



Thermal performance study of a PV-driven innovative solar dryer with and without sensible heat storage for drying of *Garcinia Pedunculata*

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Abstract

Uneven drying is the key drawback of a conventional multi-tray dryer. Therefore, an improved active solar dryer with and without integrated sensible heat storage (SHS) was proposed. A unique feature of this dryer is its movable walls from the sides of the dryer to transform it to an indirect or mixed-mode as and when necessary. *Garcinia Pedunculata* (GP) is a local seasonal medicinal fruit in Northeast India. Drying kinetics of GP, the dryer performance and economic analysis of dryer were evaluated in the indirect solar dryer without SHS (Exp. I), mixed-mode solar dryer without SHS (Exp. II), indirect solar dryer with SHS (Exp. III), mixed-mode solar dryer with SHS (Exp. IV), and open sun drying (OSD). The dryer's average efficiencies were 18.12%, 22.37%, 21.74%, and 24.46% for Exp. I, Exp. II, Exp. III, and Exp. IV, respectively. The moisture content of GP was reduced to 12.09% in wet basis (w.b.) from 87.99% (w.b.). The overall drying time for Exp. I, Exp. II, OSD, Exp. III and Exp. IV were 31, 26, 53, 28, and 10 h, respectively. From the eleven drying models, the Two-Term model was the best-fitted model for Exp. I, Exp. II, OSD and Exp. III, and Midilli and Kucuk model was for Exp. IV. The final product's fragrance and colour are better for Exp. IV. Developing this dryer for Exp. I, Exp. II, Exp. III and Exp. IV, the price required was around 25,000, 27,000, 26,000, and 28,000 INR (1 US\$ = 74.57 INR), respectively, while the economic payback periods are 1.6 years, 0.9 year, 1.4 years, and 0.59 year, respectively.

Keywords Solar dryer · Sensible Heat Storage · *Garcinia Pedunculata* · Thermal efficiency · Drying kinetics · Economic Analysis

Nomenclature

\dot{E}	Energy (W)
\dot{H}	Net heat transfer to system (W)
\dot{W}	Net work done by system (W)
T	Temperature (°C)
h	Enthalpy (J/kg)
V	Velocity (m/s)
Z	Height from the datum (m)
C_{pa}	Specific heat of air (J/kgK)
Exp.	Experiment
A	Area (m ²)
SEC	Specific Energy Consumption (Wh/kg)
t_{dry}	Total drying time (h)

Q_L	Latent heat of vaporization of water (J/kg)
m_w	Amount of moisture evaporated (kg)
$m_{i,GP}$	Initial mass of the GP (g)
$m_{j,GP}$	Final mass of the GP (g)
$M_{GP,t}$	Moisture content at time 't' (%)
$M_{GP,e}$	Moisture content at equilibrium (%)
$M_{GP,i}$	Moisture content at time 't=0' (%)
MR	Moisture ratio
I	Intensity of solar radiation (W/m ²)
n	Number of observations
z	Number of constants

Greek symbols

α	Absorptivity
τ	Transmissivity
$\eta_{e,SAH}$	Thermal efficiency of the SAH (%)
$\eta_{e,dry}$	Overall dryer efficiency (%)

Subscripts

i	Inlet
o	Outlet

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<i>m</i>	Mass
<i>u</i>	Useful
<i>c</i>	Collector
<i>l</i>	Loss
<i>ex</i>	Experimental
<i>pr</i>	Predicted
α	Air
<i>in</i>	Input
<i>out</i>	Output
<i>md</i>	Mixed-mode dryer
<i>sys</i>	System
<i>SAH</i>	Solar air heater
<i>avp</i>	Average predicted
<i>dry</i>	Dryer

Introduction

The demand for dehydrated agricultural produces, and medicinal herbs has significantly increased in the recent years (Natarajan et al. 2022). A longer shelf life is provided by lowering the moisture content (MC) in agricultural products. It stops the development of bacteria and yeasts, preventing the rotting of harvested goods (Srinivasan et al. 2021). A significant amount of energy is devoted to drying processes in a variety of uses, including agricultural, fabric, pulp, pharmaceutical and food industries. This energy is primarily derived from fossil fuels. Fossil fuels, however, are beginning to run out and their emissions of carbon dioxide are causing global warming and climate change. The innovative utilization of renewable energy, particularly solar energy, can be an answer to this problem (Cetina-Quiñones et al. 2021).

Open sun drying (OSD) is often considered the most common and cheap practice for rural populations. However, this age-old method suffers from the limitation of substantial losses due to the addition of germs, insects, bacteria, etc. In addition, unpredicted rain or storm aggravate the condition in many applications (Lamidi et al. 2019). These restrictions can be overcome with a solar dryer integrated with a solar air heater (SAH) (Dutta et al. 2021b), which provides better-dried goods than the OSD approach (Dutta and Kumar 2017). The solar dryer was therefore chosen for the experimental application. Food products must be continually dried for longer than 5 h to be preserved, that is difficult with solar drying in places with shorter solar radiation periods. Thermal energy storage (TES) systems can solve this issue. When solar energy is abundant, it can be stored using Sensible Heat Storage (SHS) (Atalay 2019). Thermal energy is conserved throughout the increase in temperature of SHS material. Solid storage substances are frequently employed in a variety of applications because they are inexpensive and widely accessible. Compared to the conventional solar

drying method, the employment of SHS systems speeds up drying and prevents product mass losses. Some of the SHS used as solid-state thermal storage for heat storage include concrete, sand, and rock bed (Ayyappan et al. 2015). Safely drying agricultural products and, most importantly, drying indigenous food for future use may solve this difficulty to a great deal.

Researchers have designed, evolved, and experimented with many solar dryers during the last few decades for a wide range of agricultural products like tea (Dutta 2014; Sharma and Dutta 2021), coconut (Govindan et al. 2022), ivy gourd (Elangovan and Natarajan 2022), etc. (Kabeel et al. 2022) studied a modified solar dryer for drying of anchovy fish and compared with OSD. The study reported that a modified drying system was able to save 20% of energy compared to OSD. A significant amount of experimental and numerical research work has been conducted by various researchers on solar dryers with and without storage (Lingayat et al. 2020; Nukulwar and Tungikar 2022). (Bhardwaj et al. 2020) experimentally studied the chili drying by using both SHS and phase-changing material in an indirect solar dryer. The MC was reduced to 4.85% (w.b.) from an initial of 86.50% (w.b.). The time required for drying was 21 h (dryer with storage), 96 h (dryer without storage), and 150 h (OSD). (Azaizia et al. 2020) experimentally studied the drying effect of red pepper using a mixed-mode (greenhouse type) using paraffin wax as a phase-changing material. They compared the results with the dryer without using paraffin wax, and OSD. Out of ten different drying models, the most suited one describing the drying kinetics was Midilli and Kucuk for the dryer. An economic study was done to check the viability of the solar dryer (Kumar et al. 2020). In a solar dryer, cherry tomatoes were dried (Nabnean et al. 2016) by using water as its SHS. The system comprised a cabinet (1.0 m wide, 1.4 m high and 3.0 m length) of 100 kg capacity, a solar collector of water type (16 m²), a heat exchanger, and a water-heat-storage system. The reported drying time was 4 days, solar collector efficiency varied from 21 to 69% and the payback period was 1.37 years. This dryer could be used to dry different agricultural products that were sensitive to the radiation of the sun. (Kareem et al. 2017) investigated the drying of *screw pine* leaves in an integrated SAH with multi-pass provision. The granite grits used as SHS material were stored below the absorber plate. The drying time of screw pine leaves in the dryer was 28 h and it was 53 h in the OSD. The efficiencies for the dryer and collector were reported to be 36.0% and 58.7%, respectively. The estimated payback period was 0.75 year.

In previous studies, both mixed-mode and indirect mode for different products were studied together either replacing only one or two sides of the walls or even in a different setup (Simate 2003; Lakshmi et al. 2019a; Djebli et al. 2020; Erick César et al. 2021). But the facility of the developed

dryer for *Garcinia Pedunculata* (GP) is the sliding walls of all the sides of the drying chamber which makes the dryer capable of converting it into any mode as and when necessary. The materials used for the walls of the drying chamber may be changed according to the user's product, usage, need, and economic requirements. The economic analysis for drying of GP in an indirect and mixed-mode dryer with and without SHS was never reported earlier. It is also to be noted that certain agricultural food products are seasonal with high nutritional and medicinal values. They may be beneficial if these are made available round the year through some appropriate food-preservation processes. One such indigenous seasonal fruit that needs great attention is GP, accessible in the North-East, of India. GP trees bloom from September to October and ripen in April. At this time of the year, the monsoon dominates, and as result, sunny days are fewer. Being a medicinal fruit, GP improves digestion, cleanses urine, serves as a heart tonic, eases constipation, and cures abdominal tumours, worm infestation, digestive problems, vomiting, hemorrhoids, and several other ailments (Yamaguchi et al. 2000; Sarma and Devi 2015; Hossain et al. 2021). In this study, the development of a novel active solar dryer capable of operating in the indirect and mixed modes, their performance studies on the drying of GP, the drying kinetics, and economic analysis of GP is presented. The following objectives precede the present study:

- To develop and evaluate an innovative active solar dryer capable of operating in both indirect and mixed modes as per need, with and without SHS for reducing drying time and quality.
- To examine and compare the drying efficiency, useful heat gain, and specific energy consumption of all the possible four modes of operation.
- To evaluate the drying kinetics of GP in an indirect and mixed-mode dryer with and without SHS along with OSD.
- To evaluate and compare the economic parameters for the four configurations.

The paper begins with the introduction, followed by the methodologies that take into account the experimental setup description, experimental technique, and uncertainty analysis. The performance study and drying kinetics are discussed in the results and discussion part, followed by the conclusion in the last section.

Description of the experimental setup

An experimental set-up for the drying of GP was developed at Tezpur University, India. The experiments were conducted at a location of latitude $26^{\circ}42' 03''$ N and longitude

