Drying kinetics and economic analysis of bitter gourd flakes drying inside hybrid greenhouse dryer

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Abstract
In this study, a heat storage–based hybrid greenhouse dryer has been developed and analysed for drying bitter gourd flakes under the climatic condition of Ranchi, India. Proposed heat storage–based hybrid greenhouse dryer consists of a solar air heater with a 2.12-m² area, greenhouse dryer and DC fan to induce and force the air. The significant objective of the present study is to analyse the drying efficiency, drying kinetics, property analysis, economic analysis, embodied energy and CO2 mitigation of the hybrid greenhouse dryer for drying of bitter gourd flakes. An experiment was performed simultaneously on proposed system and open sun drying for the proper comparative analysis. Moisture contents reduced from 88.14 to 10.14% in 6 h in proposed dryer and 88.14 to 11.01% in 15 h for open system. Thus, significant drying time is reduced in proposed system by 8 h as compared to open system. Environmental impact analysis shows that the energy payback time was found to be 0.4907 years only. Cost of the proposed system dryer is 22664.30 INR. The total embodied energy is found 1591.07 kWh and earned carbon credit ranges from 16844.76 to 67379.05 INR, while CO2 mitigation was 46.28 tonnes for 35 years of expected lifetime. Seven standard mathematical models for drying of bitter gourd flakes were studied. Ahmad and Prakash model was found to be the best as compared to other models. The metal contents of dried bitter gourd flakes were also examined. Bitter gourd dried in proposed dryers possesses superior metal content as compared to open systems. Impact analysis demonstrates that the hybrid greenhouse dryer is more suitable for reducing post-harvest loss with environmental sustainability.

Keywords Bitter gourd flakes · Hybrid greenhouse dryer · CO2 mitigation · Drying kinetics · Thermal storage

Introduction
Bitter gourd is an essential tropical crop that comes from the Cucurbitaceous family. It is mainly found in countries like China, India, Thailand, Malaysia and Japan during the rainy season. Bitter gourd is famous for its high nutrient value and a good source of iron and phosphorous. Bitter gourd consists of high moisture content, i.e. 88–93%, leading to rapid microbial spoilage and biochemical changes (Chauhan et al. 2018). Therefore, various food preservation methods are used to preserve it, like conventional drying, canning and freezing. However, all these techniques are energy-intensive and costly for small farmers. Open sun drying is a traditional method for drying bitter gourd for a long time, especially in rural areas. Still, unexpected rain and foreign particle contamination make it unsafe and unhygienic (Abubakar et al. 2018a). These issues can be resolved by applying a controlled mode of solar-drying. Solar dryer is an example of the controlled mode of solar-drying. The significant difficulties faced by the solar dryer are low drying efficiency and dependency on ambient parameters. Hence, the thermal storage concept is crucial for minimising the fluctuation of ambient parameters and increasing the drying efficiency by enhancing drying time (Abubakar et al. 2019).
Greenhouse dryer is a type of direct solar dryer. It helps in drying the crop in a larger quantity. Greenhouse dryer is an appropriate dryer for low- and medium-temperature thermal drying. Many researches have been carried out on the development of greenhouse dryers and performance enhancement. To stop heat loss from the north wall, many researchers proposed the idea to which losses can be minimised from the north wall greenhouse (Abubakar et al. 2018b). The main disadvantage of greenhouse dryers is that crops cannot be dried in off-sunshine hours (Prakash et al. 2016). To minimise this issue, the greenhouse dryer can be integrated with heat storage systems (Čiplienė et al. 2015; Kant et al. 2016). In order to improve the efficiency of greenhouse dryer, it can be coupled with solar air heater to make a hybrid system. Additional heat storage materials help to provide constant heat throughout the drying process, particularly in off-sunshine hours. A hybrid solar dryer system integrated with thermal energy storage (rock bed) was tested to dry Guduchi, ginger and turmeric (Prasad and Vijay 2005). Drying analysis was done on open sun drying, solar dryer and solar dryer with biomass. Drying efficiency was found to be highest by the author in a hybrid dryer in comparison to open sun drying and solar dryer.

Thermal performance of hybrid greenhouse dryer operating in active mode integrated with a heat exchanger was investigated to dry ginger, bitter gourd and tomatoes (Singh and Gaur 2021a). Environment suitability and economic viability had also been evaluated for the dryer. Drying time was reduced by 34.09%, 61.90% and 47.36% compared to traditional greenhouse dryer for drying crops like ginger, bitter gourd and tomatoes, while the EPBT was found to be 2.87, 1.79 and 0.69 years less than the traditional greenhouse dryer for bottle gourd, ginger and tomatoes, respectively. Heat transfer analysis of a hybrid greenhouse dryer operating in active mode with and without evacuated tube collector (ETC) has been evaluated to dry the bottle gourd, ginger and tomato (Singh and Gaur 2021b). The convective heat transfer coefficients with ETC were 305.4%, 3.8% and 153% higher than the hybrid greenhouse dryer without ETC. However, the drying time for all three crops with ETC are 6, 12 and 9 h, which is less than the drying time without ETC. Overall efficiency of the dryer with and without ETC ranges from 14.22 to 27.99% and 9.63 to 24.88%, respectively. Hybrid solar greenhouse dryer with heat exchanger and biomass unit have been designed to analyse drying rate of banana slices (Kilburi et al. 2020). The temperature difference between inside and outside was 13.21 ± 6.21 °C for a hybrid solar greenhouse dryer. However, the mean drying rate was found as 0.23 ± 0.06 g/gdm/h. The payback period of the hybrid solar greenhouse dryer is <1 year from the average life of the dryer, i.e., 4 years.

