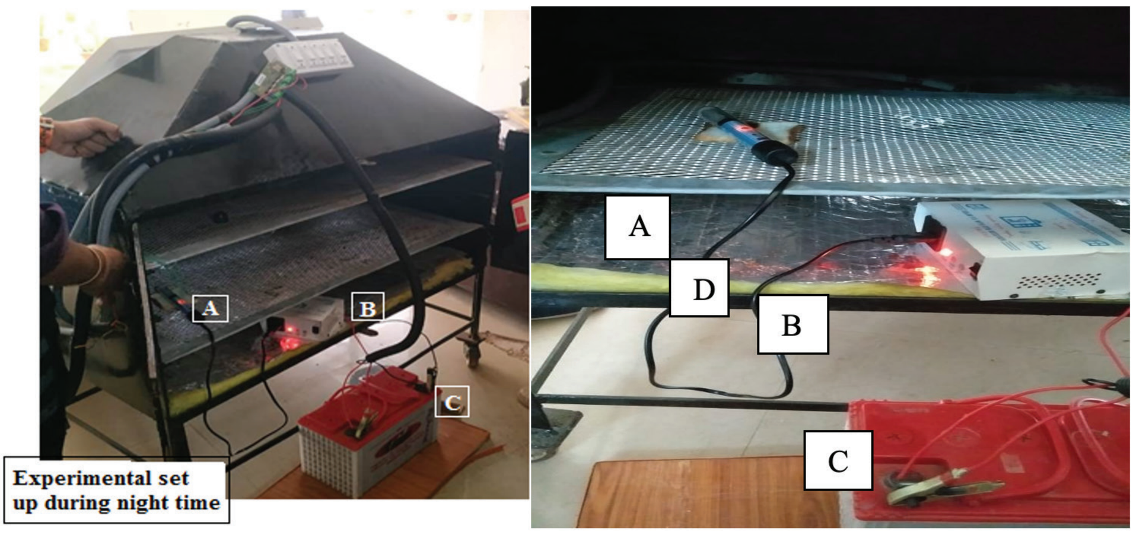


Figure 9. Experimental setup during night time; A. Electric heating coil; B. Inverter; C. Battery; D. Glass wool

Table 6. Temperature indication during night time

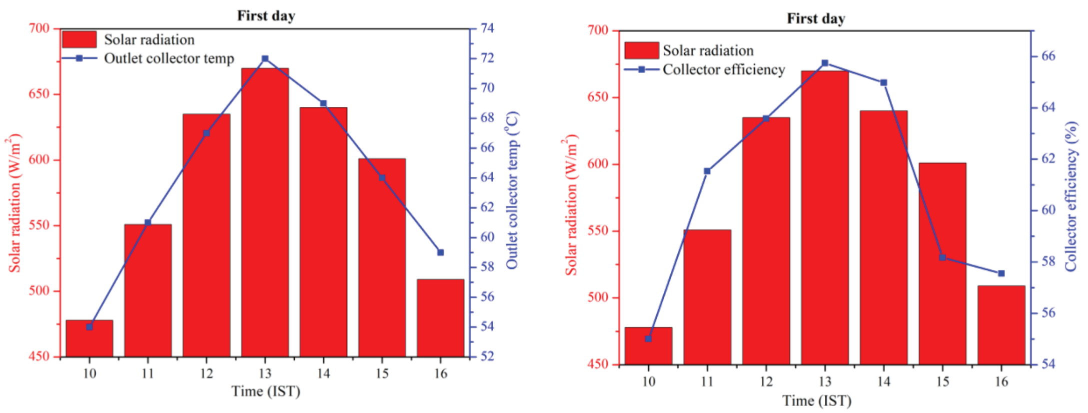
S. N.	Time (PM)	Drying chamber temp (°C)
1	6:30	43.5
2	6:40	50.8
3	6:50	54.9
4	7:00	58.6
5	7:10	62.4
6	7:20	64.7
7	7:30	66.7

Comparison Study of Hybrid Solar Dryer with Traditional Methods Of Drying

Initial and final mass of the sample, drying time, and percentage of mass reduction are compared for various solar drying methods. As shown in Fig. 13, five readings of initial and final masses recorded every hour have been assessed for both hybrid and open solar drying systems. The maximum drying rate of a hybrid solar dryer is 0.85 kg/hr, which is higher than the rates of natural convection and open solar drying (0.6 kg/hr and 0.48 kg/hr, respectively). Drying of food products using open and natural convection solar drying techniques will slowly become dehydrated and have higher moisture content because they take longer to dry. Moreover, a hybrid solar dryer preserves dried products for a longer period of time.