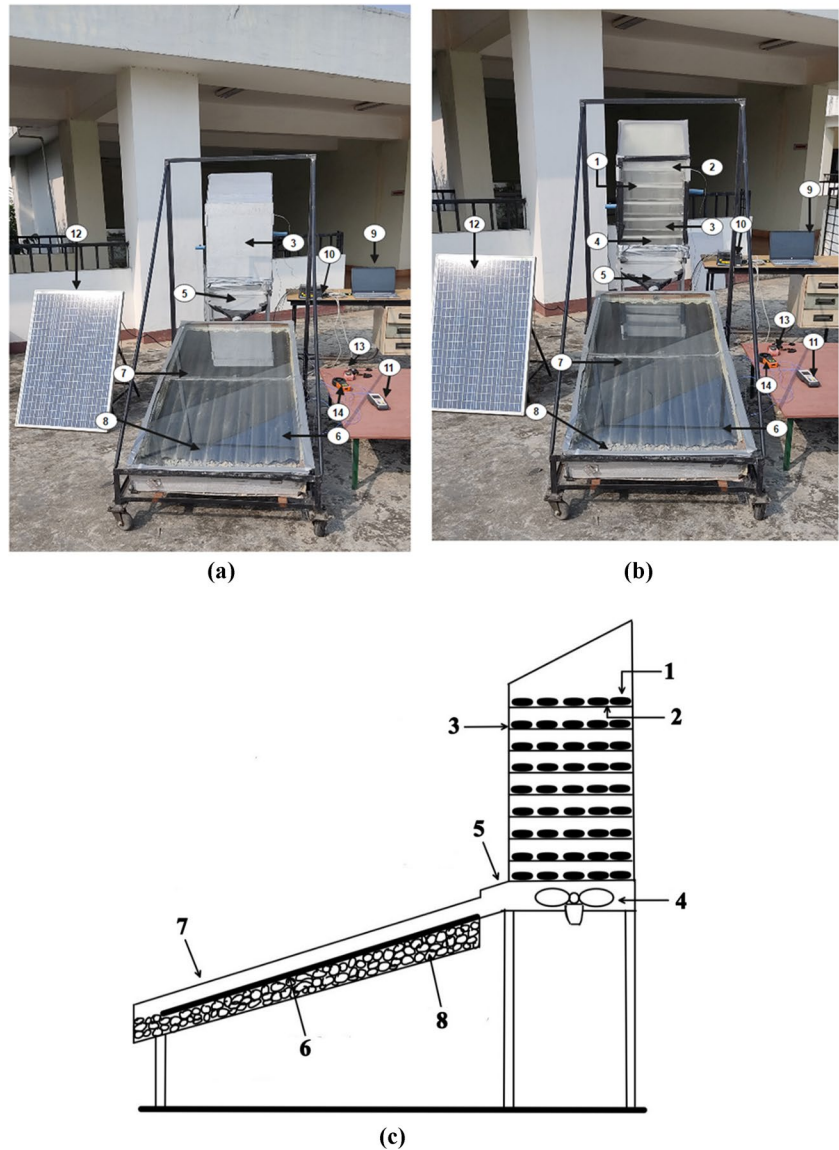
$92^{\circ}49'49''$ E. Photographs of the experimental set-up are shown in Fig. 1(a) and Fig. 1(b), and the schematic is shown in Fig. 1(c). It consisted of a SAH with SHS material (gravels) inside, a drying chamber, a DC fan, five perforated trays, and a Photovoltaic (PV) solar Module. The SAH was 180 cm in length, 80 cm in width, and 15 cm in height. A 4 mm thick glass sheet was used as a cover plate. The corrugated SAH's four sides were composed of 1.9 cm thick ply boards. The gravels were filled up to the black-colored absorber plate ($160\text{ cm} \times 80\text{ cm} \times 0.1\text{ cm}$) within the SAH for SHS. The drying chamber was 0.27 m^2 in area. The dryer can accommodate maximum 10 perforated trays (0.2 m^2 each). The removable chamber walls are a distinctive characteristic of this developed solar dryer. The same dryer may be run on indirect mode or mixed-mode as and when necessary. The drying chamber in mixed-mode operation absorbs additional solar radiation through the transparent acrylic sheets. The same dryer was also used as an indirect one with its ability to remove the acrylic sheet from the drying chamber. The instruments used and their technical specifications are mentioned in Table 1.

1) Medicinal fruit (GP), 2) Perforated trays, 3) Interchangeable walls of drying chamber, 4) DC Fan, 5) Connecting channel, 6) Corrugated absorber plate, 7) Glass plate, 8) Gravels, 9) Laptop, 10) Data acquisition system, 11) Thermocouple, 12) Photovoltaic Solar Module, 13) Pyranometer, 14) Anemometer with RH count Probe.

Working principle of the dryer

The primary source of energy for this drying system was solar energy with the use of SAH. The SAH is made of a transparent cover and an absorber plate. It is integrated with the drying chamber at an angle of 26° towards the south to achieve maximum radiation. The corrugated absorber plate was painted black for maximum absorption of solar energy. For SHS, the gravels were filled inside the SAH up to the black-coloured absorber plate. The stand of the collector was made adjustable to use in all seasons. The sensible heat storage materials stored heat during the daytime and released it when there was not sufficient radiation from the sun for drying the GP. A fraction of the incident ray was reflected in the ambient, and another fraction was transmitted through the cover. The black-painted corrugated plate of the solar collector absorbed a part of the solar energy. A substantial portion of the heat absorbed by the corrugated plate was convected to heat the air inside the chamber. The air leaving the SAH entered the dryer via a DC fan located at the entry of the dryer. The fan sucked the outgoing hot air from the SAH and created a forced draft inside the dryer. This hot air circulates steadily and continuously over GP and removes the moisture from it. Sliced GP are kept in five

Fig. 1 (a) Active indirect solar dryer with corrugated SAH. (b) Active mixed-mode solar dryer with corrugated SAH. (c) Schematic of solar dryer integrated with corrugated SAH



perforated trays inside the chamber. The temperature of the product increases inside the chamber, and the MC reduces subsequently. A Photovoltaic solar module was used to run

the DC fan. The installation of this solar dryer in rural areas with sensible heat storage is trouble-free as the materials are readily available, and the design is not very complicated. In

Table 1 Instruments along with their specifications

Instrument	Brand	Range	Accuracy
Anemometer with RH count Probe	HTC AVM-06	0–30 ms ⁻¹ 0–80% RH	±0.01 ms ⁻¹ ±0.1% RH
Pyranometer	Amprobe SOLAR-100	0–1999 Wm ⁻²	±1 Wm ⁻²
Mass balance	A&D Company Limited, HT-120	0–1000 g	±0.01 g
Data acquisition system with thermocouple (PT:100)	Libratherm	0 to 200 °C	±0.1 °C
Photovoltaic Solar Module	Loom Solar	Peak power output: 50 W, Operating voltage: 12 V, Panel Technology: Mono Perc	
DC fan	Rashri	12 V DC, maximum current 1 A, 2000 rpm	

mixed-mode operation, the drying chamber absorbs additional solar radiation through the transparent acrylic sheets (Fig. 1b).

Experimental procedure

The experiments in the active solar dryer were done in April and May 2021. These experiments were carried out between 9:00 h to 16:00 h in the solar dryer without SHS and 9:00 h to 18:00 h in the solar dryer with SHS on different days. Five kilograms of fresh GP were bought from the local market, washed with water, and sliced. The experiments were carried out in five trays. Prior to the experiment, the dryer was preheated for 1 h. The GP-loaded trays were then placed inside the solar dryer. The fan at the bottom of the dryer was run by the Photovoltaic solar module. The solar radiation, ambient temperature, ambient relative humidity, inlet, and outlet temperatures of SAH and dryer, relative humidity of air in the dryer, and weight loss were recorded at every 1 h interval. In this study, four sets of solar dryer experiments and OSD were considered: an indirect solar dryer without SHS (Exp. I), mixed-mode solar dryer without SHS (Exp. II), an indirect solar dryer with SHS (Exp. III), and mixed-mode solar dryer with SHS (Exp. IV). Figure 2

gives the complete method followed during the experiments. A sample tray of 250 g was kept inside the dryer for all the experiments to study the drying kinetics of GP. Another 5 kg of GP was placed for OSD. The hot air oven method was used to note the initial MC. The thermal efficiency of SAH, the efficiency of the dryer, SEC, MR, MC, and the drying rate for all the experiments were calculated with the help of the experimental data. To determine the possible errors, 12 systematic drying runs comprising three replicates were done for each mode of the dryer. A well-replicated experiment assures that the relationship between the independent and dependent variables is genuine and reliable (Borah et al. 2017).

Uncertainty

Uncertainty in measurements is caused by numerous factors such as calibration, environmental conditions, reading, and so on. Solar radiation, the temperature required for drying, the weight of GP, and the velocity of air were some of the variables considered in the present experiments. Equation (1) gives the uncertainty in the result (ΔZ_R), and the result R is the function of the independent variables $X_1, X_2, X_3, \dots, X_n$ (Dutta et al. 2021a) and is given in Table 2.

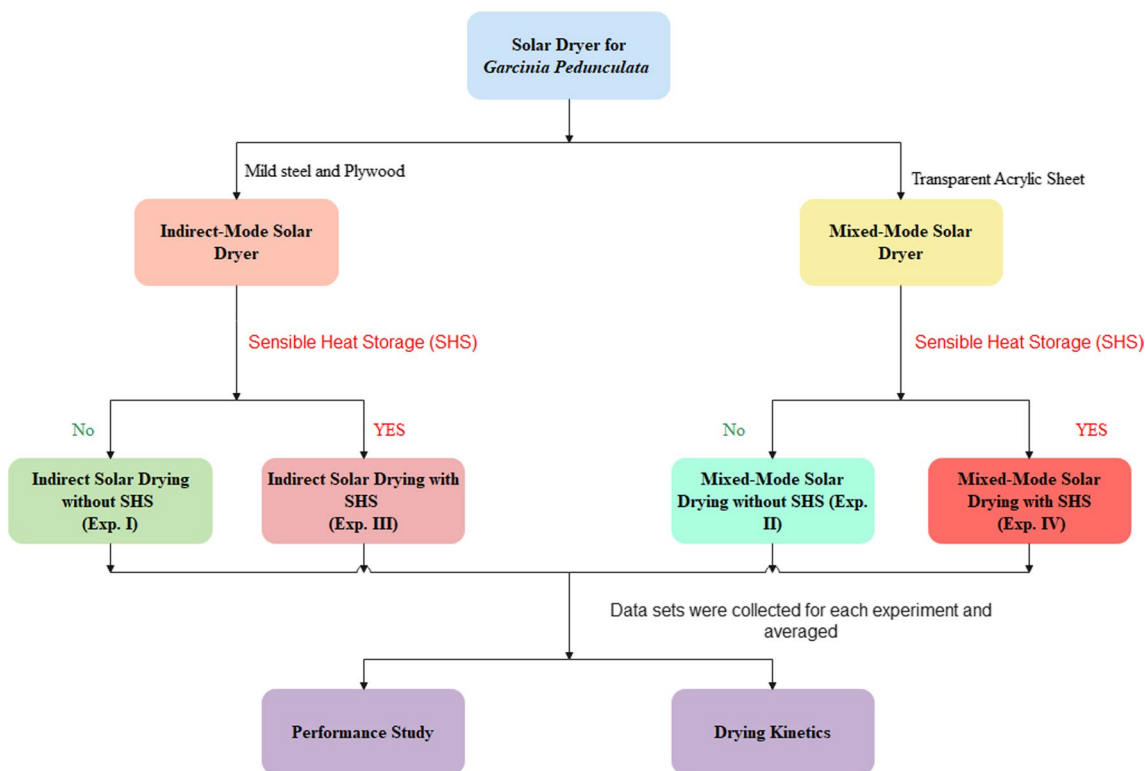


Fig.2 Diagram representation of the methodology followed for drying of Garcinia Pedunculata

Table 2 Values of uncertainties of the different parameters in the experiment

Parameter	Average Uncertainty
Moisture loss (weight)	±0.01 (g)
Temperature	±0.1 (°C)
Air velocity	±0.01 (ms ⁻¹)
Solar radiation	±1 (Wm ⁻²)
Thermal efficiency in SAH	±2.09 (%)
Thermal efficiency of the dryer	±2.75 (%)

$$\Delta Z_R = \left[\left(\frac{\partial R}{\partial X_1} Z_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} Z_2 \right)^2 + \left(\frac{\partial R}{\partial X_3} Z_3 \right)^2 + \dots + \left(\frac{\partial R}{\partial X_n} Z_n \right)^2 \right]^{1/2} \quad (1)$$

where $Z_1, Z_2, Z_3, \dots, Z_n$ are the uncertainties in the independent variables. Detailed study is given in the supplementary file.