To enhance the drying time and thermal performance in off sunshine hour, latent heat storage material/phase change material (PCM) can be used in solar drying system (Bhardwaj et al. 2020). PCM is a heat storage material that can convert from solid to liquid after accumulating energy in sunshine hour while it releases heat in off-sunshine hour (Bhardwaj et al. 2021). It has high specific heat, thermal conductivity and non-toxicity properties compared to sensible heat storage materials (Sarbu and Sebarchievici 2018). Indirect solar dryer operating in active mode integrated with thermal energy storage (TES) material (wax-based) was evolved by Shalaby and Bek (2014). Experimental analysis was done for drying of two herbs, i.e. *O. nerifolia* and *O. basilicum*. In this developed system, the heat was supplied to drying chamber at the off-sunshine hour with the help of thermal storage material. Hence, final moisture content was achieved in 18 h and 12 h for drying of *T. neriifolia* and *O. basilicum*. An indirect solar dryer operating under passive mode integrated with multiple solar air heaters was developed for drying of mint. Drying efficiency was reported as 28.2% based on total evaporation of water content and energy received on the area of the collector (Jain and Tewari 2015). Experiment was performed in a passive greenhouse dryer in different floor conditions by Ahmad and Prakash. Different floor condition is developed based on the different types of sensible thermal storage material (gravel, concrete and black-painted gravel). Drying efficiency of the passive greenhouse dryer with black-painted gravel is highest for drying tomato flakes as compared to other sensible thermal energy storage materials (Ahmad and Prakash 2020; Ahmad and Prakash 2021).

From the intense literature survey, it is found that very little research happens in the field of solar dryer coupled with thermal storage concept to dry the agricultural produce (Khanlari et al. 2020). However, there is no research published on drying bitter gourd flakes using mixed-type thermal storage–based hybrid greenhouse dryers.

Hence, drying experimentation (bitter gourd flakes) is being conducted in two modes: hybrid greenhouse dryer under mixed thermal storage and open sun drying. Drying performance (drying efficiency, moisture ratio, moisture diffusivity, moisture content), drying kinetics, energy analysis (embodied energy, carbon credit, carbon emission, energy payback period) and payback period by the cost of the proposed dryer are being evaluated. Further, quality and valuable metallic properties of the bitter gourd flakes dried in the proposed dryer and open sun drying are compared with fresh samples.

**Materials and methods**

**Experimental setup**

In the proposed hybrid greenhouse dryer, greenhouse dryer was coupled with a single-pass solar air heater (SAH). The
wall of the dryer was covered with a polycarbonate sheet of thickness 3 mm. Dimensions of the greenhouse dryer were taken as per the standard dimension, i.e. 1.5 m×1 m×0.5 m. In order to achieve maximum solar radiation, the roof of the dryer and SAH was tilted at a latitude angle of Ranchi, India, i.e. 23.34°N. Two 12V DC fan of variable speed powered by 40W solar panel was placed to ventilate the humid air out of the greenhouse dryer and to induce preheated air from SAH to pass inside the dryer. North wall of the greenhouse dryer was insulated with a combination of reflective mirror and thermocol. Mirror reflects the outgoing radiation from the north wall to inside drying space of the dryer. Thermocol reduces the heat transfer loss from the mirror to the surrounding. Mixed-type thermal heat storage material, i.e. combination of latent and sensible heat storage, was applied at the floor of the dryer. Paraffin wax of 35 kg was used as latent heat storage material, while black-painted gravel of 29 kg was used as a sensible heat storage material. Paraffin wax was kept within the leak proof aluminium jacket at the ground of the greenhouse dryer covered with black-painted gravel to provide proper thermal storage. The detailed thermo-specification of both thermal storage materials (TSM) is shown in Table 1. Initially, black-painted gravel gets heated then it leads to charge the paraffin wax. Thermal storage material (TSM) gets a charge from sunrise to noon when solar intensity increases continuously; as the solar intensity decreases, discharging process gets started. Discharging process will continue up to a few post-sunset hours. The charging period of PCM was between 5:45 AM and 5:35 PM, and solar radiation was considered zero after 5:35 PM while the discharging period was from 5:35 PM to 5:45 AM the next morning. Heat release from TSM helps to maintain constant drying process during low solar intensity.

Solar air heater (SAH) was used to provide preheated air inside drying chamber. SAH was made up of a wooden frame (5 cm thick) and has a dimension of 2.04 m×1.04 m×0.5 m. For the coupling of SAH with a greenhouse dryer, a well-insulated duct of diameter 0.5 m made of galvanised iron was used. Polyurethane foam was used as insulating material to minimise heat loss from connecting duct to surrounding. A DC fan was placed at the outlet of the SAH to provide pre-heated air from the SAH to the drying chamber through duct. A black-painted galvanised iron sheet is used as an absorber plate in a SAH which helps in achieving optical characteristics like reflection, absorption and transmission. As the heat absorbed by the absorber gets transferred to the air by convection process, DC fan helps to blow the hot air from the SAH to greenhouse dryer. Top surface of SAH was covered with a transparent glass of thickness 3 mm. Short-wave solar radiation gets transferred by the glass. Short-wave radiation gets converted into long-wave radiation with the help of absorber plate. Short-wave radiation heats the absorber plate and long-wave radiation is emitted by the absorber plate. Incoming air with higher density gets heated up due to absorber plate and accumulated inside heat. Heated air is ventilated through outlet vent and transferred to the greenhouse dryer through connecting duct. Structure of solar air heater was supported by an L-shaped mild steel angle. Exposed part of the structure was painted to protect it from adverse environmental effects. Schematic diagram with proper dimension and pictorial view of the experimental setup are presented in Fig. 1.

