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Drying Kinetics and Economic Analysis of Bitter Gourd Flakes Drying inside Hybrid Greenhouse Dryer

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ABSTRACT

In this study, heat storage-based hybrid greenhouse dryer has been developed and analysed for drying bitter gourd flakes under the climatic condition of Ranchi, India. The propose heat storage based hybrid greenhouse dryer consists of a solar air heater with 2.12 m^2 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 CO_2 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. The results show that the mass of crop reduced from 4000g to 458g in 6 hr in proposed dryer and 4000g to 500g in 15 hr for open system. Thus, significant drying time is reduced in proposed system by 8 hours as compared to open system. Environmental impact analysis shows that the EPBT was found to be 0.4907 years only. The cost analysis of the proposed system dryer was 22664.30 INR. The total embodied energy is found to be 1591.07 kWh and earned carbon credit ranges from 16844.76 INR to 67379.05 INR, while CO_2 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 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 system. 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, CO_2 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 nutrients 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 particles contamination make it unsafe and unhygienic (Abubakar et al., 2018 a). 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 difficulty faces by the solar dryer is low drying efficiency and dependency on ambient parameters. Hence, the thermal storage concept is crucial for minimizing 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 dryer 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., 2018 b). The main disadvantage in greenhouse dryer is that crops cannot be dried in off-sunshine hour (Prakash et al., 2016). To minimize this issue, the greenhouse dryer can be integrated with heat storage systems (Čipliené 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 as hybrid system. The additional heat storage materials help to provide constant heat throughout the drying process particularly in off sunshine hour. A hybrid solar dryer system integrated with thermal energy storage (rock bed) was tested for the drying of Guduchi, ginger and turmeric (Prasad and Vijay 2005). The 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. The indirect solar dryer operating in active mode integrated with TES (wax-based) was evolved by (Shalaby and Bek 2014). The experimental analysis was done for drying of two herbs, i.e. T. Neriifolia 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 hours and 12 hours 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. The 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). The experiment was performed in passive greenhouse dryer in different floor conditions by Ahmad and Prakash. The different floor condition is developed based on the different types of sensible thermal storage material (Gravel, Concrete and Black painted gravel). The drying efficiency of the passive greenhouse dryer with black painted gravel is highest for drying of tomato flakes as compared to other sensible thermal energy storage material (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, the drying experimentation (bitter gourd flakes) is being conducted in two different modes: hybrid greenhouse dryer under mixed thermal storage and open sun drying. The 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 is being evaluated. Further, the quality and valuable metallic properties of the bitter gourd flakes dried in the proposed dryer and open sun drying are compared with fresh samples.

EXPERIMENTAL SETUP

In the proposed hybrid greenhouse dryer, Greenhouse dryer is coupled with a single pass solar air heater (SAH). The wall of the dryer is covered with a polycarbonate sheet of thickness 3 mm. The 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 is tilted at a latitude angle of Ranchi, India, i.e. 23.34^{o}N. The two 12V DC fan of variable speed powered by 40W solar panel is placed to ventilate the humid air out of the greenhouse dryer and to induce preheated air from SAH to pass inside the dryer. The north wall of the greenhouse dryer is insulated with the combination of reflective mirror and thermocol. The mirror reflects the outgoing radiation from the north wall to inside drying space of the dryer. The thermocol reduces the heat transfer loss from the mirror to the surrounding. The mixed type thermal heat storage material, i.e. combination of latent and sensible heat storage is applied at the floor of the dryer. The paraffin wax of 35 kg is used as latent heat storage material, while black-painted gravel of 29 kg is used as a sensible heat storage material. The paraffin wax is 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 charge then it leads to charge the paraffin wax. The thermal storage material (TSM) gets charge from sunrise to noon when solar intensity increases continuously, as the solar intensity decreases discharging process gets starts. The discharging process will continue up to few post sunset hour. The heat release from TSM helps to maintain constant drying process during low solar intensity.

The solar air heater (SAH) is used provide the preheated air inside the drying chamber. The SAH is made up of wooden frame and have the dimension of 2.04 m×1.04 m×0.5 m. For the coupling of SAH with greenhouse dryer, a well insulated duct of diameter 0.5 m made of galvanized iron is being used. The insulating material (polyurethane foam) is used to minimize the heat loss from the connecting duct to surrounding. A DC fan is placed at the outlet of the SAH to provide pre heated air from the SAH to the drying chamber through duct. A black painted galvanized iron sheet is used as an absorber plate in a SAH. The SAH is covered with transparent glass of thickness 3mm. The structure of solar air heater is supported by L shaped Mild steel angle. The exposed part of the structure is painted to protect it from adverse environmental effects. The detailed schematic diagram with proper dimension and pictorial view of the experimental setup are explained in Fig 1(a & b).

MATERIALS & METHODS

SAMPLE PREPARATION

The author aimed to evaluate the performance of the proposed system in load condition for drying of bitter gourd flakes. The experiment was conducted for two consecutive days, i.e. 11-13 May 2021, from 10 AM morning to 5 PM evening in BIT Mesra, Ranchi, Jharkhand, India for drying of crops in hybrid mode and open mode. The fresh bitter gourde of 4 kg were purchased from the local market of Ranchi were washed and dried with cotton clothes. This bitter gourd were sliced into 1–2 mm thick flakes and taken for the experimentation.

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. The 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. The uncertainty analysis for the dependent parameters can be evaluated by Eq. 1 (Ahmad and Prakash 2020).

$$\Delta p = \sqrt{\left(\frac{\partial p}{dk_1}\Delta k_1\right)^2 + \left(\frac{\partial p}{dk_2}\Delta k_2\right)^2 + \ldots\ldots\ldots\ldots\ldots + \left(\frac{\partial p}{dk_n}\Delta k_n\right)^2} \tag{1}$$

Where, p is the dependent parameters and k_1, k_2,…k_n is 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_{ratio})

The moisture ratio can be defined as the ratio of the hourly moisture content to the initial moisture content of the crop. The initial moisture content (M_{ini}) for bitter gourd flakes on the wet basis (w.b.) can be calculated as

$$M_{ini} = \frac{W_{ini} - W_{hr}}{W_{ini}} \times 100 \tag{2}$$

Where, W_{ini} is the initial weight of bitter gourd flakes, W_{hr} is the hourly weight of bitter gourd flakes. The final and initial moisture content help to determine the total removal of water content (W_{ttl}) from bitter gourd flakes (Fudholi et al., 2014)

$$W_{ttl} = \frac{M_{ini} - M_{fnl}}{100 - M_{fnl}} \times W_{ini} \tag{3}$$

Where M_{ini} the initial moisture is content and M_{fnl} is the final moisture content on w.b.

The instantaneous moisture content on d.b. can be calculated as (El-Sebaii and Shalaby 2013)

$$M_{ins} = \left[\frac{(M_{ini} + 1) W_{hr}}{W_{ini}} - 1 \right] \tag{4}$$

The moisture ratio (M_{ratio}) can be calculated as (Akpinar, E.K., 2010; Sethi and Dhiman 2020)

$$M_{ratio} = \frac{(M_{ins} - M_{eqm})}{(M_{ini} - M_{eqm})} \tag{5}$$

Where M_{eqm} is the equilibrium moisture content and M_{ini} is very high as compared to M_{eqm}. Thus, equilibrium moisture content can be neglected. Hence, the equation can be expressed as

$$M_{ratio} = \frac{M_{ins}}{M_{ini}} \tag{6}$$

Drying efficiency (η_{hgd})

Drying efficiency is the ratio of the heat utilize 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. 7. (Banout et al., 2011; Prakash and Kumar 2014; Doymaz, I. 2007):

$$\eta_{hgd} = \frac{W_{ttl} \times h_{lh}}{A_{tr} \times I_{grd}} \tag{7}$$

Embodied Energy & Cost Analysis

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

The total cost incurred for the fabrication of the proposed system is INR 22664.30; it majorly consists of polycarbonate sheet, paraffin wax and polycrystalline solar cell. The details of cost of the various component used in the proposed system is shown in Table 5.