Performance study

The first law of thermodynamics was used to carry out the energy analysis. In the analysis, the solar air collector and drying chamber were considered as steady flow devices. According to the mass conservation principle in a system, the rate of incoming air is equal to the rate of outgoing air (Cengel and Boles 2007).

$$\sum \dot{m}_{i,a} = \sum \dot{m}_{o,a} \quad (2)$$

According to the energy conservation principle in a system, the rate of energy transfer into the system is equal to the rate of energy transfer out of the system.

$$\sum \dot{E}_{in,sys} = \sum \dot{E}_{out,sys} \quad (3)$$

$$\dot{H} + \sum \dot{m}_{i,a} \left(h_{i,a} + \frac{V_{i,a}^2}{2} + Z_{i,a}g \right) = \sum \dot{m}_{o,a} \left(h_{o,a} + \frac{V_{o,a}^2}{2} + Z_{o,a}g \right) + \dot{W} \quad (4)$$

In the present analysis, there isn't any work done by the dryer, and the difference between kinetic energy, and potential energy is neglected, as it is very small.

Energy analysis of SAH

Equations (5) and (6) were obtained from Eqs. (2) to (4) by applying the mass and energy conservation equation for a steady flow to SAH (Cengel and Boles 2007).

$$\sum \dot{m}_{i,a} = \sum \dot{m}_{o,a} = \sum \dot{m}_a \quad (5)$$

$$\dot{H} = \dot{H}_{u,SAH} = \dot{H}_{in,SAH} - \dot{H}_{l,SAH} = \dot{m}_a (h_{out,a} - h_{in,a}) \quad (6)$$

The heat input of the SAH is given by

$$\dot{H}_{in,SAH} = \alpha \tau I A_{SAH} \quad (7)$$

The useful heat supplied by SAH is given (Sharma and Dutta 2022b)

$$\dot{H}_{u,SAH} = \dot{m}_a c_{pa} (T_{o,c} - T_{i,c}) \quad (8)$$

The energy efficiency of the corrugated collector is given by the ratio of useful heat supplied by SAH to heat input to SAH (Mugi and Chandramohan 2020; Sharma and Dutta 2022a).

$$\eta_{e,SAH} = \frac{\dot{H}_{u,SAH}}{\dot{H}_{in,SAH}} = \frac{\dot{m}_a c_{pa} (T_{o,c} - T_{i,c})}{\alpha \tau I A_{SAH}} \quad (9)$$

Energy study of the drying chamber

The energy input to the solar dryer is calculated as

$$E_{in,dry} = [(I_{SAH} \times A_{SAH}) + (I_d \times A_{md})] \times t_{dry} \quad (10)$$

For indirect solar drying, $(I_d \times A_{md}) = 0$. SEC is the ratio of the energy input to the dryer to the amount of moisture evaporated (Rabha et al. 2017).

$$SEC = \frac{E_{in,dry}}{m_w} \quad (11)$$

The ratio of the amount of energy required to remove moisture from GP to the amount of energy input to the solar dryer is the solar dryer's total thermal efficiency (Lakshmi et al. 2020).

$$\eta_{e,dry} = \frac{m_w Q_L}{E_{in,dry}} \quad (12)$$

Drying kinetics

For all four trials and OSD, the drying kinetics of GP were investigated. To check the drying kinetics, the samples in each experiment were weighed at a 1 h interval until the weight did not show any weight change. Eleven different drying models available in the literature were tested to find the best fit for each of the four batches and OSD of experiments. Table 3 gives the list of the eleven drying models considered for the analysis of the drying kinetics in Exp. I, Exp. II, Exp. III, Exp. IV, and OSD. Equations 13–15 can be used to calculate

Table 3 Different mathematical models to characterize the drying kinetics of GP

Model No	Name of the Model	Model equation	References
A	Newton	$MR = \exp(-kt)$	(Mathew and Thangavel 2021)
B	Page	$MR = \exp(-kt^n)$	(Wang et al. 2018)
C	Modified Page	$MR = \exp(-kt)^n$	(Nidhul et al. 2020)
D	Henderson and Pabis	$MR = a \exp(-kt)$	(Koua et al. 2009)
E	Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	(Atalay 2019)
F	Logarithmic	$MR = a \exp(-kt) + c$	(Chauhan et al. 2018)
G	Two Term	$MR = a \exp(-k_1t) + b \exp(-k_2t)$	(Lakshmi et al. 2018)
H	Two Term exponential	$MR = a \exp(-kt) + (1 - a) \exp(kat)$	(Srivastava et al. 2021)
I	Wang and Singh	$MR = 1 + at + bt^2$	(Blanco-Cano et al. 2016)
J	Diffusion Approximation model	$MR = a \exp(-kt) + (1 - a) \exp(kbt)$	(Atalay et al. 2017)
K	Midilli and Kucuk	$MR = a \exp(-kt^n) + bt$	(Midilli and Kucuk 2003)

the MC and moisture ratio (MR) of GP during the drying experiments (Dutta et al. 2021a).

$$MC_{GP} = \frac{m_{i,GP} - m_{j,GP}}{m_{i,GP}} \tag{13}$$

$$MR_{GP} = \frac{M_{GP,t} - M_{GP,e}}{M_{GP,i} - M_{GP,e}} \tag{14}$$

The simplified MR:

$$MR = \frac{M_{GP,t}}{M_{GP,i}} \tag{15}$$

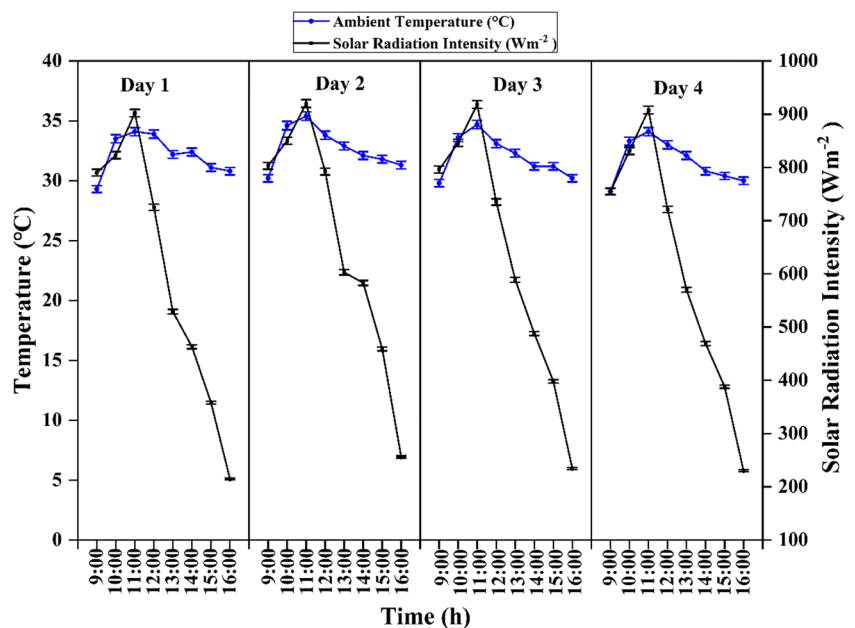
The values of $M_{GP,e}$ are comparatively smaller than $M_{GP,t}$ and $M_{GP,i}$, and subsequently ignored. In the case of uniform relative humidity of the drying air, Eq. (14) is used.

The variation in relative humidity, on the other hand, leads to Eq. (15). The variation of MR with time was plotted. The non-linear regression analysis was carried out in Matlab. The values of root mean square error (RMSE), reduced chi-square (χ^2), coefficient of determination (R^2) and Akaike information criterion (AIC) were calculated using Eq. (16), Eq. (17), Eq. (18), and Eq. (19), respectively. The lower values of RMSE, χ^2 , and AIC along with higher values of R^2 were considered for the determination of the best drying model.

$$RMSE^2 = \frac{1}{n} \sum_{i=1}^n (MR_{pr,i} - MR_{ex,i})^2 \tag{16}$$

$$\chi^2 = \frac{\sum_{i=1}^n (MR_{ex,i} - MR_{pr,i})^2}{n - z} \tag{17}$$

Fig. 3 Variations of Solar radiation and ambient temperature with time during Exp. I and Exp. II



$$R^2 = 1 - \frac{\sum_{i=1}^n (MR_{pr,i} - MR_{ex,i})^2}{\sum_{i=1}^n (MR_{avp} - MR_{ex,i})^2} \tag{18}$$

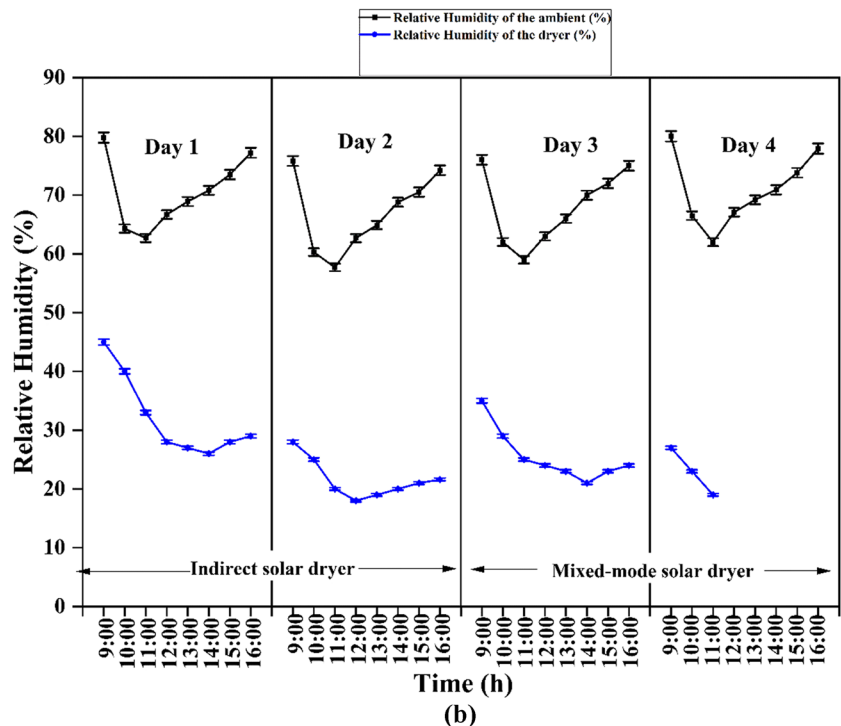
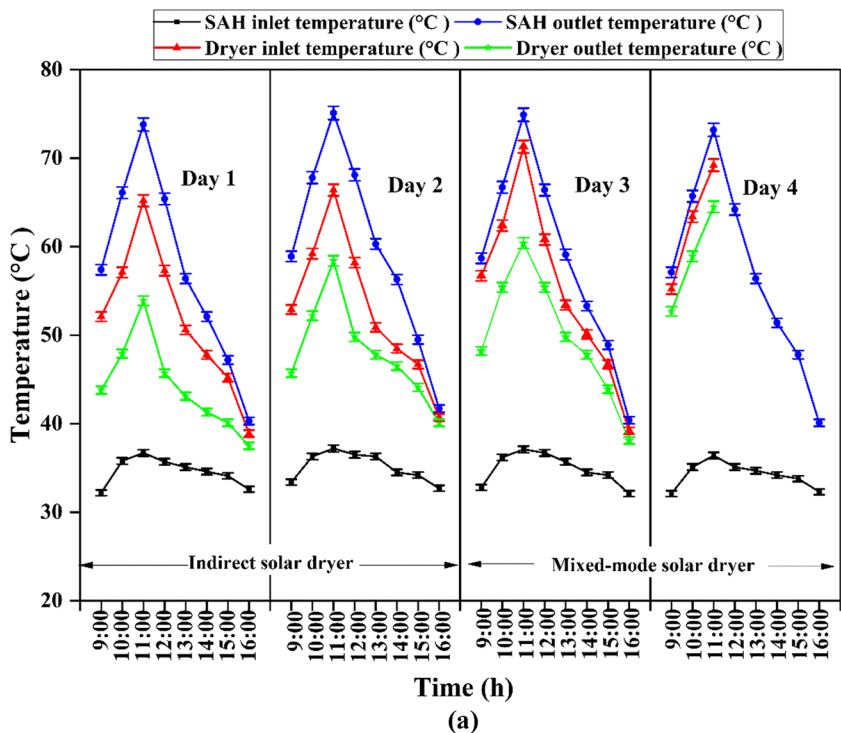
$$AIC = \ln(SSE) - \ln(f) + 2j \tag{19}$$

where *SSE* is the sum of square error, *j* is the number of model and *f* is the no of observations.