Sample preparation

Authors aimed to evaluate the performance of the proposed system in load conditions for drying of bitter gourd flakes in hybrid mode and open mode. Experiment was conducted for two consecutive days, i.e. 11–13 May 2021, from 10 AM to 5 PM in BIT Mesra, Ranchi, Jharkhand, India, having a longitude 85.43° E and latitude 23.41° N. Fresh bitter gourds of 4 kg purchased from the local market of Ranchi were washed and dried with cotton clothes. These bitter gourds were sliced into 1–2-mm-thick flakes and taken for experimentation (Fig. 2).

Instrument

Suitable instruments were used to observe the crucial parameters on an hourly basis like ambient temperature, relative humidity, global radiation, wind velocity, mass of crops, crop temperature, outlet temperature and room temperature. Details of the instruments are shown in Table 2.

Uncertainty analysis

Experimental errors come from the environmental conditions, selection of the instruments and the measured value. This analysis is very appropriate to estimate the error between the estimated and observed parameters. Uncertainty analysis for the dependent parameters can be evaluated by Eq. 1 (Ahmad and Prakash 2020).

Table 1 Thermo-physical properties of paraffin wax (RT35)

| Property                                | Value             |
|-----------------------------------------|-------------------|
| Melting temperature of paraffin wax     | 35°C              |
| Kinematic viscosity (m²/s)              | 3.3×10⁻⁶          |
| Density (Kg/m³)                         | 880/760 (liquid/solid) |
| Thermal Conductivity                    | 25 W/m·K          |
| Specific heat capacity (KJ/Kg·K)        | 1.8/2.4 (liquid/solid) |
| Latent heat (KJ/Kg)                     | 157               |
Fig. 1  Schematic diagram of hybrid greenhouse dryer

Fig. 2  Experimental setup of hybrid greenhouse dryer

Table 2  Instrument used in experimentation

| S. no. | Instrument                  | Objective                                                      | Least count   |
|--------|-----------------------------|----------------------------------------------------------------|---------------|
| 1.     | Solar power metre           | Measure radiation                                              | 0.1 W/m²      |
| 2.     | Infrared thermometer        | Measure ground and crop temperature                             | 0.1°C         |
| 3.     | Digital anemometer          | Measure wind flow and relative humidity                         | 0.01 m/s and 0.1% |
| 4.     | Digital weighing machine    | Measure weight                                                  | 0.5 g         |
\[ \Delta p = \sqrt{\left( \frac{\partial p}{\partial k_1} \right)^2 + \left( \frac{\partial p}{\partial k_2} \right)^2 + \ldots + \left( \frac{\partial p}{\partial k_n} \right)^2} \]  

(1)

where \( p \) is the dependent parameters and \( k_1, k_2, \ldots, k_n \) are the measured value.

The total uncertainty of the experiment was evaluated as ±0.68%, which is under the permissible range. The detailed uncertainty of the experiment is shown in Table 3

### Numerical analysis

#### Moisture ratio \( (M_{\text{ratio}}) \)

Moisture ratio can be defined as the ratio of the hourly moisture content to the initial moisture content of the crop. Initial moisture content \( (M_{\text{ini}}) \) for bitter gourd flakes on the wet basis (w.b.) can be calculated as per Eq. 2

\[ M_{\text{ini}} = \frac{W_{\text{ini}} - W_{\text{hr}}}{W_{\text{ini}}} \times 100 \]  

(2)

where \( W_{\text{ini}} \) is the initial weight of bitter gourd flakes, and \( W_{\text{hr}} \) is the hourly weight of bitter gourd flakes. Final and initial moisture content helps to determine the total removal of water content \( (W_{\text{ttl}}) \) from bitter gourd flakes (Fudholi et al. 2014).

\[ W_{\text{ttl}} = \frac{M_{\text{ini}} - M_{\text{fnl}}}{100 - M_{\text{fnl}}} \times W_{\text{ini}} \]  

(3)

where \( M_{\text{ini}} \) is the initial moisture content and \( M_{\text{fnl}} \) is the final moisture content on w.b.

Instantaneous moisture content on d.b. can be calculated as per Eq. 4 (El-Sebai and Shalaby 2013)

\[ M_{\text{ins}} = \left( \frac{M_{\text{ini}} + 1}{W_{\text{hr}}} \right) \frac{1}{W_{\text{ini}}} - 1 \]  

(4)

Moisture ratio \( (M_{\text{ratio}}) \) can be calculated as per Eq. 5 (Akpinar 2010; Sethi and Dhiman 2020)

\[ M_{\text{ratio}} = \frac{(M_{\text{ini}} - M_{\text{eqm}})}{(M_{\text{ini}} - M_{\text{eqm}})} \]  

(5)

where \( M_{\text{eqm}} \) is the equilibrium moisture content and \( M_{\text{ini}} \) is very high as compared to \( M_{\text{eqm}} \). Thus, equilibrium moisture content can be neglected. Hence, the equation can be expressed as Eq. 6

\[ M_{\text{ratio}} = \frac{M_{\text{ini}}}{M_{\text{ini}}} \]  

(6)

#### Thermal efficiency of SAH \( (\eta_{\text{SAH}}) \)

Thermal efficiency of SAH can be expressed by the ratio of heat collected to the amount of solar radiation compelling the collector surface at any period of time. It can be evaluated as Eq. 7 (Banout et al. 2011; Prakash and Kumar 2014; Doymaz 2007):

\[ \eta_{\text{SAH}} = \frac{mC_p(T_0 - T_i)}{I \times A_c} \]  

(7)

where \( C_p = \) specific heat of air (kJ/kg K), \( T_0 = \) air temperature at outlet SAH (K), \( A_c = \) Solar absorber area (m²), \( m = \) mass flow rate of air (kg/s), \( T_i = \) air temperature at inlet SAH (K), and \( I = \) solar irradiance (W/m²).