Energy Payback Time (EPBT)

The time requires to recover the embodied energy of the system or service is called energy payback time. The dryer payback period is evaluated as (Banout et al., 2011)

$$EPBT = \frac{E_m}{AE_o} \tag{8}$$

The annual energy output (AE_o) is the product of daily energy output (DE_o) and the number of working days (N_{day}).

$$AE_o = DE_o \times N_{day} \tag{9}$$

$$DE_o = \frac{W_{ttl} \times h_{lh}}{3.6 \times 10^6} \tag{10}$$

$$DE_i = I_{grd} \times N_{hr} \times A_{rm} \times 10^{-3} \tag{11}$$

Where E_m is the Embodied Energy of Hybrid greenhouse dryer, AE_o is annual energy output, DE_o is daily energy output, DE_i is 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 hours as annual average sunny hours and seven sunny hr on a daily basis which is represented as N_{hr}.

CO_2 Emission

The average emission of CO_2 is equivalent to 0.98 kg of CO_2 per kWh for the coal based electricity generation. CO_2 emission per year ($CO_{2\ em/yr}$) depends on the parameters like embodied energy and lifetime of the system (LT). CO_2 emission rate/yr can be evaluated as (Prakash and Kumar 2014)

$$CO_{2\ em/yr} = \frac{E_m \times 0.98}{LT} \tag{12}$$

Effective moisture diffusivity

The 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. 13 or Eq. 14.

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{4r^2} gt \right) \tag{13}$$

Where D_{eff} is the actual diffusivity coefficient (m^2/s), t is the drying time, r is the thickness of the slab (m), and n is the positive integer. Only the first term of Equation (13) can be used for a long drying period [25]: Many researchers demonstrated that Equation (13) could be further simplified to a straight-line equation as Eq. 14 (Lopez et al., 2000; Sacilik et al., 2006):

$$\ln\left(MR\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4r^2} gt\right) \tag{14}$$

The actual moisture diffusivity (D_{eff}) is typically determined by plotting experimental drying data in terms of ln (MR) versus time and the slope (k_o) as shown in Eq. 15 (Wang et al., 2004):

$$k_o = \frac{\pi^2 D_{eff}}{4r^2} \tag{15}$$

where r is the thickness of drying crop in mm, 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. The first 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 up-gradation of the Newton model is developed by Henderson and Pabis consist of coefficient a. The up-gradation 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. The 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 during experimentation.

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 Fig. 3-5. 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. The maximum ambient temperature was found at 13th hour in all the days of the experimentation. For open and hybrid mode, the maximum ambient temperature was found to be 36.35 ^oC and 40.90 ^oC. For open and hybrid mode 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 wind speed during the both day of experimentation was remains 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 Fig.6-7. The higher solar radiation leads to a high rise in-ground and room temperature of the proposed dryer. During sunshine hours, heat is absorbed by thermal storage materials applied on ground of the dryer. In off sunshine hours, stored heat gets released inside the drying chamber, which helps in maintaining the favourable drying temperature. The maximum ground temperature for proposed dryer on day 1 was 77.20^{o}C while on day 2 it was 71.40 ^{o}C. The maximum room temperature for proposed dryer on day 1 was 67.20 ^{o}C while on day 2 it was 61.40 ^{o}C. The SAH outlet air temperature is an important factor for providing pre heated air inside the drying chamber of present designed system. The maximum outlet temperature of SAH is reported as 37.6^{o}C which is 2.7^{o}C more than ambient/inlet temperature.

Effects on Moisture Ratio, Moisture Contents and Effective moisture diffusivity for drying of bitter gourd flakes.

In this section, the effect on moisture content, moisture ratio and actual moisture diffusivity during bitter gourd flakes drying were discussed. Fig. 8 represents the variation of moisture ratio and moisture content with respect to drying time. The 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%) achieved in 14h. The drying time in the proposed dryer is low as compared to open sun drying due to supply of pre heated 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 decreases with the decrease in the moisture content of bitter gourd flakes.

The effective moisture diffusivity for bitter gourd flake drying under open and hybrid mode 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). Fig. 9 shows the variation of ln (MR) and drying time in different modes, i.e. hybrid mode and open mode. The effective moisture diffusivity of bitter gourd flakes was found to be 11.650 x 10^{10} m^2/s for hybrid mode and 0.8666 x 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. The fabrication of the hybrid system is done with the help of locally skilled workers by using locally available materials. The cost of heat storage based hybrid greenhouse dryer was 22664.30 INR; it majorly consists of polycarbonate sheet, paraffin wax and polycrystalline solar cell. The detailed cost of the material used to fabricate hybrid greenhouse dryer is shown in Table 5. Various materials were used for the fabrication of the proposed system is also shown in Fig.10. The emission rate of CO_2/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 & Quality of dried crops

The energy payback period of the greenhouse dryer was calculated as per Eqn.9. The energy payback period of the developed hybrid greenhouse dryer is 1.87 year. The lifetime of the hybrid greenhouse dryer was found as 35 years; hence, the payback period is found very low as compared to the lifetime of the system.

To analyse the quality of dried bitter gourde, the dried bitter gourde sample of 0.5g was taken and placed in the burning cup. This cup is added with 15 ml of HNO_3 (pure form). Further, it is incinerated in the microwave oven at 200^{o}C, and it is diluted by distilled water (50 ml). ICP-OES analysed mineral concentration with 3 seconds (copy time), 1-5 second (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. The material concentration is shown in Table 7. The metal concentration of Na and K comes under the range of Suarez at al. while other metal like Mn, Mg, Fe and Cu is higher in our case. This is because various factors influence metal concentration like production region, cultivation method, cultivator and sampling period (Arslan and Özcan 2011). These metal contents also depend on the types of crops used for drying, soil quality of the crops, the water quality of the crops, Hence it varies as per the geographical locations (Suárez et al., 2007).

Drying Kinetics

The 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 & Prakash model is the extension of the Logarithmic model. The equation describing Ahmad & Prakash model has four constant a, b, k and n. The variable t describes the time required for drying. Ahmad & Prakash model was selected as one of the best technique of curve fitting for analysis of non-linear regression based on R-square, adjusted R- square, SSE and RMSE. The statistical parameter values of the Ahmad & 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 & 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 0.0405. The Table 8 and 9 summarises all the thin layer models statistical analysis results for hybrid greenhouse and open sun dryer condition. The 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

The daily thermal efficiency of a hybrid greenhouse dryer varies with the dryer's annual thermal Output and input energy. The daily thermal efficiency 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. The experimental result shows that, as the solar radiation increases, the drying rate also increases, resulting in an increase in thermal efficiency. The thermal storage at the ground of the dryer provides steady heat inside the drying chamber, which results in large amount of transfer of heat to the crop in off sunshine hour. The 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 air inside the drying chamber. Hence it is necessary to maintain proper mass flow rate of air for enhanced efficiency.