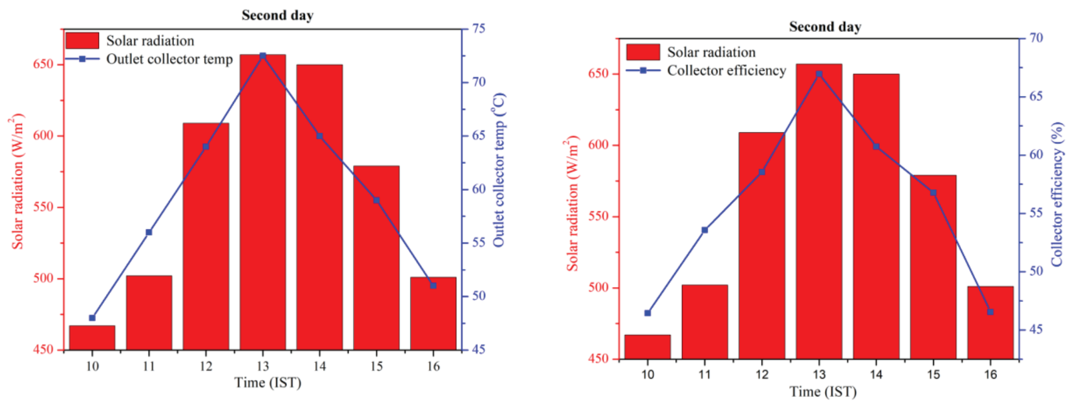
Comparative Analysis of Experimental Results with Similar Study

Parameters including drying chamber temperature, collector efficiency, and drying efficiency have all been compared with the experimental findings from previous studies conducted under similar testing conditions as presented in Table 7. The drying efficiency found in the present study is quite good by the use of hot exhaust air recirculation.



A) B)

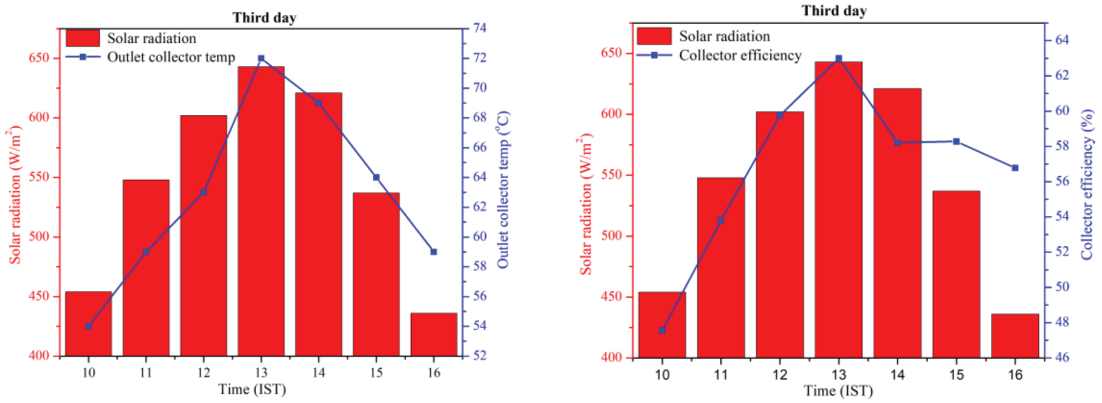
Figure 10. A. Variation of solar radiation and outlet collector temperature with time. B. Variation of solar radiation and collector efficiency with time.



A) B)