#### Drying efficiency \( (\eta_{\text{hgd}}) \)

Drying efficiency is the ratio of the heat utilised for drying of crop to the total energy consumed by the dryer. Drying efficiency depends on the parameters like latent heat, total removal of water, area of tray and global solar radiation. It can be evaluated as Eq. 8 (Banout et al. 2011; Prakash and Kumar 2014; Doymaz 2007):

\[ \eta_{\text{hgd}} = \frac{W_{\text{tl}} \times h_{\text{lh}}}{A_{\text{tr}} \times I_{\text{grd}}} \]  

(8)

### Embodied energy and cost analysis

The total amount of energy used for the production of any product or service is termed as embodied energy. Embodied energy for the various components used in the fabrication of a hybrid greenhouse dryer is represented in Table 4 (Banout et al. 2011; Prakash and Kumar 2014; Amin et al. 2021; Doymaz 2007).

Total cost incurred for the fabrication of the proposed system is INR 22664.30; it majorly consists of polycarbonate

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Table 3 Uncertainty analysis of hybrid greenhouse dryer

| Parameters          | Least count | Total uncertainty |
|---------------------|-------------|-------------------|
| Room temperature    | 0.10%       | ±0.68%            |
| Crop temperature    | 0.10%       |                   |
| Air temperature     | 0.10%       |                   |
| Relative humidity   | 0.10%       |                   |
| Voltage             | 0.01%       |                   |
| Current             | 0.01%       |                   |
| Wind speed          | 0.01%       |                   |
| Moisture evaporation| 0.50%       |                   |
sheet, paraffin wax and polycrystalline solar cell. Details of cost of the various components used in the proposed system are shown in Table 5.

### Energy payback time

The time required to recover the embodied energy of the system or service is called energy payback time. Dryer payback period is evaluated as Eq. 9 (Banout et al. 2011).

\[
EPBT = \frac{E_m}{AE_o} \quad (9)
\]

Annual energy output (AE_o) is the product of daily energy output (DE_o) and the number of working days (N_day). It can be evaluated as per Eqs. 10–12.

\[
AE_o = DE_o \times N_{day} \quad (10)
\]

\[
DE_o = \frac{W_{tot} \times h_{lp}}{3.6 \times 10^6} \quad (11)
\]

\[
DE_i = I_{grad} \times N_{hr} \times A_{rm} \times 10^{-3} \quad (12)
\]

where \( E_m \) is the embodied energy of hybrid greenhouse dryer, \( AE_o \) is the annual energy output, \( DE_o \) is the daily energy output, and \( DE_i \) is the daily energy input. According to the climatic condition in Ranchi, India, there are 300 days as an annual average sunny day, which is represented by \( N_{day} \) and 1800 h as annual average sunny hours and seven sunny hours on a daily basis which is represented as \( N_{hr} \).

### CO₂ emission

Average emission of CO₂ is equivalent to 0.98 kg of CO₂ per kWh for the coal-based electricity generation. CO₂ emission

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**Table 4** Embodied analysis of heat storage–based hybrid greenhouse dryer

| S. no. | Item                        | Wt (kg) | Energy (kWh) | Total energy (kWh) | References                  |
|--------|-----------------------------|---------|--------------|--------------------|-----------------------------|
| 1      | Polycarbonate sheet         | 15.6    | 10.19        | 159.07             | Prakash and Kumar (2014)    |
| 2      | Mirror                      | 5.40    | 7.28         | 39.31              |                             |
| 3      | Coating                     | 0.75    | 0.27         | 0.20               |                             |
| 4      | Black PVC sheet             | 0.32    | 19.44        | 6.31               |                             |
| 5      | Aluminium angle             | 4.81    | 55.28        |                    |                             |
| 6      |                             |         |              |                    |                             |
| 7      | Fitting                     |         |              |                    |                             |
| 8      | DC exhaust fan              |         |              |                    |                             |
| 9      |                             |         |              |                    |                             |
| 10     | Aluminium jacket            | 2       | 55.28        | 110.56             |                             |
| 11     | Thermocoal                  | 0.25    | 29.39        | 7.34               |                             |
| 12     | Wooden frame                | 10.50   | 0.44         | 4.62               |                             |
| 13     | Glass                       | 5.50    | 7.28         | 40.04              |                             |
| 14     | Putty                       | 1       | 1.472        | 1.472              |                             |
| 15     | Metal sheet                 | 2       | 55.28        | 110.56             |                             |
| 16     | Frame                       | 20      | 5.55         | 111                |                             |
| 17     | Pipe                        | 1       | 15.59        | 15.59              |                             |
| 18     | Polycrystalline solar cell  | 0.059 m²| 1130.60      | 66.13              |                             |
| 19     | Battery                     | 0.58    |              | 46                 |                             |
| 20     | Paraffin wax                | 35      | 16           | 560                |                             |
| 21     | Solar charge controller      | 1       |              | 33                 |                             |

**Embodied Energy** 1591.07 kWh
per year \( (\text{CO}_2 \text{em/yr}) \) depends on the parameters like embodied energy and lifetime of the system (LT). \( \text{CO}_2 \) emission rate/year can be evaluated as per Eq. 13 (Prakash and Kumar 2014)

\[
\text{CO}_2 \text{em/yr} = \frac{E_m \times 0.98}{\text{LT}}
\]