Comparative Analysis of Hybrid Greenhouse Dryer with other Invigilator

The drying of bitter gourd flakes in hybrid greenhouse dryer 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 as 7.8% for the proposed hybrid greenhouse dryer, while for the forced convection indirect greenhouse dryer used by it reached up to 9% in 7 h. The 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 10.

CONCLUSION

The present study considers the techno-environmental analysis & drying kinetics of hybrid heat storage based proposed dryer. The 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. The proposed hybrid system is the combination of the active mode greenhouse dryer and single-pass solar air heater. The 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:

- The moisture content of bitter gourd flakes was decreased from 88.64% to 0.78% in the hybrid system, while in the open system, it reduces from 88.64% to 54.19% in 6 hours.
- Thus, the reduction in moisture content is 98.56% more in hybrid greenhouse dryer in comparison to open mode.
- The daily drying efficiency of the proposed hybrid system is 50.20 % at 0.06147 kg/s of the mass flow rate of exhaust air.
- The effective moisture diffusivity of bitter gourd flakes was found to be 11.650 x 10^{-10} m^2/s for hybrid mode, whereas, for open mode, it was 0.8666 x 10^{-10} m^2/s.
- The embodied energy and CO_2 emission per year of the proposed system were 1591.07 kWh and 33.86 kg.

- The 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 be higher metal content as compared to the open sun-dried product.
- The energy payback time for the proposed system was 1.88 years.
- The Ahmad and Prakash model and logarithmic models were selected as the best drying model for drying bitter gourd flakes in a Hybrid greenhouse dryer and open sun drying, respectively.

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

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Author contribution:

Asim Ahmad: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft.

Om Prakash: Validation, Supervision, Writing - review & editing.

Anil Kumar: Investigation.

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

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Nomenclature

A_{rm} = Area of room (m^2)	$EPBT$ = Energy Payback time (Yr)	M_{ins} = Instantaneous Moisture Content
AE_o = Annual Energy Output (W)	E_m = Embodied Energy (kWh)	h_{lh} = Latent heat of evaporation (KJ/kg)
A_{tr} = Area of tray (m^2)	$CO_{2\ emmision/yr}$ = Emission rate of CO_2 per year (kg)	LT = Life time (Yr)
N_{day} = Average annual sunny days	M_{eqm} = Equilibrium Moisture Content	M_{ratio} = Moisture ratio
η_{hgd} = Drying system efficiency (%)	M_{fnl} = Final Moisture content	I_{grd} = Solar Radiation (W/m^2)
DE_o = Daily Energy output (W)	W_{hr} = Hourly Weight of Bitter gourd (kg/h)	W_{ttl} = Total removal of water content (kg)
DE_i = Daily Energy input (W)	M_{ini} = Initial Moisture Content	
N_{hr} = Daily sunny hour (hr)	W_{ini} = Initial Weight of Bitter gourd (kg)	