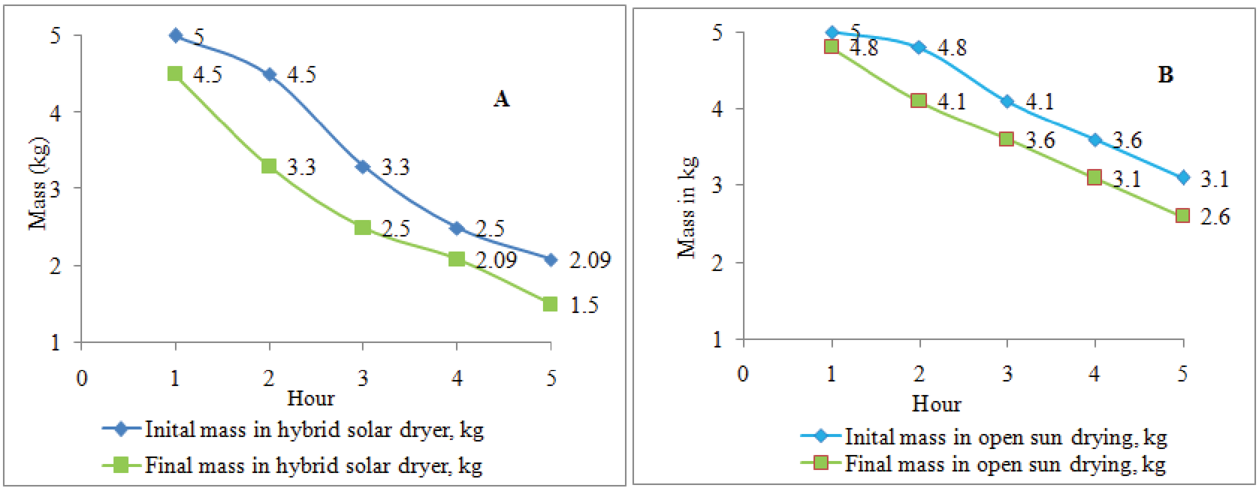
Figure 11. A. Variation of outlet collector temperature with incident solar radiation. B. Variation of efficiency incident solar radiation.

J Ther Eng, Vol. 11, No. 5, pp. 1−14, September, 2025



A) B)

Figure 12. A. Variation of outlet collector temperature with incident solar radiation. B. Variation of efficiency incident solar radiation.



A) B)

Figure 13. Initial and final mass of mangoes for five hours during the drying process. A. hybrid solar drying B. Open sun drying.

CONCLUSION

A hybrid solar dryer has been developed for day and night operation for drying mango slices and preparing bread toasts. The present work has been investigated with a new approach with the recirculation of exhaust hot air and turbulence generation through a baffle. Because of these provisions, the drying rate (0.95 kg/hr), drying efficiency (32.89%), collector efficiency (74.1%), and maximum drying temperature (69°C) are found quite improved over the previous studies. Economic indicators such as payback period (1.4394 years) and cost-benefit ratio (2.0008) have been evaluated. The above values being more than 1.0 signifies that the designed hybrid model is viable and feasible. The hybrid solar dryer can be utilized during the night period using an electric heating coil powered by a battery, which is charged by a solar panel during the day time. It can be utilized for industrial applications such as food processing industries, agro-industries, and domestic purposes. The drying process in case of hybrid solar dryers is faster and more effective even in the adverse weather conditions.

Future Recommendations

The present work can be extended for future research by using different heat storage materials for drying purposes during night time and cloudy weather. Experiments can be performed inside the laboratory at a constant source of light intensity incident on a solar collector.

Table 7. Comparison of current findings with previous studies

Reference	Testing condition	Modification	Drying chamber temp (°C)	Collector efficiency (%)	Drying efficiency (%)
Present study	Specimen: Green Mangoes; Mass: 5 kg; Duration: 24 h	Using exhaust hot air recirculation	69	74.1	32.89
Hao et al. [19]	Specimen: Lemon slices; Mass: 4 kg; Duration: 27 h	Flat plate collector with dual function	48.97	44.6	9.5
Nwakuba et al. [5]	Specimen: sliced red pepper; Mass: 0.5 kg; Duration: 24 h	Solar dryer integrated with electric heater	60	40.6	24.4
Asnaz et al. [20]	Specimen: Mushroom slices; Duration: 9 h	Forced convection solar dryer	43.8	67.85	67.66
Wang et al. [21]	Specimen: Mango; Mass: 24 kg; Duration: 24 h	Indirect type forced convection solar dryer	52	49.06	30.9
Mugi, and Chandramohan [22]	Specimen: Guava slices; Mass: 800 gm; Duration: 14 h	Indirect type forced convection solar dryer	47.5	65.37	6.84
Gilago and Chandramohan [23]	Specimen: ivy gourd; Mass: 800 gm; Duration: 13 h	Indirect type forced convection solar dryer	32-62	77.2	7.8

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article

REFERENCES

[1] Şirin C, Selimefendigil F, Öztop HF. Performance analysis and identification of an indirect photovoltaic thermal dryer with aluminum oxide nano-embedded thermal energy storage modification. Sustainability 2023;15:2422. [CrossRef]

[2] Veeramanipriya E, Sundari AU. Performance evaluation of hybrid photovoltaic thermal (PVT) solar dryer for drying of cassava. Solar Energy 2021;215:240–51. [CrossRef]