(13)

**Effective moisture diffusivity**

Amount of movement of moisture in the crops during drying process is known as effective moisture diffusivity. Effective moisture diffusivity is affected by the porosity of the crop, temperature, moisture content and compositions. It can be evaluated as per Eq. 14 or Eq. 15.

\[
\text{MR} = \frac{M_i - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_{\text{eff}}}{4r^2} \cdot t \right)
\]

(14)

where \( D_{\text{eff}} \) is the actual diffusivity coefficient \( (\text{m}^2/\text{s}) \), \( t \) is the drying time, \( r \) is the thickness of the slab \( (\text{m}) \), and \( n \) is the positive integer. Only the first term of Eq. (13) can be used for a long drying period [25]: Many researchers demonstrated that Eq. (13) could be further simplified to a straight-line equation as Eq. 15 (Lopez et al. 2000; Sacilik et al. 2006):

\[
\ln(\text{MR}) = \ln \left( \frac{8}{\pi^2} \right) - \left( \frac{\pi^2 D_{\text{eff}}}{4r^2} \right) \cdot t
\]

(15)

Actual moisture diffusivity \( (D_{\text{eff}}) \) is typically determined by plotting experimental drying data in terms of \( \ln(\text{MR}) \) versus time and the slope \( (k_o) \) as shown in Eq. 16 (Wang et al. 2004):

\[
k_o = \frac{\pi^2 D_{\text{eff}}}{4r^2}
\]

(16)

where \( r \) is the thickness of drying crop in millimetres, i.e. bitter gourd flakes in our case.

**Drying kinetics**

The drying kinetics have been analysed to dry bitter gourd flakes inside hybrid greenhouse dryers and open mode drying. First drying kinetic model is developed by Newton for thin-layer types of solar drying. The variable \( k \) is the
exponential variable in this model, which is taken as constant. Another exponential equation is a page model. Further, the upgradation of the Newton model is developed by Henderson and Pabis which consists of coefficient $a$. Upgradation of Henderson and Pabis is the logarithmic model, which consists of an extra constant $c$. Further, Wang and Singh model is proposed, which is a quadratic function, and the performance of this function is better than the previous models. A suitable selection of the drying model is necessary to describe the drying process. Table 6 represents the seven drying models for drying bitter gourd flakes. Results of the investigation were fitted in the mathematical model mentioned in Table 6 with the help of Matlab 13a using non-linear regression. For the validation of the statistical analysis, the drying kinetics has been settled on the basis of sum of square (SSE) due to error, degree of freedom Adj $R^2$, root mean square error (RMSE) and R square.

### Metallic concentration of dried bitter gourd flake

Dried bitter gourd flakes under both modes of drying were converted into diluted solution by microbial digestion. After dilution, it was mixed with nitric acid (HNO$_3$) and tested in the central instrumentation facility (CIF) BIT Mesra. Six important metal concentration has been measured namely sodium (Na), potassium (K), manganese (Mn), magnesium (Mg), iron (Fe) and copper (Cu).

### Result and discussion

#### Variation of ambient parameters

Ambient parameters like solar radiation, air temperature, relative humidity and wind speed were taken on an hourly basis during experimentation. These parameters are presented in Figs. 3, 4 and 5. Ambient parameters on both days were almost similar. Variation of solar radiation was observed as 660–1050 W/m$^2$ during the first day and 900–1072 W/m$^2$ during the second day while the average value of solar radiation was found as 936 W/m$^2$ and 932 W/m$^2$ on the first and second day, respectively. Relative humidity is inversely proportional to ambient temperature; as ambient temperature increases, relative humidity decreases. Maximum ambient temperature was found at the 13th hour on all the days of the experimentation. For open and hybrid modes, the maximum ambient temperature was found to be 36.35 °C and 40.90 °C. For open and hybrid modes, the minimum relative humidity on day 1 was 38.20% and 29.90% while on day 2 it was 45.20% and 40.70%, respectively. The variation in

### Table 6 Various types of drying models

| S. no. | Types of model               | Equation for drying model | References                        |
|-------|------------------------------|---------------------------|-----------------------------------|
| 1     | Henderson and Pabis          | $M_{ratio} = a \exp(-kt)$  | Prakash and Kumar (2014)          |
| 2     | Newton model                 | $M_{ratio} = \exp(-kt)$    |                                   |
| 3     | Page model                   | $M_{ratio} = \exp(-kt^n)$  |                                   |
| 4     | Wang and Singh model         | $M_{ratio} = 1 + ax + bx^2$|                                   |
| 5     | Prakash and Kumar model      | $M_{ratio} = at^3 + bt^2 + ct + d$|                               |
| 6     | Logarithmic model            | $M_{ratio} = a \exp(-kt) + c$|                                   |
| 7     | Ahmad and Prakash model      | $M_{ratio} = a \exp(-kt^n) + bx^2$| Ahmad and Prakash (2021)         |

Fig. 3 Variation of solar radiation in day 1 and day 2

Fig. 4 Variation of ambient temperature in day 1 and day 2
wind speed during both days of experimentation remained constant, i.e. 0.29–0.45 m/s.