Abbreviation

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

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Figures

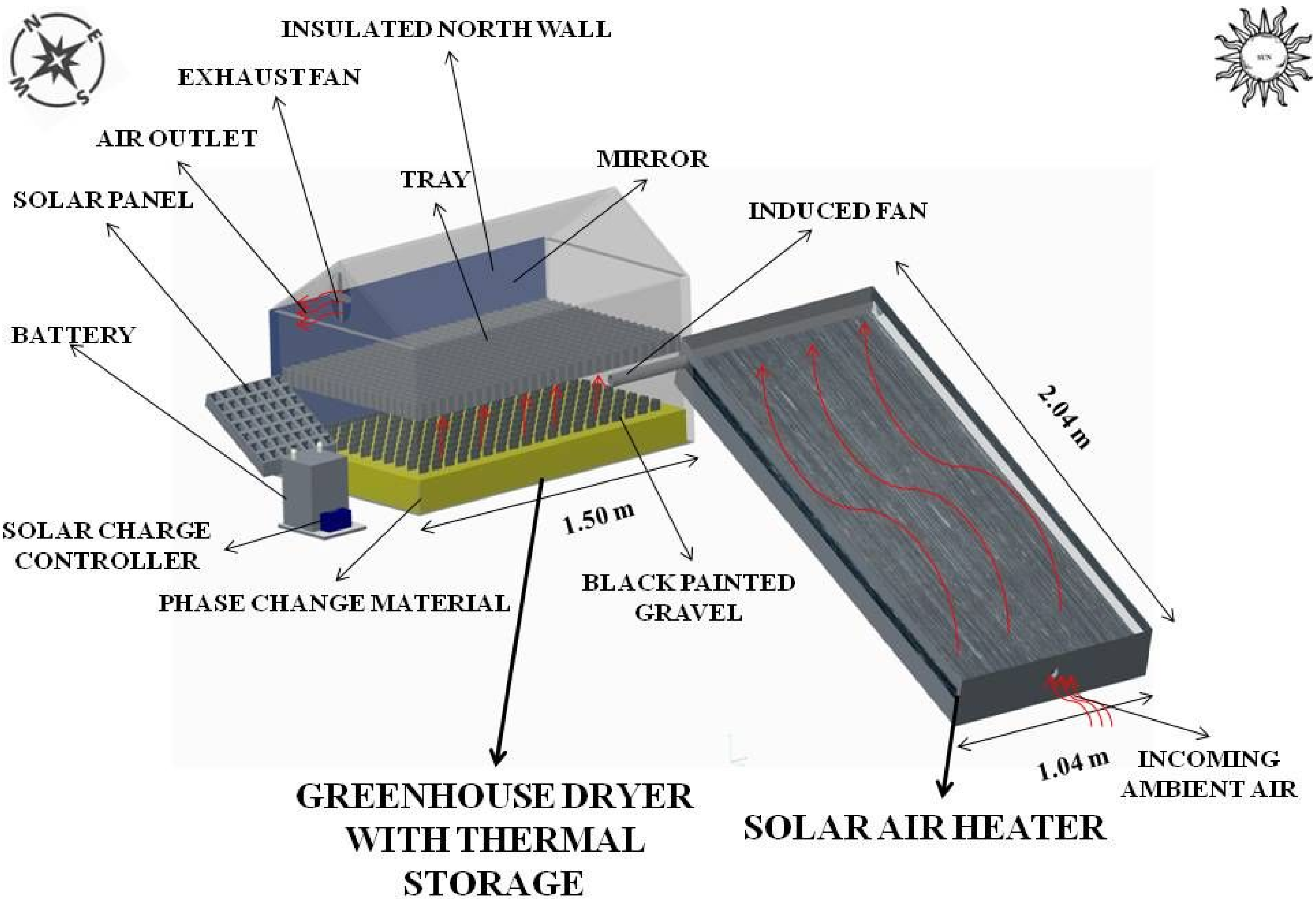

Figure 1

Schematic Diagram of Hybrid Greenhouse Dryer

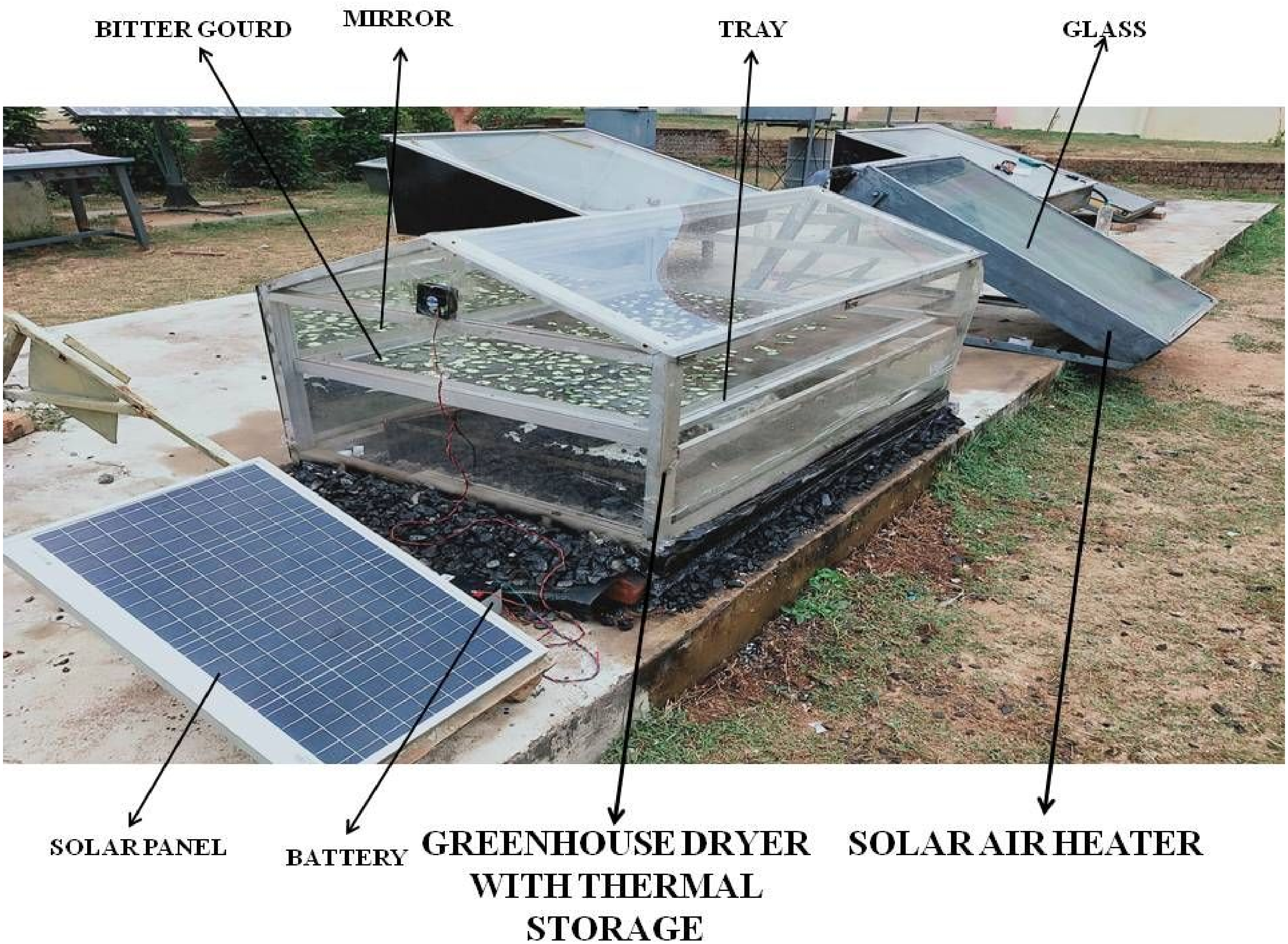

Figure 2