Fig. 4 (a) Variations of SAH inlet temperature, SAH outlet temperature, dryer inlet temperature, dryer outlet temperature with time for Exp. I and Exp. II. (b) Variations of relative humidity of the ambient and relative humidity of dryer with time for Exp. I and Exp. II

Economic study

The economic study determines the price-effectiveness of the solar dryer for commercial use with various agricultural products. In this study, life cycle savings (LCS) and payback period methods were employed to study the viability of the solar dryer for drying GP (Lakshmi et al. 2019b). The price of fresh GP per kg of dried GP (*C_{dGP}*) is determined by Eq. (20).



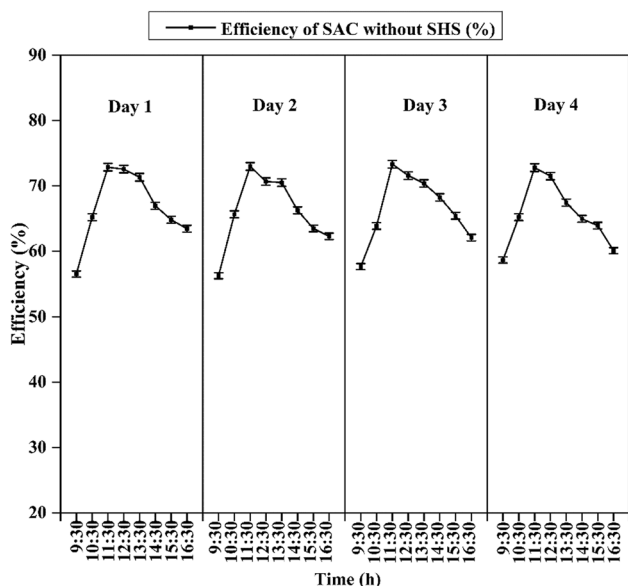


Fig. 5 Variations of energy efficiency of SAH without SHS with time

$$C_{dGP} = C_{fGP} \times \frac{m_{fGP}}{m_{dGP}} \tag{20}$$

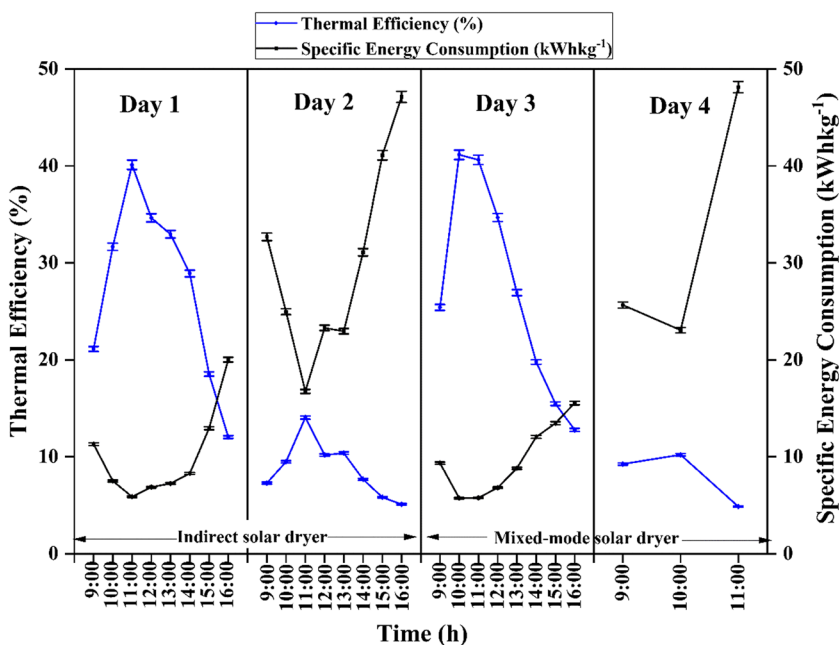
where, C_{fGP} (INR/kg), m_{fGP} (kg) is the price and mass of fresh GP, respectively and m_{dGP} is the mass of dried GP (kg) per batch.

The price needed to dry 1 kg of GP (C_{ds}) is determined by using Eq. (21).

$$C_{ds} = C_{dGP} + C_{sGP} \tag{21}$$

where C_{sGP} is the price of drying per kg of dried GP.

Fig. 6 Variations of thermal efficiency and SEC of the dryer with time for Exp. I and Exp. II



The annualized price (C_{anc}) of the solar dryer for drying the GP is given by

$$C_{anc} = C_{acc} + C_{amc} + C_{rfc} + C_{ec} - S_v \tag{22}$$

where C_{cc} is the annual capital price, C_{amc} is the annualized maintenance price and C_{rfc} is the annual running fuel price. For the solar dryer, the annual running fuel price is zero. C_{ec} is the electricity price, which is again zero as the dc motor runs on a solar panel. S_{av} is the annualized salvage value. C_{amc} is a fixed percentage of C_{acc} (assumed 10% of C_{acc}).

The annualized capital price C_{acc} is given by

$$C_{acc} = C_{cc} \times R_f \tag{23}$$

where C_{cc} is the capital price of the dryer and R_f is capital recovery factor respectively. The capital recovery factor R_f is given by

$$R_f = \frac{d \times (1 + d)^k}{(1 + d)^k - 1} \tag{24}$$

where d is the rate of interest (in %) on the investment and k is the life of the domestic solar dryer.

Salvage fund factor (S_F) is given as

$$S_F = \frac{d}{(1 + d)^k - 1} \tag{25}$$

Annualized salvage value is given as

$$S_a = S \times S_F \tag{26}$$

where S is the salvage value of 10% of the capital price.

Mass of GP dried per year in the solar dryer m_{yGP}

Table 4 Comparative analysis of present dryer with different dryers without storage

Type of Dryer	Type of dryer	Drying time (h)	Efficiency (%)	Product used for Drying
Present Study (Exp. I)	Indirect	31	18.12	GP
Present Study (Exp. II)	Mixed-mode	26	22.37	GP
(Fudholi et al. 2014)	Indirect	33	13	Red chili
(Erick César et al. 2020)	Indirect	26	8.80	Tomato
	Mixed-mode	17	10.66	Tomato

$$m_{yGP} = m_{dGP} \times \frac{t_s}{t_d} \tag{27}$$

t_s is the total days a solar dryer is used (120 days assumed) per year and t_d in days is the drying time per batch.

The price of solar drying (C_{sGP}) for 1 kg of dried GP in the dryer is given by

$$C_{sGP} = \frac{C_{anc}}{m_{yGP}} \tag{28}$$

Savings for GP per kg (S_{kg}) is the difference between the expense of the GP available in the market (C_{mGP}) and the expense needed to dry 1 kg of GP in the dryer (C_{ds}) evaluated using Eq. 29

$$S_{kg} = C_{mGP} - C_{ds} \tag{29}$$

Saving per day (S_d) is calculated by

$$S_d = \frac{S_b}{t_d} = \frac{S_{kg} \times m_{dGP}}{t_d} \tag{30}$$

where S_b is the savings and t_d (in days) is the drying time required in each batch. Yearly savings of drying of GP (S_k) in the (j^{th}) year is calculated using the following equation

$$S_k = S_d \times t_{sun} \times (1 + i)^{j-1} \tag{31}$$

where i is the inflation rate

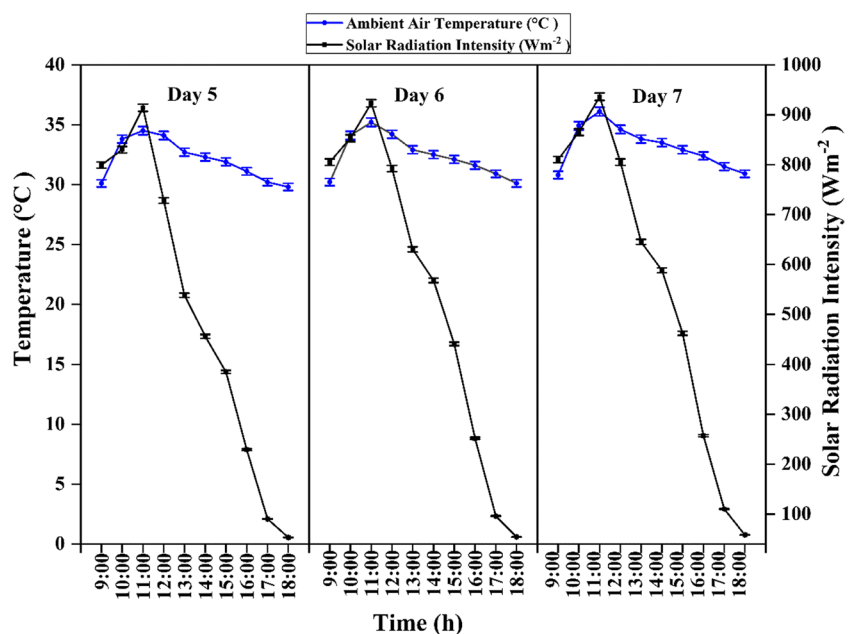
Payback period (P_p) of the developed solar dryer is given (Dutta et al. 2021a)

$$P_p = \frac{\ln \left[1 - \frac{C_{cc}}{S_1} (d - i) \right]}{\ln \left[\frac{1+i}{1+d} \right]} \tag{32}$$

where S_1 is saving for the first year.

The rate of interest and inflation were taken as 10% (Dutta et al. 2021a) and 5.59%, respectively. The maintenance price and salvage value were taken as 10% of the annualized capital price and 10% of the capital price of the dryer, respectively (Dutta et al. 2021a). The life of the dryer has been assumed as 20 years (Singh et al. 2021).