**Effect of SAH outlet temperature, ground and room temperature during drying of bitter gourd flakes**

Room and ground temperature of the proposed dryer is shown in Figs. 6 and 7. Higher solar radiation leads to a high rise in ground and room temperature of the proposed dryer. For the purpose of heat storage in hybrid greenhouse dryer, paraffin wax with black-painted gravel is used at the bottom of the greenhouse dryer. Firstly, paraffin wax with black-painted gravel floor is mixed and put above the black-painted PVC sheet. Initially, black-painted gravel gets heated then it leads to charge the paraffin wax. Thermal storage material (TSM) gets charge from sunrise to noon when solar intensity increases continuously; as the solar intensity decreases, discharging process gets started. Discharging process will continue up to a few post-sunset hours. Charging period of PCM was between 05:45 h and 17:35 h and solar radiation was considered zero after 17:35 h 5:35 PM while the discharging period was from 17:35 h to 05:45 h the next morning.

Heat release from TSM helps in maintaining the favourable drying temperature. Maximum ground temperature for proposed dryer on day 1 was 77.20 °C, while on day 2 it was 71.40 °C. Maximum room temperature for proposed dryer on day 1 was 67.20 °C, while on day 2 it was 61.40 °C. The SAH outlet air temperature is an important factor for providing preheated air inside the drying chamber of present designed system. Maximum outlet temperature of SAH is reported as 52°C which is 17°C more than ambient/inlet temperature. Efficiency of a single-pass solar air heater is shown in Table 7; as can be seen from Table 7, the efficiencies increase to a maximum value at 10:00–13:00 h in the noon. The results show that the collector efficiency increases by increasing the air mass flow rate and amount of solar radiation. It can be seen that the maximum efficiency is observed as 42.27%, while the minimum efficiency is observed as 23.04%. Average efficiency of the proposed SAH is found to be 34.86%.

**Effects on moisture ratio, moisture contents and effective moisture diffusivity for drying of bitter gourd flakes**

This section discussed the effect on moisture content, moisture ratio and actual moisture diffusivity during bitter gourd flake drying. Figure 8 represents the variation of moisture ratio and moisture content with respect to drying time. Final moisture content of bitter gourd flakes (0.78%) reached in hybrid system in 6 h at 0.063391 kg/s
air mass flow rate. For open system, final moisture content of bitter gourd flakes (9.10%) was achieved in 14h. Drying time in the proposed dryer is low compared to open sun drying due to the supply of preheated air from SAH. During the initial phase of drying, higher removal of moisture takes place because of high moisture content. As the drying time increases, the moisture evaporation rate gets decreased with the decrease in the moisture content of bitter gourd flakes.

Effective moisture diffusivity for bitter gourd flake drying under open and hybrid modes was evaluated by Eq. 12. The effective moisture diffusivity at two different mass flow rates can be presented by the graph between drying time and ln (MR). Figure 9 shows the variation of ln (MR) and drying time in different modes, i.e. hybrid mode and open mode. It was found to be $11.650 \times 10^{10}$ m$^2$/s for hybrid mode and $0.8666 \times 10^{10}$ m$^2$/s for open mode. It yields the maximum value at the mass flow rate of 0.06147 kg/s due to the fact that the drying time is slower than other flow rates.

Effects on embodied analysis, cost analysis and CO$_2$ emission of hybrid greenhouse dryer

Table 4 represents the embodied energy analysis of the proposed dryer for the drying of bitter gourd flakes. Fabrication of the hybrid system is done with the help of locally skilled workers by using locally available materials. Cost of a heat storage–based hybrid greenhouse dryer was 25364.30 INR; it majorly consists of polycarbonate sheet, paraffin wax and polycrystalline solar cell. The detailed cost of the material used to fabricate a hybrid greenhouse dryer is shown in Table 5. Various materials used for
the fabrication of the proposed system are also shown in Fig. 10. Emission rate of CO₂/annum for the hybrid greenhouse dryer was reported as 33.86 kg, which is quite low as compared to the existing hybrid solar dryer (Prakash and Kumar 2014).

**EPBT of hybrid greenhouse dryer and quality of dried crops**

Energy payback period of the greenhouse dryer was calculated as per Eq. 9. Energy payback period of the developed hybrid greenhouse dryer is 1.88 year. Lifetime of the hybrid greenhouse dryer was found as 35 years; hence, the payback period is found very low compared to the lifetime of the system.

To analyse the quality of dried bitter gourd, the dried bitter gourd sample of 0.5 g was taken and placed in the burning cup. This cup is added with 15 ml of HNO₃ (pure form). Further, it is incinerated in the microwave oven at 200°C, and it is diluted by distilled water (50 ml). ICP-OES analysed mineral concentration with 3 s (copy time), 1–5 s (reading time), 5 to 12 mm (viewing height), 10.5–15 L/min (rate of flow of plasma gas) and 0.8–1.4 kW (R.F Power). Mn and Mg types of minerals are highest in sun-drying due to the formation of ferric oxide from a chemical reaction that takes place in the microwave oven. Material concentration is shown in Table 8. Metal concentration of Na and K comes under the range of Suarez at al. while other metals like Mn, Mg, Fe and Cu are higher in our case. This is because various factors influence metal concentration like production region, cultivation method, cultivator and sampling period (Arslan and Özcän 2011). These metal contents also depend on the types of crops used for drying, soil quality of the crops and the water quality of the crops. Hence, it varies as per the geographical locations (Suárez et al. 2007).