Experimental Setup of Hybrid Greenhouse Dryer

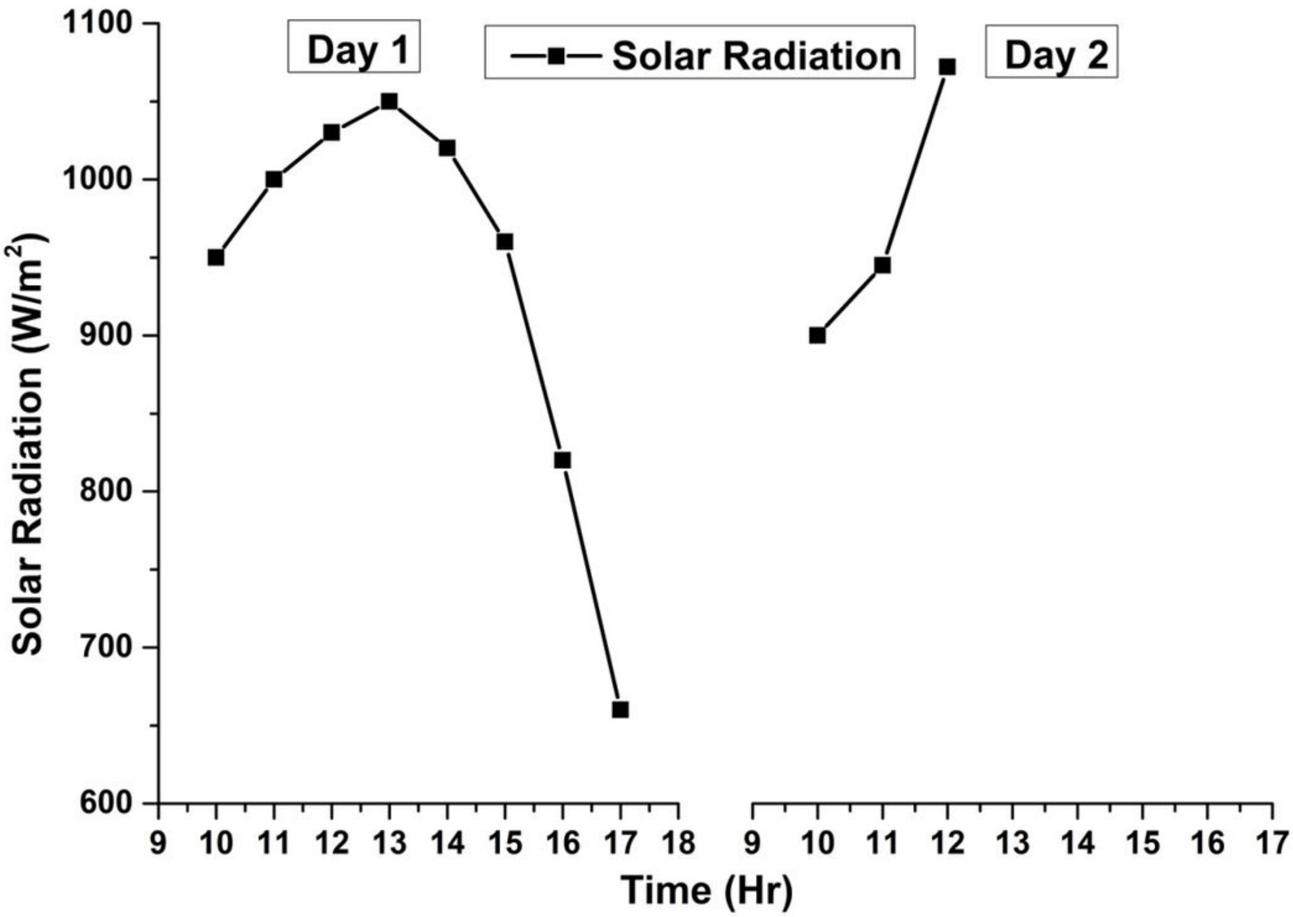

Figure 3

Variation of Solar Radiation in Day 1 & Day 2

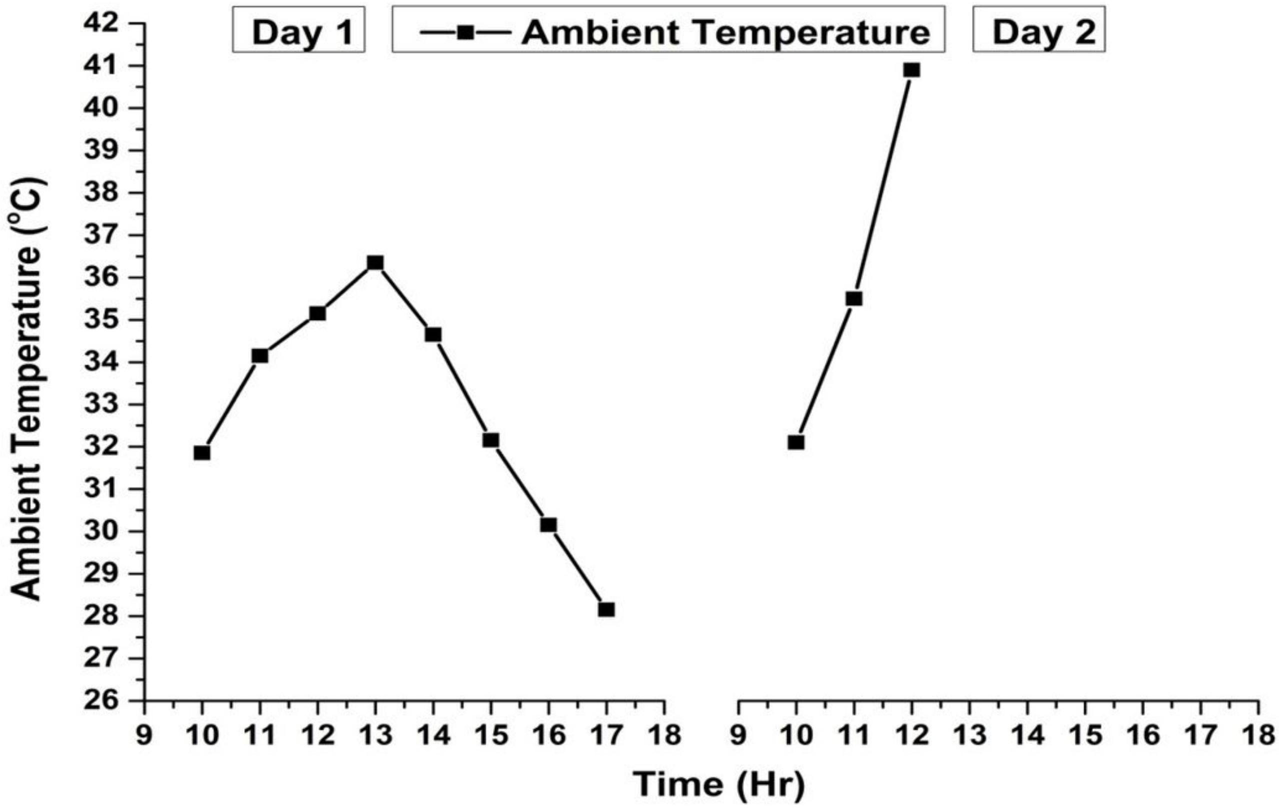

Figure 4

Variation of Ambient Temperature in Day 1 & Day 2

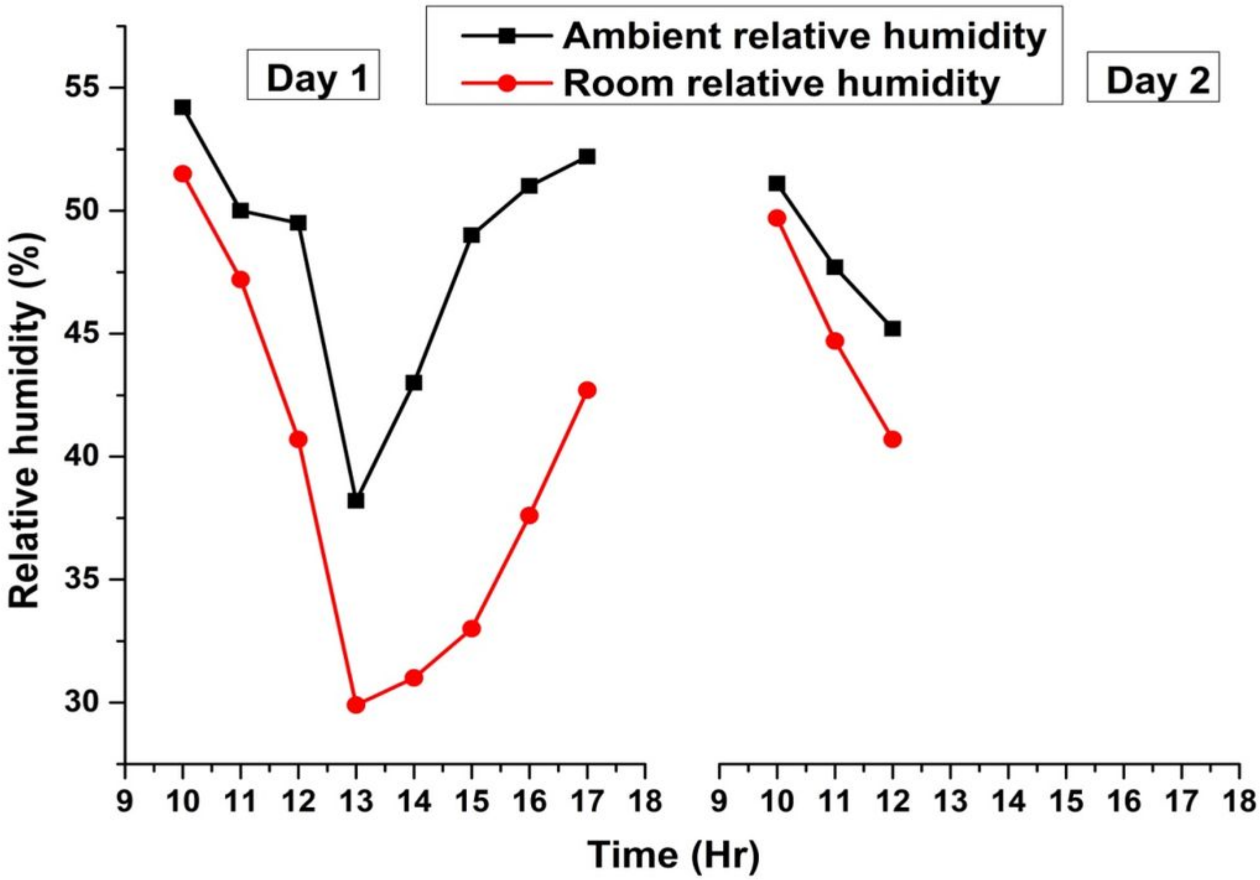