Fig. 7 Variations of solar radiation and ambient temperature with time during Exp. III and Exp. IV



Results and Discussion

The weather conditions were all reported for similar sunny days. The experiments for the indirect solar dryer without SHS (Exp. I) were performed on Day 1 and continued till

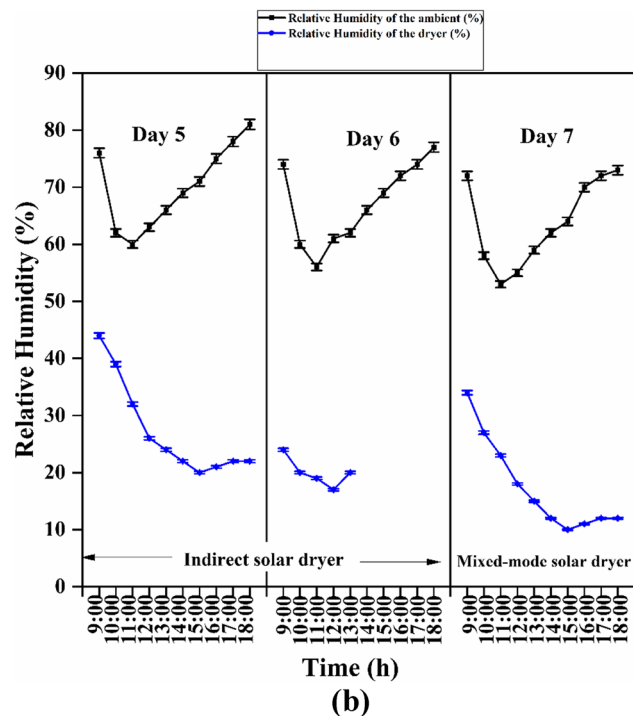
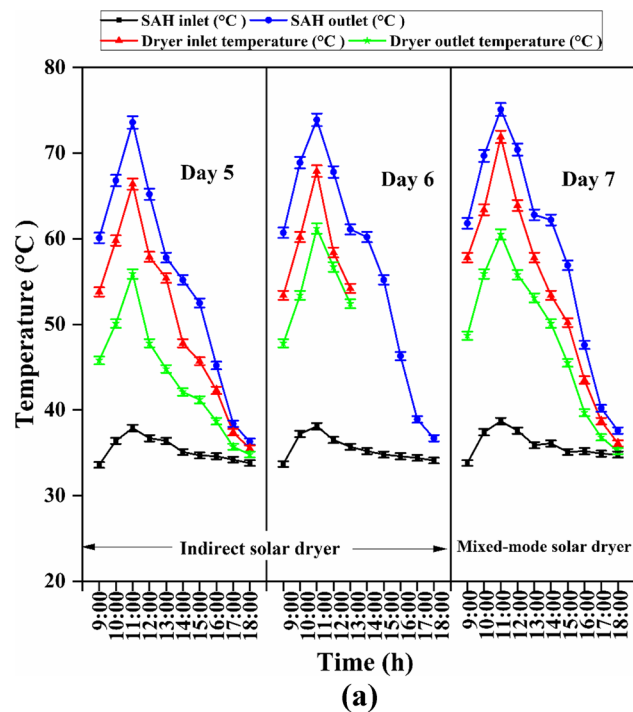


Fig. 8 (a) Variations of SAH inlet temperature, SAH outlet temperature, dryer inlet temperature, dryer outlet temperature with time for Exp. III and Exp. IV. (b) Variations of relative humidity of the ambient and relative humidity of dryer with time for Exp. III and Exp. IV

Day 2. The mixed-mode solar dryer with SHS (Exp. II) was performed on Day 3 and continued till Day 4. In addition, open sun-drying OSD was also carried from Day 1 to Day 3. An indirect solar dryer with SHS (Exp. III) was performed on Day 5 and continued till Day 6, and on Day 7, the experiment for a mixed-mode solar dryer with SHS (Exp. IV) was performed.

Performance study of drying *Garcinia Pedunculata*

The experiments for Exp. I and Exp. II were performed from 9:00 h to 16:00 h and from 9:00 h to 18:00 h for Exp. III and Exp. IV. All four modes in the solar dryer were performed for forced convection. To avoid the reabsorption of moisture, the dried products were kept in airtight containers.

Experiments without SHS

The climatic conditions during solar drying of GP are shown in Fig. 3. The average ambient temperatures for Day 1 and Day 2 varied in the range of 29.3 °C to 34.1 °C and 30.2 °C to 35.4 °C, respectively. The corresponding ranges for Day 3 and Day 4 were 29.8 °C to 34.7 °C and 29.1 °C to 34.1 °C. The solar radiation reached its peak at 11:00 h on each day and subsequently decreased in the afternoon on all four days. The maximum solar radiation on Day 1, Day 2, Day 3, and Day 4 were 902, 920, 918, and 908 W/m², respectively.

The variations of SAH inlet temperature, SAH outlet temperature, dryer inlet temperature, and dryer outlet temperature with time for Exp. I and Exp. II are plotted in Fig. 4(a).

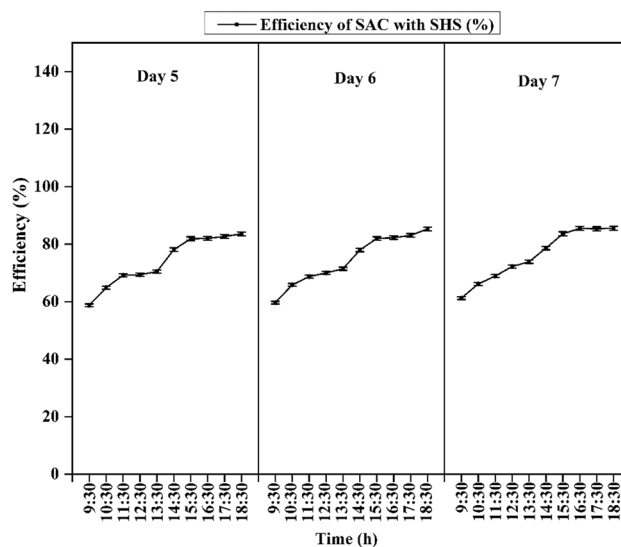
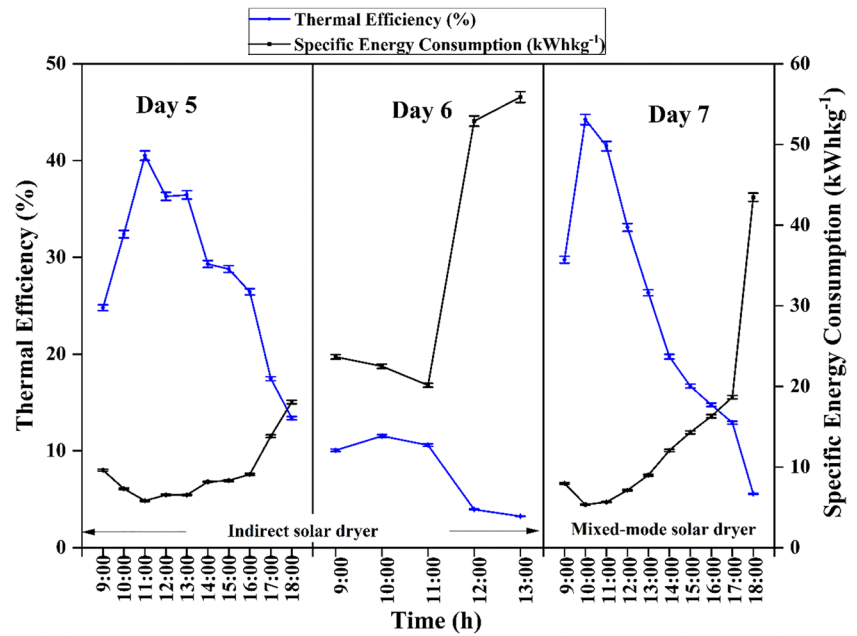


Fig. 9 Variations of energy efficiency of SAH with SHS with time

Fig. 10 Variation of thermal efficiency and SEC of the dryer with time for Exp. III and Exp. IV



The average inlet temperatures of SAH on Day 1, Day 2, Day 3, and Day 4 were observed as 34.6 °C, 35.1 °C, 34.9 °C, and 34.2 °C, respectively. The air mass flow rate was 0.02 kg/s. Furthermore, the average outlet temperatures of SAH were 57.3 °C, 59.7 °C, 58.5 °C, and 56.9 °C, respectively on Day 1, Day 2, Day 3, and Day 4. The solar drying of GP in Exp. I took 31 h or 2 days. The inlet temperature of the dryer varied between 38.9 °C–66.4 °C for Exp. I and 39.2 °C–71.3 °C for Exp. II. The outlet temperature of the dryer varied in the range of 37.5 °C to 58.4 °C for Exp. I and 38.1 °C and 64.5 °C for Exp. II. The time required for drying was 26 h for Exp. II. As expected, the maximum temperature was observed at 11:00 am. Temperatures decreased as the intensity of radiation from the sun decreased subsequently. Additionally, the dryer inlet temperature of mixed-mode (Exp. II) was 4.9 °C more than the indirect mode (Exp. I) at 11:00 am. Moreover, it took around 5 h less in Exp. II than in Exp. I to complete the drying process. This is due to the drying chamber being covered with plywood in indirect mode, that prevented solar radiation from penetrating the food. The OSD of GP required around 53 h to reach the final MC of 12.09% (w.b.).

The relative humidity of the ambient and dryer for Exp. I and Exp. II is plotted in Fig. 4(b). The variations in the relative humidity of the dryer for Exp. I and Exp. II reached its lowest at 17.8% and 12.7%, respectively.

The variations in the thermal efficiency of SAH on Day 1, Day 2, Day 3, and Day 4 are shown in Fig. 5. The SAH efficiency as per Eq. (9) depends upon the mass-flow rate, inlet, and outlet temperatures, SAH area, and solar radiation incident on it. These efficiencies were estimated without the energy storage material. The absorber plate (black coated) was a corrugated aluminium plate. The reasons to use the corrugated SAH in place of others are higher outlet temperature, increased heat transfer, and hence higher thermal efficiency (Raam Dheep and Sreekumar 2020). The average efficiencies were 66.71%, 65.45%, 66.56%, and 65.44%, respectively, on Day 1, Day 2, Day 3, and Day 4. All the efficiencies were maximum at 11:00 h.

The variations of SEC and efficiency for Exp. I and Exp. II were calculated by Eqs. (11) and (12), respectively, and plotted in Fig. 6. The Exp. I was done on Day 1, and it continued till Day 2. On Day 2, as the MC of the material being dried

Table 5 Comparative analysis of present dryer with different dryers with storage

Type of Dryer	Type of dryer	TES	Drying time (h)	Efficiency (%)	Product used for Drying
Present Study (Exp. III)	Indirect	Gravels	28	21.74	GP
Present Study (Exp. IV)	Mixed mode	Gravels	10	24.46	GP
(Vijayan et al. 2016)	Indirect	Pebble	7	19	Bitter Gourd
(Ayyappan et al. 2015)	Greenhouse	Concrete	78	9.5	Copra
		sand	66	11	
		rock-bed	53	11.65	

decreases, the energy utilization to evaporate the remaining moisture also decreases. This means that the dryer needs to utilize less heat energy which results in a decrease in thermal efficiency. The maximum efficiency was calculated as 40.11% with an average of 18.12%. Exp. II was performed on Day 3 and continued till Day 4. Exp. II was performed on Day 3 and continued till Day 4. It is observed that the efficiency on the Day 4 is significantly less than the corresponding values during Exp. II. This is due to the higher moisture removal rate in the mixed-mode on the first day of the Exp. II (Day 3) and lower moisture removal rate on the second day (Day 4) due to the near completion of the drying process. It exhibited the maximum efficiency (41.15%) at 11:00 h with an average of 22.37%. This leads to the shorter time required for drying GP.

The lowest SEC for Exp. I and Exp. II were calculated as 5.87 and 5.73 kWh/kg, respectively. A comparative analysis of the present dryer with different dryers without storage available in the literature is shown in Table 4. It is clear from Table 4 that the present solar dryer's average thermal efficiency is comparable to or better than the other previously studied similar solar dryer.

Experiments with SHS

The ambient conditions for Exp. III and Exp. IV is presented in Fig. 7. The experiments were carried out with SHS material from 9:00 h to 18:00 h. Gravels were used as the SHS material that was placed below the corrugated absorber plate.