**Regression analysis**

Regression analysis has proceeded under hybrid mode and open mode for 7 thin-layer drying model for correlation of drying time and moisture ratio at the mass flow rate of air 0.06147 kg/s as shown in Table 6. Ahmad and Prakash model is the extension of the Logarithmic model. Equation describing Ahmad and Prakash model has four constants $a$, $b$, $k$ and $n$. The variable $t$ describes the time required for drying. Ahmad and Prakash model was selected as one of the best techniques of curve fitting for analysis of non-linear regression based on R-square, adjusted R-square, SSE and RMSE. Statistical parameter values of the Ahmad and Prakash model were SSE 0.0186, R-square 0.9861, adjusted R-square 0.9823 and RMSE 0.04112. For the open sun mode, Ahmad and Prakash model was again found to be the best fitting curve model for non-linear regression analysis with SSE 0.01804, R-square 0.987, adjusted R-square 0.9835 and RMSE 0.04112. For the open sun mode, Ahmad and Prakash model was again found to be the best fitting curve model for non-linear regression analysis with SSE 0.01804, R-square 0.987, adjusted R-square 0.9835 and RMSE 0.04112. For the open sun mode, Ahmad and Prakash model was again found to be the best fitting curve model for non-linear regression analysis with SSE 0.01804, R-square 0.987, adjusted R-square 0.9835 and RMSE 0.04112. For the open sun mode, Ahmad and Prakash model was again found to be the best fitting curve model for non-linear regression analysis with SSE 0.01804, R-square 0.987, adjusted R-square 0.9835 and RMSE 0.04112. Tables 9 and 10 summarise all the thin-layer models’ statistical analysis results for hybrid greenhouse and open sun dryer conditions. Moisture ratios for the experimental and predicted values comparison are done for the confirmation of model selection for greenhouse dryer shown in Fig. 11 and for the open sun in Fig. 12. The fittingness of the statistical models is specified by the predicted values connected by a dotted line.

**Efficiency of hybrid greenhouse dryer for drying**

Daily thermal efficiency of a hybrid greenhouse dryer varies with the dryer’s annual thermal output and input energy. It is found to be 50.20%, while the annual thermal output is calculated as 732.20 kW, and input energy is found as 4.80 kWh. Experimental result shows that, as the solar radiation increases, the drying rate also increases, resulting in an increase in thermal efficiency. Thermal storage at the dryer’s ground provides steady heat inside the drying chamber, which results in a large amount of heat transfer to the crop in off-sunshine hours. Mass flow rate of air is also an important parameter that affects the efficiency of the drying system. The increase in mass flow rate of air results in the decrease of outlet temperature due to less contact duration of
### Table 9 Statistical analysis for drying bitter gourd flakes at hybrid mode

| S. no. | Types of mode          | Types of model     | SSE     | $R^2$      | Adj $R^2$ | RMSE   | Constants |
|--------|------------------------|--------------------|---------|------------|-----------|--------|-----------|
| 1      | Bitter gourd flakes (hybrid) | Henderson and Pabis | 0.001849 | 99.82%     | 99.80%    | 0.01193 | $a = 1.005$ |
| 2      | Newton model           | 0.001877           | 99.82%     | 99.82%    | 0.01158   | $k = 0.9264$ |
| 3      | Page model             | 0.0008441          | 99.92%     | 99.91%    | 0.008058  | $k = 0.8735$ |
| 4      | Wang and Singh model   | 0.5818             | 43.04%     | 38.65%    | 0.2116    | $a = -0.2417$ |
| 5      | Prakash and Kumar model | 0.04392           | 95.70%     | 94.53%    | 0.06319   | $a = -0.000106$ |
| 6      | Logarithmic model      | 0.001847           | 99.82%     | 99.79%    | 0.0124    | $a = 1.006$ |
| 7      | Ahmad and Prakash model | 0.0008265       | 99.92%     | 99.90%    | 0.008668  | $a = 1.001$ |

### Table 10 Statistical analysis for drying bitter gourd flakes at open mode

| S. no. | Types of mode (open) | Types of model       | SSE     | $R^2$      | Adj $R^2$ | RMSE   | Constants |
|--------|-----------------------|----------------------|---------|------------|-----------|--------|-----------|
| 1      | Bitter gourd flakes (open) | Henderson and Pabis | 0.07968 | 91.61%     | 90.96%    | 0.07829 | $a = 0.9461$ |
| 2      | Newton model          | 0.08256             | 91.30%     | 91.30%    | 0.07679   | $k = 0.4654$ |
| 3      | Page model            | 0.03381             | 96.44%     | 96.16%    | 0.051     | $k = 0.6869$ |
| 4      | Wang and Singh model  | 0.3648              | 61.56%     | 58.61%    | 0.1675    | $a = -0.2141$ |
| 5      | Prakash and Kumar model | 0.06418         | 93.24%     | 91.39%    | 0.07638   | $a = -0.00158$ |
| 6      | Logarithmic model     | 0.03166             | 96.66%     | 96.11%    | 0.05136   | $a = 0.9202$ |
| 7      | Ahmad and Prakash model | 0.03362         | 96.46%     | 95.49%    | 0.05529   | $a = 1.009$ |

Note: SSE = Sum of Squares Error, $R^2$ = Coefficient of Determination, Adj $R^2$ = Adjusted Coefficient of Determination, RMSE = Root Mean Square Error.
air inside the drying chamber. Hence, it is necessary to maintain proper mass flow rate of air for enhanced efficiency.

**Comparative analysis of hybrid gr dryer with other invigilator**

Drying of bitter gourd flakes in hybrid greenhouse dryer was compared with forced convection indirect greenhouse dryer (Vijayan et al. 2020). It was observed that a hybrid greenhouse dryer is more efficient in comparison to a forced convection indirect greenhouse dryer. This is because the drying time required for getting a stagnant crop weight is 6 h; i.e. final moisture content was 7.8% for the proposed hybrid greenhouse dryer, while for the forced convection indirect greenhouse dryer it reached up to 9% in 7 h. Hybrid greenhouse dryer is more efficient because preheated air comes into the dryer section from SAH; also, the hybrid thermal energy storage concept is applied on the ground of the proposed dryer, which gives a proper distribution of heat inside the dryer. The detail comparative analysis of different parameters is shown in Table 11.