Figure 5

Variation of Relative humidity in Day 1 & Day 2

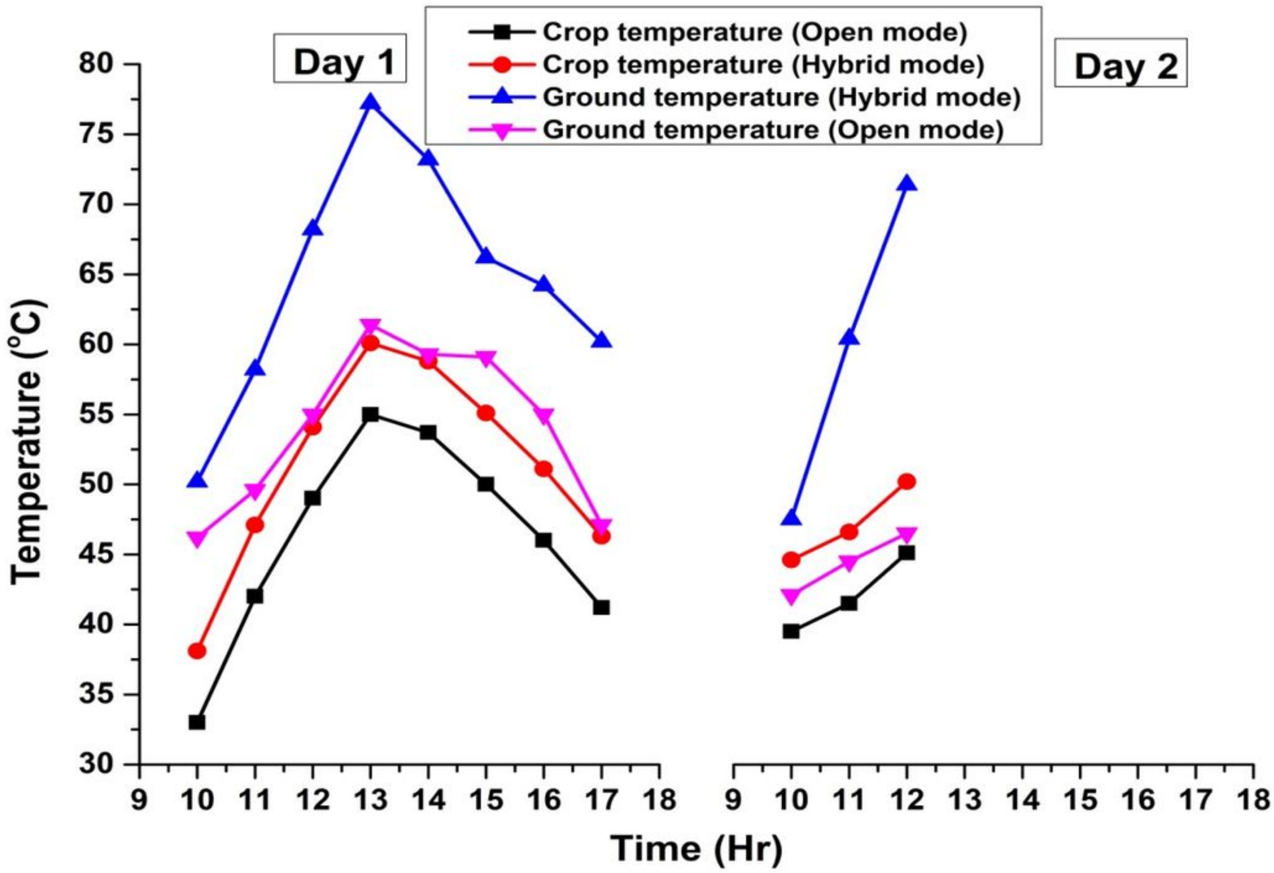

Figure 6

Variation of crop & room temperature in Day 1 & Day 2 for Hybrid and Open Mode

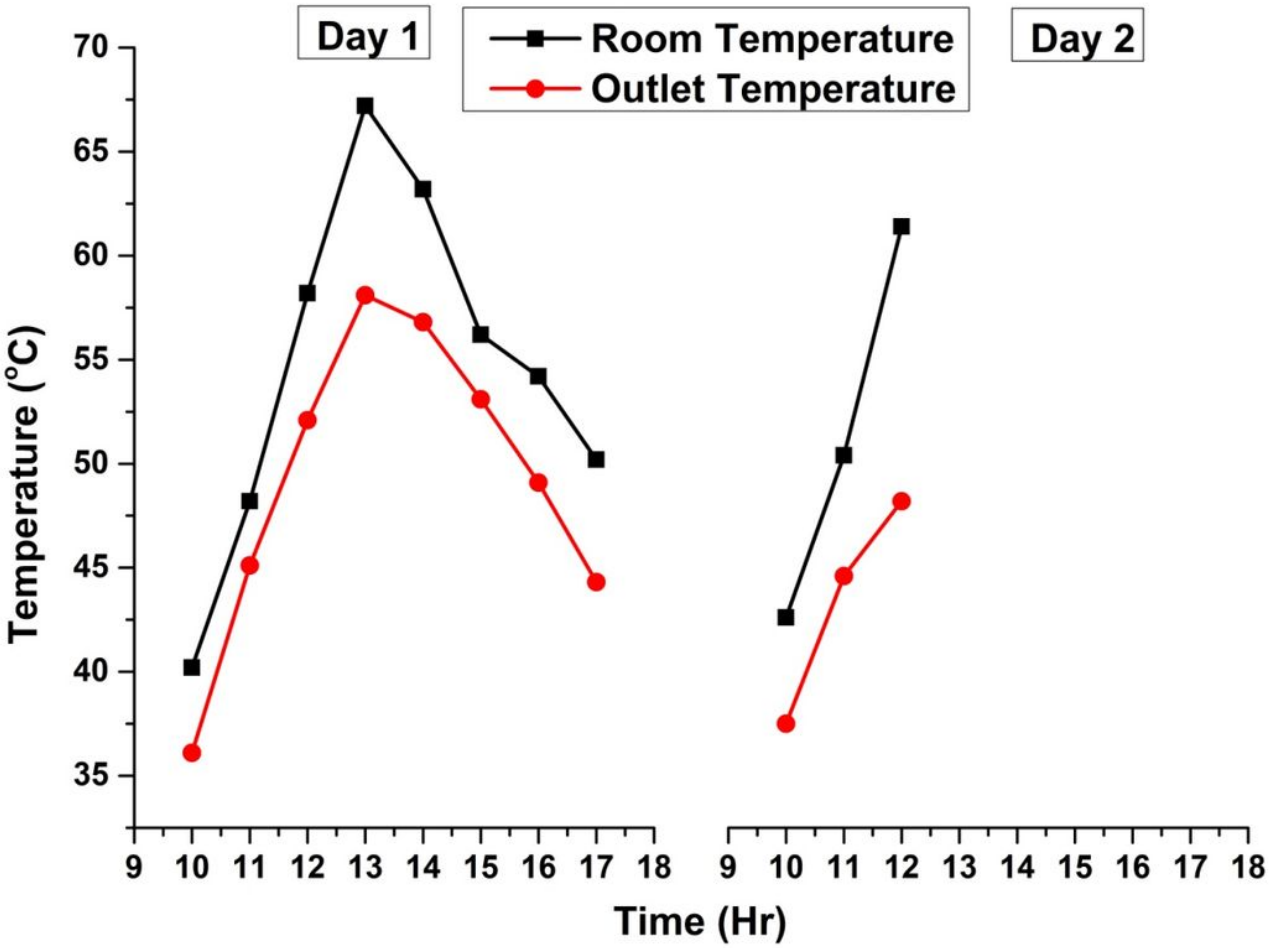

Figure 7