[3] Singh P, Gaur MK. Environmental and economic analysis of novel hybrid active greenhouse solar dryer with evacuated tube solar collector. Sustainable Energy Technol Assess 2021;47:101428. [CrossRef]

[4] Singh P, Gaur MK. Heat transfer analysis of hybrid active greenhouse solar dryer attached with evacuated tube solar collector. Solar Energy 2021;224:1178–92. [CrossRef]

[5] Nwakuba NR, Ndukwu MC, Asonye GU, Asoegwu SN, Nwandikom GI. Environmental sustainability analysis of a hybrid heat source dryer. Polytechnica 2020;3:99–114. [CrossRef]

[6] Suherman S, Hadiyanto H, Susanto EE, Utami IAP, Ningrum T. Hybrid solar dryer for sugar-palm vermicelli drying. J Food Process Eng 2020;43:e13471. [CrossRef]

[7] Srithanyakorn S, Bunchan S, Krittacom B, Luampon R. Comparison of mixed-mode forced-convection solar dryer with and without stainless wire mesh in solar collector. Clean Energy 2023;7:1316–29. [CrossRef]
[8] Deef M, Samy Helal H, El-Sebaee I, Nadimi M, Paliwal J, Ibrahim A. Harnessing solar energy: A novel hybrid solar dryer for efficient fish waste processing. AgriEngineering 2023;5:2439–57. [CrossRef]
[9] Salve S, Fulambarkar AM. Experimental studies on drying characteristics of green chilies in a solar dryer. J Therm Eng 2022;8:587–94. [CrossRef]
[10] Srimanickam B, Kumar S. Drying investigation of coriander seeds in a photovoltaic thermal collector with solar dryer. Int J Mech Eng Technol 2021;14:659–68. [CrossRef]
[11] Shrivastava A, Gaur MK, Singh P. Mango leather (Aam Papad) drying in hybrid greenhouse solar dryer with evacuated tube collector and finned drying tray: Drying behavior and economic analysis. Energy Sources Part A Recover Util Environ Eff 2025;47:2029974. [CrossRef]
[12] Behera DD, Mohanty RC, Mohanty AM. Experimental investigation of a hybrid solar dryer for vegetable drying with and without phase change material. J Braz Soc Mech Sci Eng 2024;46:303. [CrossRef]
[13] Heydari A, Forati M, Khatam S. Thermal performance investigation of a hybrid solar air heater applied in a solar dryer using thermodynamic modeling. J Therm Eng 2021;7:715–30. [CrossRef]
[14] Awasthi A, Kallioğlu MA, Sharma A, Mohan A, Chauhan R, Singh T. Solar collector tilt angle optimization for solar power plant setup-able sites at Western Himalaya and correlation formulation. J Therm Anal Calorim 2022;147:11417–31. [CrossRef]
[15] Padhi MR, Ghose P. Performance prediction of a model rotary air preheater through porous media approach. J Therm Sci Eng Appl 2023;15:071008. [CrossRef]
[16] Behera DD, Mohanty RC, Mohanty AM. Thermal performance of a hybrid solar dryer through experimental and CFD investigation. J Food Process Eng 2023;46:e14386. [CrossRef]
[17] Behera DD, Mohanty RC, Mohanty AM. Performance evaluation of indirect type forced convection solar mango dryer: A sustainable way of food preservation. Therm Sci 2023;27:1659–72. [CrossRef]
[18] Ampah J, Dzisi KA, Addo A, Bart-Plange A. Drying kinetics and chemical properties of mango. Int J Food Sci 2022;2022:6243228. [CrossRef]
[19] Hao W, Liu S, Mi B, Lai Y. Mathematical modeling and performance analysis of a new hybrid solar dryer of lemon slices for controlling drying temperature. Energies 2020;13:350. [CrossRef]
[20] Asnaz MSK, Dolcek AO. Comparative performance study of different types of solar dryers towards sustainable agriculture. Energy Rep 2021;7:6107–18. [CrossRef]
[21] Wang W, Li M, Hassanien RHE, Wang Y, Yang L. Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango. Appl Therm Eng 2018;134:310–21. [CrossRef]
[22] Mugi VR, Chandramohan VP. Comparison of drying kinetics, thermal and performance parameters during drying guava slices in natural and forced convection indirect solar dryers. Solar Energy 2022;234:319–29. [CrossRef]
[23] Gilago MC, Chandramohan VP. Performance evaluation of natural and forced convection indirect type solar dryers during drying ivy gourd: An experimental study. Renew Energy 2022;182:934–45. [CrossRef]