**Conclusion**

Present study considers the techno-environmental analysis and drying kinetics of hybrid heat storage–based proposed dryer. Paraffin wax is being used as latent storage material, while black-painted gravel is used as sensible storage material on the ground of the drying chamber in the proposed system. Proposed hybrid system is the combination of the active mode greenhouse dryer and single-pass solar air heater. Bitter gourd flakes were dried in a hybrid greenhouse dryer and simultaneously in natural (open sun) drying. The results observed by the above experimentation are as follows:

- Moisture content of bitter gourd flakes was decreased from 88.64 to 0.78% in the hybrid system, while in the open system, it reduced from 88.64 to 54.19% in 6 h.
- Thus, the reduction in moisture content is 98.56% more in hybrid greenhouse dryer than in open mode.

**Table 11 Comparative analysis for drying bitter gourd flakes**

| Objective                        | Present study | Other investigators | References          |
|----------------------------------|---------------|---------------------|---------------------|
| Drying time                      | 6 h           | 7 h                 | (Vijayan et al. 2020) |
| Final moisture content           | 7.8%          | 9%                  |                     |
| Effective moisture diffusivity   | $11.650 \times 10^{-10}$ m$^2$/s | $8.6293 \times 10^{-10}$ m$^2$/s |                     |
| CO$_2$ mitigation (tons)         | 46.28         | 33.52               |                     |
| Embodied energy (kWh)            | 1591.07       | 1109.307            |                     |
| Energy payback time              | 1.88 years    | 2.21 years          |                     |
| Earned carbon credit             | 16844.76 to 67379.05 INR | 10894 to 43576 INR |                     |
• Daily drying efficiency of the proposed hybrid system is 50.20% at 0.06147 kg/s of the mass flow rate of exhaust air. Maximum and minimum thermal efficiency of SAH is observed as 42.27% and 23.04%.

• Effective moisture diffusivity of bitter gourd flakes was found to be 11.650 × 10^{−10} m^{2}/s for hybrid mode, whereas for open mode, it was 0.8666 × 10^{−10} m^{2}/s.

• Embodied energy and CO₂ emission per year of the proposed system were 1591.07 kWh and 33.86 kg.

• Cost analysis of heat storage–based hybrid greenhouse dryer was 22664.30 INR; it majorly consists of polycarbonate sheet, paraffin wax and polycrystalline solar cell.

• After drying, both the modes’ dried product was tested in the laboratory to find out the important metal content in it. The product dried in the proposed system was found to have higher metal content than the open sun-dried product.

• Energy payback time for the proposed system was 1.88 years.

• Ahmad and Prakash and logarithmic models were selected as the best drying models for drying bitter gourd flakes in a hybrid greenhouse dryer and open sun drying, respectively.

Heat storage–based hybrid greenhouse dryer was more consistent in drying and produced better quality dried products than open sun drying. Since the hybrid greenhouse dryer consumes less drying time than open sun drying, i.e. 8 h for drying bitter gourd flakes; the heat storage–based hybrid greenhouse dryer is economically viable for small-scale farmers and industries.

**Nomenclature**

- \( A_m \): area of room (m²);
- \( A_t \): area of tray (m²);
- \( AE \): annual energy output (W);
- \( \lambda_{\text{ini}} \): initial moisture content;
- \( \lambda_{\text{f}} \): final moisture content;
- \( \lambda_{\text{eqm}} \): equilibrium moisture content;
- \( M_{\text{ini}} \): initial moisture content;
- \( M_{\text{eqm}} \): equilibrium moisture content;
- \( h_{\text{i}} \): latent heat of evaporation (KJ/kg);
- \( I_{\text{grd}} \): solar radiation (W/m²);
- \( LT \): lifetime (Yr);
- \( M_{\text{eqm}} \): equilibrium moisture content;
- \( \eta_{\text{ini}} \): initial weight of bitter gourd (kg/h);
- \( \eta_{\text{f}} \): final weight of bitter gourd (kg/h);
- \( W_{\text{ini}} \): hourly weight of bitter gourd (kg/h);
- \( W_{\text{eqm}} \): equilibrium moisture content (kg);
- \( W_{\text{f}} \): total removal of water content (kg);
- \( \eta_{\text{ini}} \): average annual sunny days;
- \( \eta_{\text{f}} \): drying system efficiency (%);
- \( \eta_{\text{ini}} \): daily sunny hour (h);
- \( W_{\text{ini}} \): hourly weight of bitter gourd (kg/h);
- \( W_{\text{eqm}} \): equilibrium moisture content (kg);
- \( W_{\text{f}} \): total removal of water content (kg);
- \( W_{\text{ini}} \): initial weight of bitter gourd (kg);
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- \( \eta_{\text{ini}} \): daily sunny hour (h);
- \( W_{\text{ini}} \): hourly weight of bitter gourd (kg/h);
- \( W_{\text{eqm}} \): equilibrium moisture content (kg);
- \( W_{\text{f}} \): total removal of water content (kg);

**Abbreviations**

- eqm: equilibrium; fnl: final; grd: global radiation;
- hgd: hybrid greenhouse dryer; hr: hourly; ini: initial;
- ins: instantaneous; lh: latent heat; pbt: payback time;
- rm: room; tr: tray; ttl: total

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**Availability of data and materials**

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

**Author contribution**

Asim Ahmad: conceptualization, methodology, investigation, data curation, writing—original draft.

Om Prakash: validation, supervision, writing—review and editing.

Anil Kumar: investigation, review and editing.

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The authors declare no competing interests.

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