Variation of Room Temperature & Outlet Temperature in Day 1 & Day 2

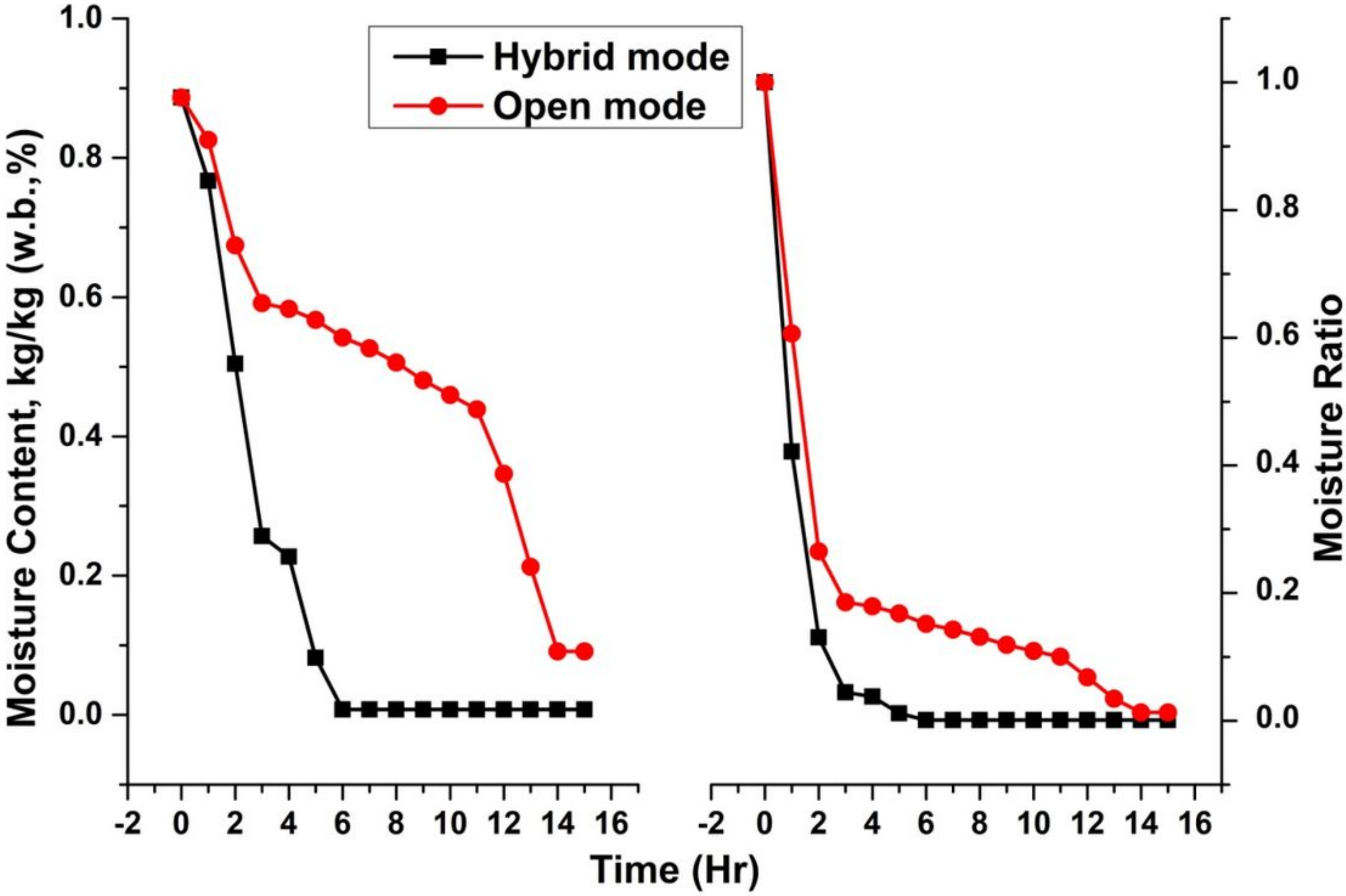

Figure 8

Variation of Moisture Content & Moisture Ration for Hybrid & Open Mode

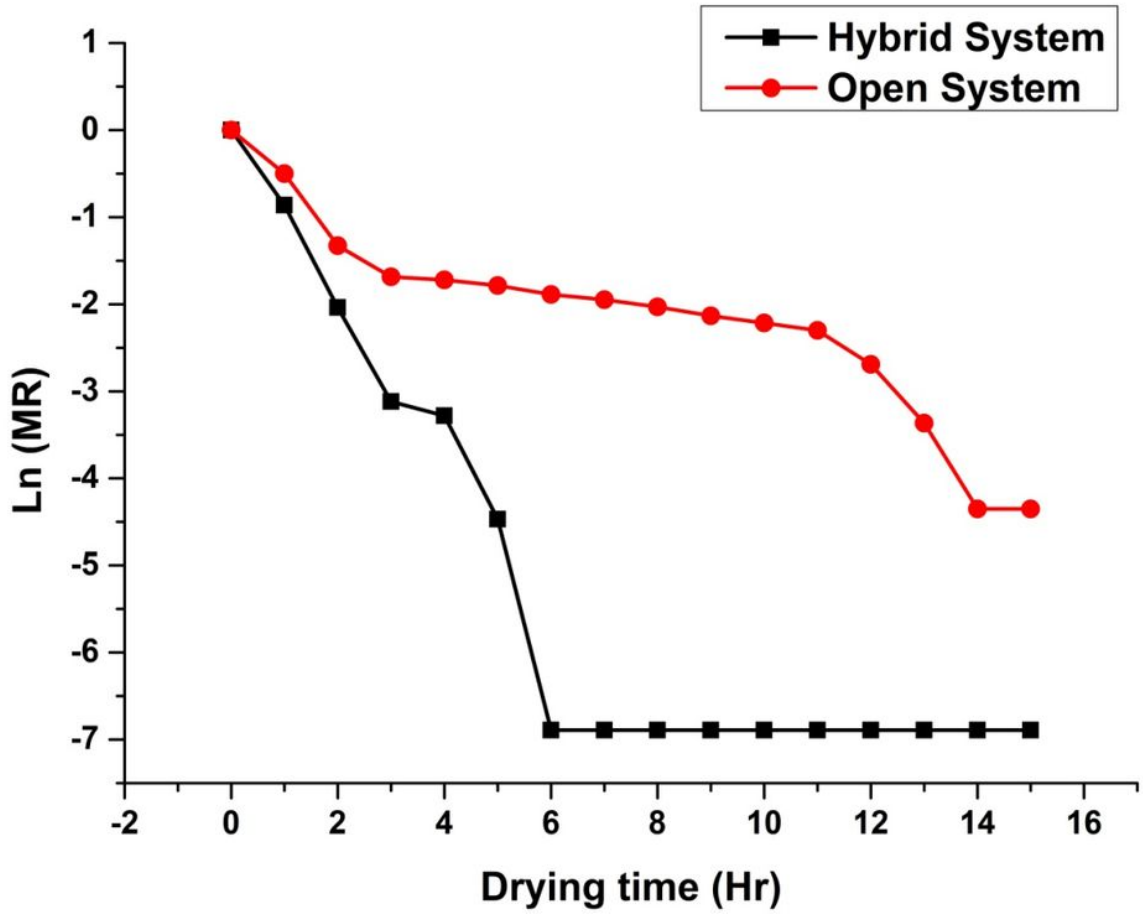

Figure 9

Variation of Ln MR and drying time for drying of bitter gourd flakes