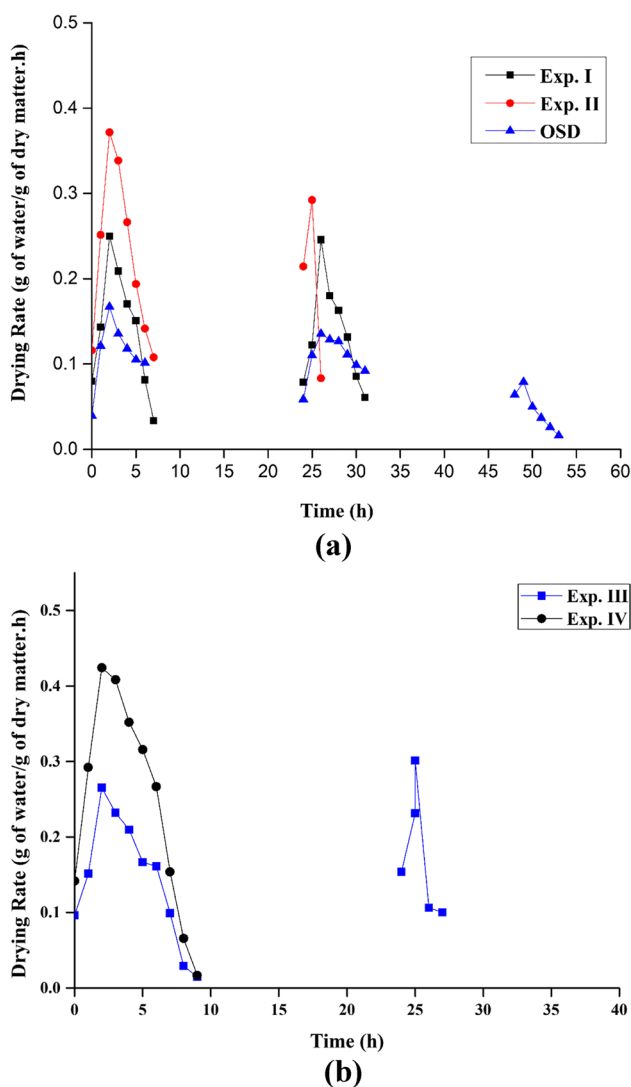


Fig. 11 (a). Variation of drying rate with drying time for Exp. I, Exp. II and OSD. (b) Variation of drying rate with drying time for Exp. III and Exp. IV

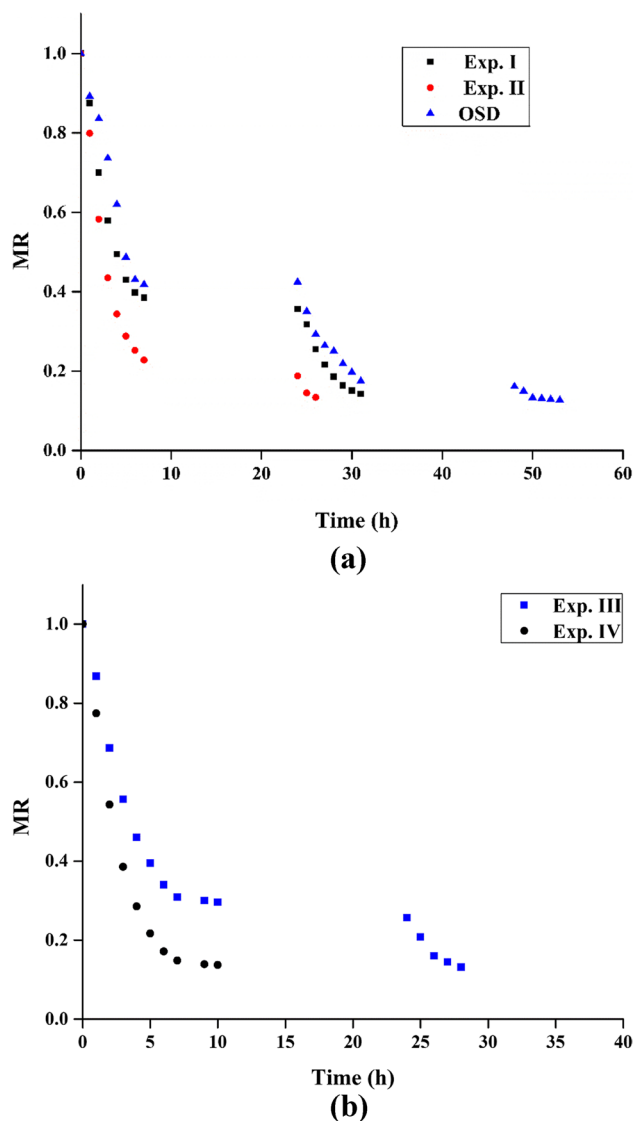


Fig. 12 (a). Variation of MR with drying time for Exp. I, Exp. II and OSD. (b). Variation of MR with drying time for Exp. III and Exp. IV

Table 6 Fitting statistics of thin layer drying model of Exp. I of GP

Model No	Coefficients and constants	R2	χ^2	RMSE	AIC
A	$k = 0.1457$	0.9788	0.0015	0.03772	-88.81
B	$k = 0.1976; n = 0.8462$	0.9902	0.0007	0.02656	-97.59
C	$k = 0.2215; n = 0.6576$	0.9788	0.0015	0.03904	-86.81
D	$k = 0.1386; a = 0.9586$	0.9823	0.0012	0.03563	-89.36
E	$a = 0.7968; b = -0.3073; c = 0.5105; g = 22.59; h = 1.123; k = 0.114$	0.9926	0.00053	0.02731	-93.52
F	$a = 0.8919; k = 0.09977; c = 0.1828$	0.9883	0.0008	0.03017	-93.07
G	$a = 0.7949; k_1 = 0.114; b = 0.4999; k_2 = 1.092$	0.9929	0.00051	0.02449	-100.03
H	$a = 0.2271; k = 0.4966$	0.9917	0.00059	0.02444	-99.93
I	$a = -0.1267; b = 0.004832$	0.9654	0.0024	0.0499	-79.94
J	$a = 0.243; b = 0.2287; k = 0.4835$	0.9917	0.00059	0.02531	-97.98
K	$a = 1.014; b = -0.000272; k = 0.2078; n = 0.825$	0.9904	0.0006	0.02836	-93.92

The maximum solar radiation intensity on Day 5, Day 6, and Day 7 were 914, 923, and 936 W/m² at 11:00 h. The ambient temperatures varied in the range of 29.8 °C to 36.1 °C on Day 5, 30.1 °C to 35.2 °C on Day 6, and 30.8 °C to 36.1 °C on Day 7.

The variations of SAH inlet temperature, SAH outlet temperature, dryer inlet temperature, and dryer outlet temperature with time for Exp. III and Exp. IV are plotted in Fig. 8(a). It was observed that during the initial hours, SAH outlet temperature with SHS material was somewhat lesser than the corresponding temperature without SHS for similar solar radiation intensity. However, during the latter half of the day, the outlet temperature increased in the SAH with SHS material than the one without SHS because of the heat absorbed by the SHS material. It was also witnessed that the temperature of the outlet of SAH with SHS was (2.5–6.7) °C more than the ambient temperature during 17:00–18:00 h. This is because the heat is stored in these SHS materials during the daytime and released when there is not sufficient radiation from the sun. The average inlet temperature of SAH was 35.3 °C, 35.4 °C, and 35.9 °C, respectively on Day

5, Day 6, and Day 7. In addition to this, the range of outlet temperatures of the SAH was 36.3–73.6 °C, 36.7–73.9 °C, and 37.6–75.1 °C, respectively, on Day 5, Day 6, and Day 7. The dryer inlet temperature varied in the range of 35.5–67.9 °C for Exp. III and 36.1–71.9 °C for Exp. IV. The drying time for these Exp. III (indirect with SHS) was 28 h. However, the drying time for Exp. IV (mixed mode with SHS) was 10 h. The dryer outlet temperature varied in the range of 34.8–61.2 °C for Exp. III and 35.2–60.5 °C for Exp. IV. The variations of relative humidity of the ambient and dryer are plotted in Fig. 8(b). The lowest relative humidity of the dryer was recorded at 17.2% and 10.1% for Exp. III and Exp. IV, respectively.

When design, material, availability, and cost are counted upon, solar dryers with SHSs are much simpler. The medium for SHS can be of two types: solids (pebbles, gravels, brick, concrete, etc.) and liquids (water, molten salts, petroleum oils, etc.). The stored energy in SHS is charged and discharged in due course of time (Vengadesan and Senthil 2020; Bhardwaj et al. 2021). The variation of thermal efficiency of

Table 7 Fitting statistics of thin layer drying model of Exp. II of GP

Model No	Coefficients and constants	R2	χ^2	RMSE	AIC
A	$k = 0.2395$	0.9828	0.00153	0.03711	-56.34
B	$k = 0.3469; n = 0.7712$	0.9952	0.00042	0.02058	-65.90
C	$k = 0.6545; n = 0.366$	0.9827	0.00154	0.0393	-54.26
D	$k = 0.2336; a = 0.9785$	0.9829	0.00152	0.03901	-54.39
E	$a = -6.909; b = 0.3508; c = 7.577; g = 0.0993; h = 0.3231; k = 0.3157$	0.9962	0.00034	0.02475	-59.87
F	$a = 0.9052; k = 0.319; c = 0.1067$	0.9954	0.00041	0.02156	-64.12
G	$a = 0.6604; k_1 = 0.715; b = 0.5498; k_2 = 0.1395$	0.9973	0.00024	0.01764	-68.94
H	$a = 0.3296; k = 0.5303$	0.9941	0.00052	0.02299	-63.91
I	$a = -0.206; b = 0.01245$	0.9789	0.00188	0.04339	-52.48
J	$a = 0.8728; b = 0.0618; k = 0.3181$	0.996	0.00036	0.02012	-65.36
K	$a = 1.008; b = 0.009418; k = 0.2796; n = 1.016$	0.9959	0.00036	0.02162	-63.28

Table 8 Fitting statistics of thin layer drying model of OSD of GP

Model No	Coefficients and constants	R2	χ^2	RMSE	AIC
A	$k = 0.1256$	0.9822	0.000557	0.03749	-120.88
B	$k = 0.256; n = 0.4613$	0.9421	0.001817	0.07119	-102.72
C	$k = 0.3327; n = 0.3776$	0.9822	0.000557	0.03841	-126.38
D	$k = 0.1283; a = 1.02$	0.9828	0.000539	0.0378	-127.02
E	$a = -1.239; b = 0.9772; c = 1.259; g = 0.1241; h = 1.034; k = 1.163$	0.9839	0.000505	0.04089	-120.33
F	$a = 0.9879; k = 0.1492; c = 0.05401$	0.9859	0.000442	0.03511	-129.00
G	$a = 0.0001123; k_1 = -0.3112; b = 1.036; k_2 = 0.1351$	0.9889	0.000347	0.03198	-133.81
H	$a = 0.6064; k = 0.1541$	0.9827	0.000543	0.03793	-126.88
I	$a = -0.1044; b = 0.00308$	0.9888	0.000351	0.03051	-131.60
J	$a = 0.5052; b = 0.222; k = 0.3583$	0.9818	0.000518	0.03615	-125.82
K	$a = 0.9792; b = 0.9559; k = 1.147; n = 0.9558$	0.9809	0.000599	0.04321	-120.92

SAH with SHS, calculated with Eq. (9), is shown in Fig. 9. The average energy efficiencies of SAH with SHS were 74.08%, 74.60%, and 76.09%, respectively. The value of the SAH with SHS was consistently found to be higher than the SAH without SHS when comparing the outlet air temperatures of the SAHs. As a result, it was observed that the SAH without SHS was less efficient than SAH with SHS at the same mass flow rate. During the former half of the day, the efficiencies of both the cases (without and with SHS) were similar but after 12:30 h the efficiency of the SAH without storage decreased whereas the one with storage increased. The efficiency of SAH with SHS has sharply increased as a result of energy storage, which captured excess energy in the morning and discharged it in the evening.

The SEC and thermal efficiency for Exp. III and Exp. IV calculated using Eqs. (11) and (12) are plotted in Fig. 10. The maximum efficiencies for Exp. III and Exp. IV were calculated as 40.51% and 44.25%, respectively. Exp. III and Exp. IV had average efficiencies of 21.74% and 24.46%, respectively, and took 28 h and 10 h to dry,

respectively. In comparison to similar studies, (Vijayan et al. 2016) developed a mathematical model to explain an active solar collector with SHS material (pebble) for drying of bitter gourd. The drying time was 7 h with a drying efficiency of 19%. In another study, (Ayyappan et al. 2015) compared different SHS materials, including concrete, sand, and rock bed, to investigate their thermal performance. The drying times for Copra in a greenhouse dryer using concrete, sand, and rock bed were 78 h, 66 h, and 53 h, respectively, with dryer efficiencies of 9.5%, 11%, and 11.65%, respectively. The developed dryer in the present study showed improved results. The summary is given in Table 5. Comparing Exp. I and Exp. III, the incorporation of SHS material increased the average efficiency from 18.12% to 21.74%. Similarly, the average efficiency increased to 24.46% in Exp. IV from 22.37% in Exp. II. The lowest SEC for Exp. III and Exp. IV were 5.81 and 5.33 kWh/kg, respectively. Considering all four experiments in the solar dryer, Exp. I had the minimum and Exp. IV had the maximum efficiency. Along with the

Table 9 Fitting statistics of thin layer drying model of Exp. III of GP

Model No	Coefficients and constants	R2	χ^2	RMSE	AIC
A	$k = 0.1623$	0.9748	0.00188	0.04182	-79.57
B	$k = 0.2193; n = 0.84$	0.9871	0.00096	0.03113	-86.22
C	$k = 0.4354; n = 0.3727$	0.9748	0.00188	0.0434	-77.57
D	$k = 0.1554; a = 0.9637$	0.9774	0.00169	0.04111	-78.98
E	$a = -12.03; b = 13.11; c = -0.1308; g = 0.1777; h = 0.638; k = 0.1782$	0.965	0.00262	0.06156	-65.26
F	$a = 0.8876; k = 0.1214; c = 0.2224$	0.9891	0.00081	0.02969	-86.48
G	$a = 0.5392; k_1 = 0.09363; b = 0.4829; k_2 = 0.3671$	0.9912	0.00066	0.02795	-89.18
H	$a = 0.2712; k = 0.4486$	0.9894	0.00079	0.02817	-88.80
I	$a = -0.1413; b = 0.005977$	0.962	0.00284	0.05336	-72.20
J	$a = 0.4875; b = 0.2732; k = 0.3338$	0.9906	0.00070	0.02769	-88.30
K	$a = 1.017; b = 0.004103; k = 0.2193; n = 0.9017$	0.9887	0.00084	0.03156	-84.03

high moisture removal rate in the mixed-mode solar dryer, the SHS material inside the SAH in Exp. IV led to higher efficiency and lower SEC.

Drying kinetics

This section presents the drying kinetics of *Garcinia Pedunculata* for different experiments from an initial MC of 87.99% (w.b.) to a final MC of 12.09% (w.b.). The total drying time was 31, 26, 53, 28, and 10 h for Exp. I, Exp. II, OSD, Exp. III and Exp. IV, respectively. It can be noted that the drying time was the least in Exp. IV and most in OSD. The temperature inside the mixed-mode was sufficiently higher than the indirect-mode. This is because of the experiments in Exp. II and Exp. IV added supplementary solar radiation using the cabinet's transparent cover. Additionally, SHS material inside the SAH increased the inlet temperature of the dryer during the low radiation period. The variation of MR and drying rate with drying time are discussed here. Eleven models available in the literature were evaluated for the selection of suitable drying models for the four sets of experiments in the solar dryer and OSD.

Figure 11(a) gives the drying rate versus time graph for Exp. I, Exp. II and OSD. The drying rate in OSD was observed slower than Exp. I and Exp. II. Figure 11(b) shows the variation of drying rate with drying time for Exp. III and Exp. IV. Comparing all the experiments, the drying rate was fastest in Exp. IV and least in OSD. Moreover, the maximum drying rate was observed at 11:00 h that was during the peak solar radiation hour for all experiments. At the latter part of the day, the drying rate decreased for all the experiments due to the slower removal of moisture from GP slices.

Figure 12(a) exhibits the variation of MR as a function of drying time for Exp. I, Exp. II and OSD. The non-linear regression evaluation of MR versus drying time is necessary

to find the best-fitted drying model from the eleven models in Table 3. Figure 12(b) give the MR versus drying time for Exp. III and Exp. IV. Tables 6, 7, and 8 summarize the regression analysis for Exp. I, Exp. II and OSD, respectively. Similarly, Tables 9 and 10 gives the regression analysis for Exp. III and Exp. IV, respectively. All the eleven models were evaluated to check the best-suited model following the highest value of R^2 and lowest values of χ^2 , $RMSE$ and AIC . Fulfilling the mentioned conditions, the best-fit model was Two-Term for Exp. I, Exp. II, OSD and Exp. III. Midilli and Kucuk model was observed to be the best-fitted model for Exp. IV. The values were $R^2 = 0.9929, \chi^2 = 0.0005139, RMSE = 0.02449$ and $AIC = -100.03$ for Exp. I; $R^2 = 0.9973, \chi^2 = 0.00024, RMSE = 0.01764$ and $AIC = -68.94$ for Exp. II; $R^2 = 0.9889, \chi^2 = 0.00347, RMSE = 0.03198$ and $AIC = -133.81$ for OSD; $R^2 = 0.9912, \chi^2 = 0.00066, RMSE = 0.02795,$ and $AIC = -89.18$ for Exp. III and $R^2 = 0.9998, \chi^2 = 0.000020, RMSE = 0.005261$ and $AIC = -78.26$ for Exp. IV.

The Two-Term model for Exp. I is given as:

$$MR = 0.7949exp(-0.114t) + 0.4999exp(-1.092t) \tag{33}$$

The Two-Term model for Exp. II is given as:

$$MR = 0.6604exp(-0.715t) + 0.5498exp(-0.1395t) \tag{34}$$

The Two-Term model for OSD is given as:

$$MR = 0.0001exp(0.3112t) + 1.036exp(-0.1351t) \tag{35}$$

The Two-Term model for Exp. III is given as:

$$MR = 0.5392exp(-0.09363 t) + 0.4829exp(-0.3671t) \tag{36}$$

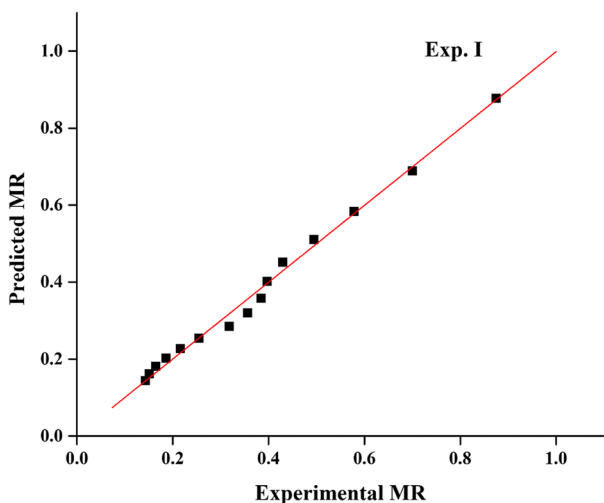
The Midilli and Kucuk model for Exp. IV is given as:

$$MR = 1.002exp(-0.2851t^{1.185}) + 0.01305 t \tag{37}$$

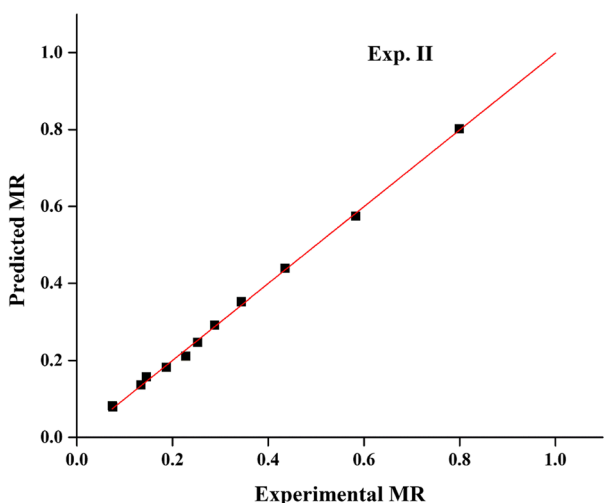
Figure 13(a), (b) and (c) show the comparison of experimental and predicted MR for Exp. I, Exp. II and OSD

Table 10 Fitting statistics of thin layer drying model of Exp. IV of GP

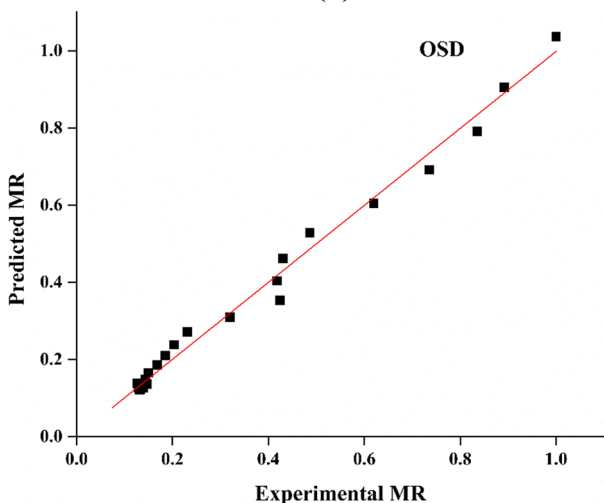
Model No	Coefficients and constants	R2	χ^2	RMSE	AIC
A	$k = 0.2913$	0.9888	0.00114	0.03186	-52.20
B	$k = 0.3182; n = 0.934$	0.9902	0.001	0.03168	-51.23
C	$k = 0.5986; n = 0.4865$	0.9888	0.00114	0.03379	-50.20
D	$k = 0.2906; a = 0.9978$	0.9888	0.00114	0.03378	-50.21
E	$a = 0.2663; b = -3.682; c = 4.41; g = 0.242; h = 0.2448; k = 0.4043$	0.99	0.00102	0.04528	-43.06
F	$a = 0.9432; k = 0.3634; c = 0.07876$	0.9958	0.00042	0.02214	-56.04
G	$a = 0.00118; k_1 = -0.4715; b = 1.015; k_2 = 0.316$	0.998	0.00020	0.01656	-59.92
H	$a = 0.4455; k = 0.4677$	0.9922	0.000791	0.02813	-53.13
I	$a = -0.2441; b = 0.0169$	0.993	0.00070	0.02664	-54.01
J	$a = 0.9993; b = -1.708; k = 0.3085$	0.9976	0.00024	0.01679	-60.46
K	$a = 1.002; b = 0.01305; k = 0.2851; n = 1.185$	0.9998	0.00002	0.00526	-78.26



(a)



(b)

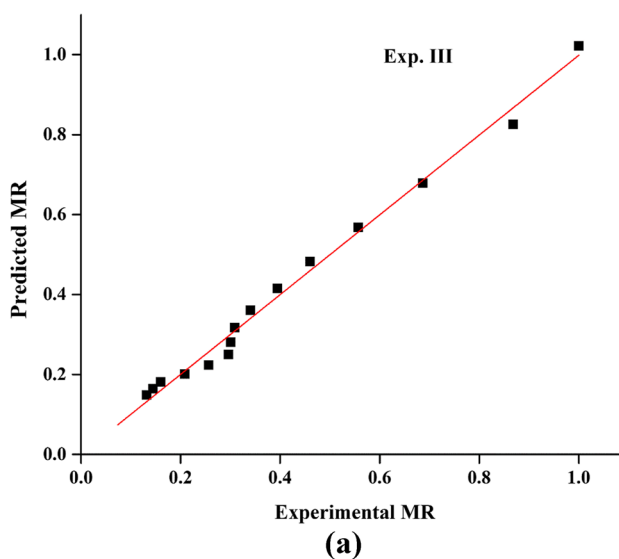


(c)

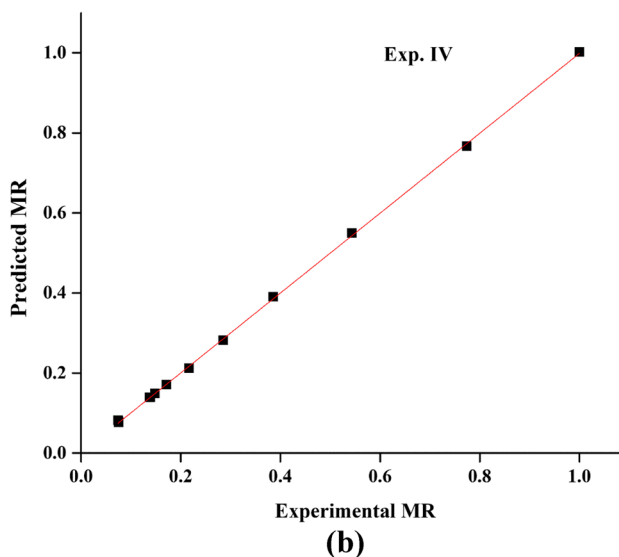
Fig. 13 (a). Comparison of predicted and experimental MR for Exp. I. (b). Comparison of predicted and experimental MR for Exp. II. (c). Comparison of predicted and experimental MR for OSD

using the Two-Term model. In the same way, Fig. 14(a) and (b) show the comparison of experimental and predicted MR for Exp. III and Exp. IV using the Two-Term model and Midilli and Kucuk model, respectively. The straight line for Exp. I and Exp. II validates the model’s suitability, as can be seen in these figures.

A comparison of different performance parameters of all four and OSD experiments is shown in Table 11. The photos of fresh and dried GP from the experiments are shown in Fig. 15(a), (b), (c), (d), (e) and (f). The final products Fragrance, colour are better for Exp. IV.



(a)



(b)

Fig. 14 (a). Comparison of predicted and experimental MR for Exp. III. (b). Comparison of predicted and experimental MR for Exp. IV

Table 11 Performance parameters of the solar dryer for Exp. I, Exp. II, Exp. III and Exp. IV

Parameter	Exp. I	Exp. II	Exp. III	Exp. IV	OSD
Maximum inlet temperature of the dryer (°C)	66.4	71.3	67.9	71.9	-
Drying time (h)	31 h	26 h	28 h	10 h	53
Average Dryer efficiency (%)	18.12	22.37	21.74	24.46	-
Lowest SEC (kWh/kg)	5.87	5.73	5.81	5.33	-
Initial MC	87.99% (w.b.)	87.99% (w.b.)	87.99% (w.b.)	87.99% (w.b.)	87.99% (w.b.)
Final MC	12.09% (w.b.)	12.09% (w.b.)	12.09% (w.b.)	12.09% (w.b.)	12.09% (w.b.)
Best Drying Model	Two-Term	Two-Term	Two-Term	Midilli and Kucuk	Two-Term

Economic study

The growth of the economy of the product depends on how it is processed. Currently, the solar dryer prices were 25000 INR, 27000 INR, 26000 INR, and 28000 INR for Exp. I, Exp. II, Exp. III and Exp. IV, respectively. The price of gravel has been added for Exp. III and Exp. IV. The inflation rate has been set at 5.20%, and the rate of interest has been set at 10%. The expected lifespan of the dryer is 20 years. The life cycle savings have been calculated using the life cycle price keeping in mind the long-term economic benefits of the solar dryer. Additionally,

the payback period, a key indicator of economic feasibility in any system, has been established. Table 12 provides an estimate of the price of the solar dryer with and without storage. The savings for drying GP using solar energy have been calculated in comparison to branded goods that are readily available on the open market. When comparing the price of the solar-dried product with the price of commercially labeled GP, the price of additional post-harvest processes, such as washing and packing, has also been added. GP is sold for 900 INR per kg in the Indian market. Savings for the base year were determined to be 148 INR, 249 INR, 166 INR, and 426 INR per day for Exp. I, Exp. II, Exp. III and Exp. IV, respectively.

Fig. 15 (a). Fresh GP. (b). Dried GP in Exp. I. 15 (c). Dried GP in Exp. II. (d). Dried GP in Exp. III. (e). Dried GP in Exp. IV. (f). Dried GP in OSD

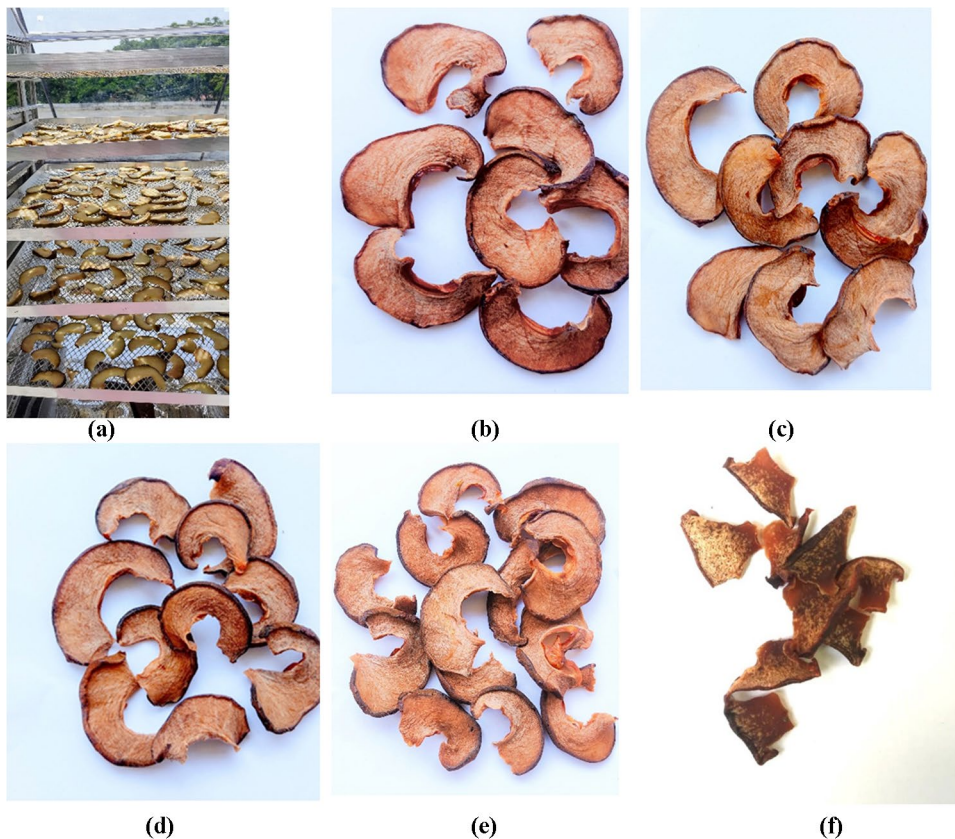


Table 12 Economic study of Exp. I, Exp. II, Exp. III and Exp. IV for GP

Items	Exp. I	Exp. II	Exp. III	Exp. IV
Price of the development of the dryer in INR	25000	27000	26000	28000
Predicted lifespan of the dryer	20 years	20 years	20 years	20 years
Price of fresh GP in INR	70 per kg	70 per kg	70 per kg	70 per kg
Interest rate	10%	10%	10%	10%
Inflation rate	5.20%	5.2%	5.20%	5.2%
Annualized capital price in INR	2936	3171	3054	3289
Maintenance price in INR	294	317	305	329
Salvage value in INR	2500	2700	2600	2800
Annual salvage value in INR	44	47	45	49
Annualized price in INR	3186	3441	3314	3569
Price of dried GP available in market in INR	900 per kg	900 per kg	900 per kg	900 per kg
Savings in INR	148	249	166	426
First-year annual savings in INR	17810	29900	19932	51151
Payback period (1 US\$ = 74.57 INR)	1.6 years	0.9 year	1.4 years	0.59 year

The payback period of the developed dryer, estimated using was 1.6 years, 0.9 year, 1.4 years, and 0.59 year for Exp. I, Exp. II, Exp. III and Exp. IV, respectively. This was estimated for 120 days per year. This amount is considerably lower than the dryer's useful life (normally 20 years). This payback period only applies to drying one product. But different seasonal vegetables and fruits are nearly always dried throughout the year. Consequently, the value of the payback period will decrease. As a result, the payback period for this dryer is quite low compared to its life (20 years).

Conclusions

Performance and drying kinetics analysis of drying of *Garcinia pedunculata* (GP) in an active indirect and mixed-mode solar dryer with and without SHS were studied and compared. For the studies, the work was divided into four sets of experiments with OSD: indirect solar drying without SHS (Exp. I), mixed-mode solar drying without SHS (Exp. II), an indirect solar drying with SHS (Exp. III), and mixed-mode solar drying with SHS (Exp. IV). The following conclusions were inferred from the experiments:

- During 17:00–18:00 h, the output temperature of SAH with SHS was (2.5–6.7) °C higher than the ambient temperature (Exp. IV). This is because the heat was stored in these SHS materials throughout the day and released when the sun's light is insufficient.
- The maximum efficiencies of SAH without the SHS were 72.86%, 72.97%, 73.34%, and 71.79%, respectively on Day 1, Day 2, Day 3, and Day 4, whereas with

SHS were 83.56%, 85.29%, and 85.52%, respectively on Day 5, Day 6 and Day 7.

- The average efficiencies of the dryer for Exp. I, Exp. II, Exp. III and Exp. IV were calculated as 18.12%, 22.37%, 21.74% and 24.46%, respectively. If all the four experiments were taken into consideration, it could be observed that, Exp. I had the least efficiency and Exp. IV had the most. This is due to the high moisture removal rate in a mixed-mode solar dryer and the addition of SHS material inside the SAH in Exp. IV. The lowest SEC for Exp. I, Exp. II, Exp. III and Exp. IV were calculated as 5.87, 5.73, 5.81 and 5.33 kWh/kg, respectively.
- In all four sets of experiments along with OSD, the MC of GP was reduced to 12.09% (w.b.) from 87.99% (w.b.). For Exp. I, Exp. II, OSD, Exp. III, and Exp. IV, the overall drying times were 31, 26, 53, 28, and 10 h, respectively. Eleven models were evaluated to select suitable drying models; the Two-Term model was the best-fitted model for Exp. I, Exp. II, OSD, and Exp. III. For Exp. IV, the Midilli and Kucuk model was found to be the best fit.
- The lower values of SEC and higher values of SAH efficiency and dryer efficiency clearly demonstrated higher performance in mixed mode solar dryer with sensible heat storage (Exp. IV).
- The construction of the dryer for Exp. I, Exp. II, Exp. III and Exp. IV was around 25,000, 27,000, 26,000, and 28,000 INR, respectively for 120 usage days in a year. The payback period, a direct economic measure, is particularly attractive. The calculated economic payback periods for IN-WOS, MM-WOS, IN-WS, and MM-WS, respectively, are 1.6 years, 0.9 years, 1.4 years, and 0.59 years.

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Author contribution Pooja Dutta: Methodology, Formal analysis, Investigation, Writing- Original draft preparation, Visualization, Data curation. Partha Pratim Dutta: Conceptualization, Supervision, Formal analysis, Writing- Reviewing and Editing. Paragmoni Kalita: Supervision, Writing- Reviewing and Editing.

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Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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