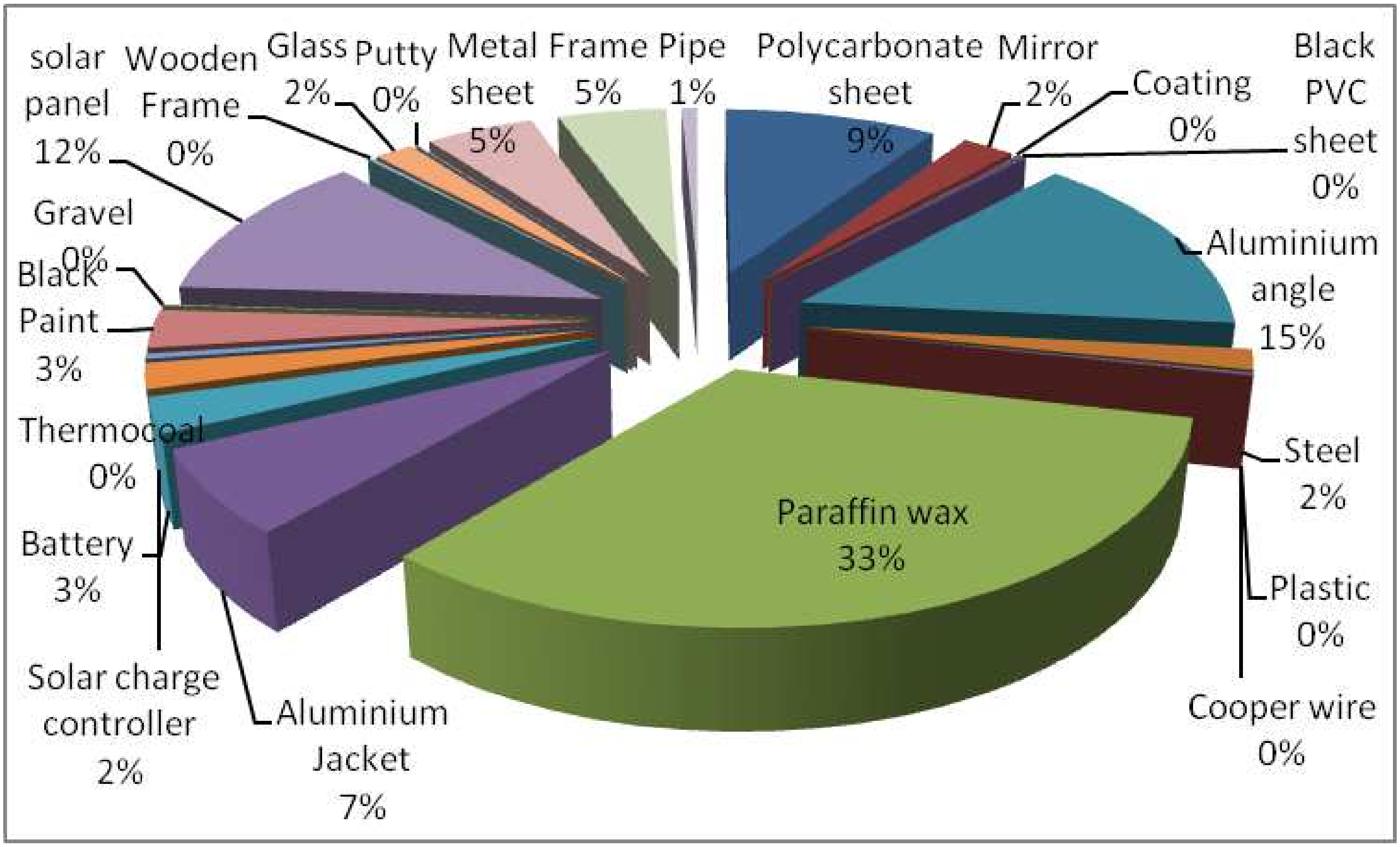

Figure 10

Breakup of Embodied Energy for Hybrid Greenhouse Dryer

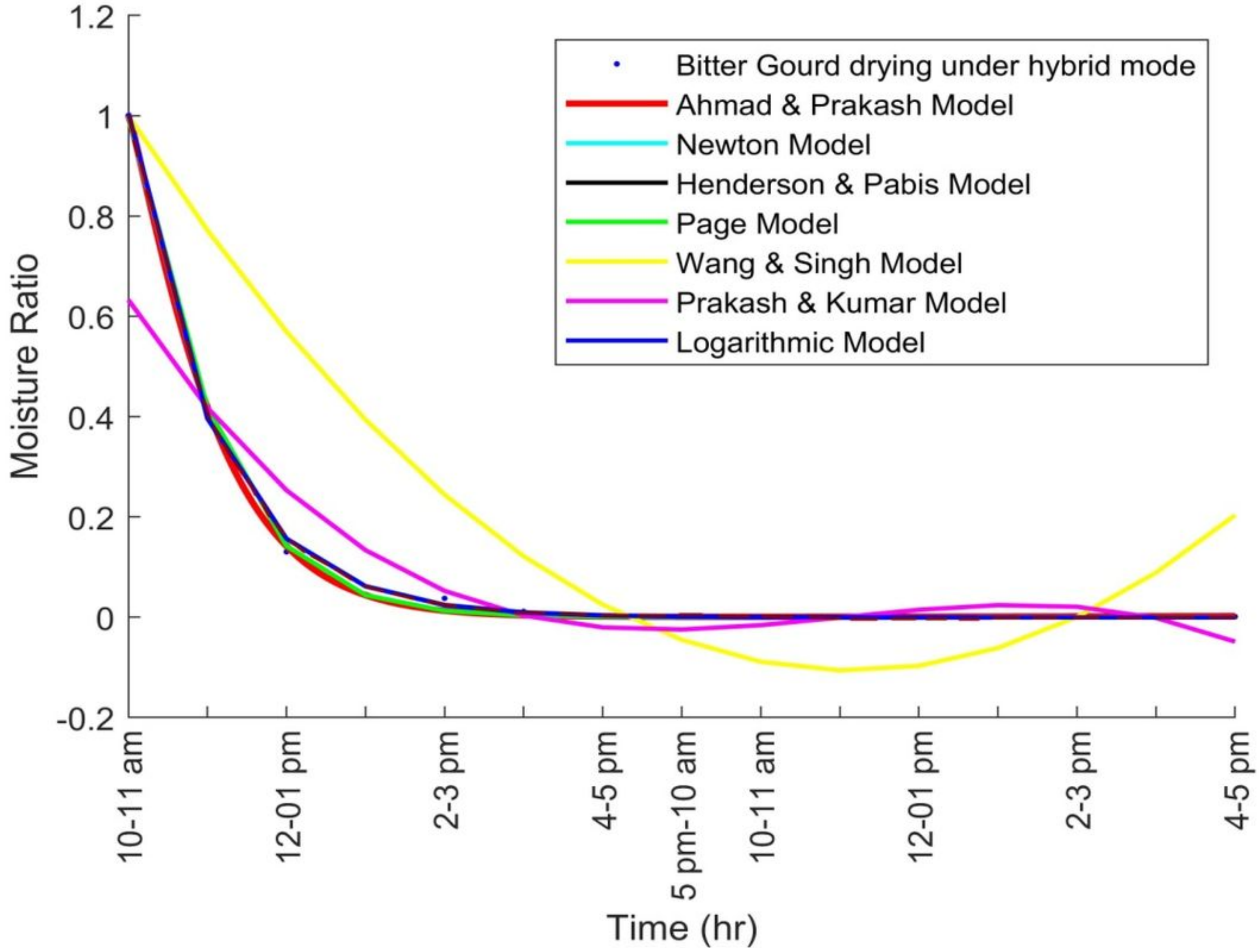

Figure 11

Variation of Prediction & Experimental Value of Moisture ration for different Mathematical Model in Hybrid Mode

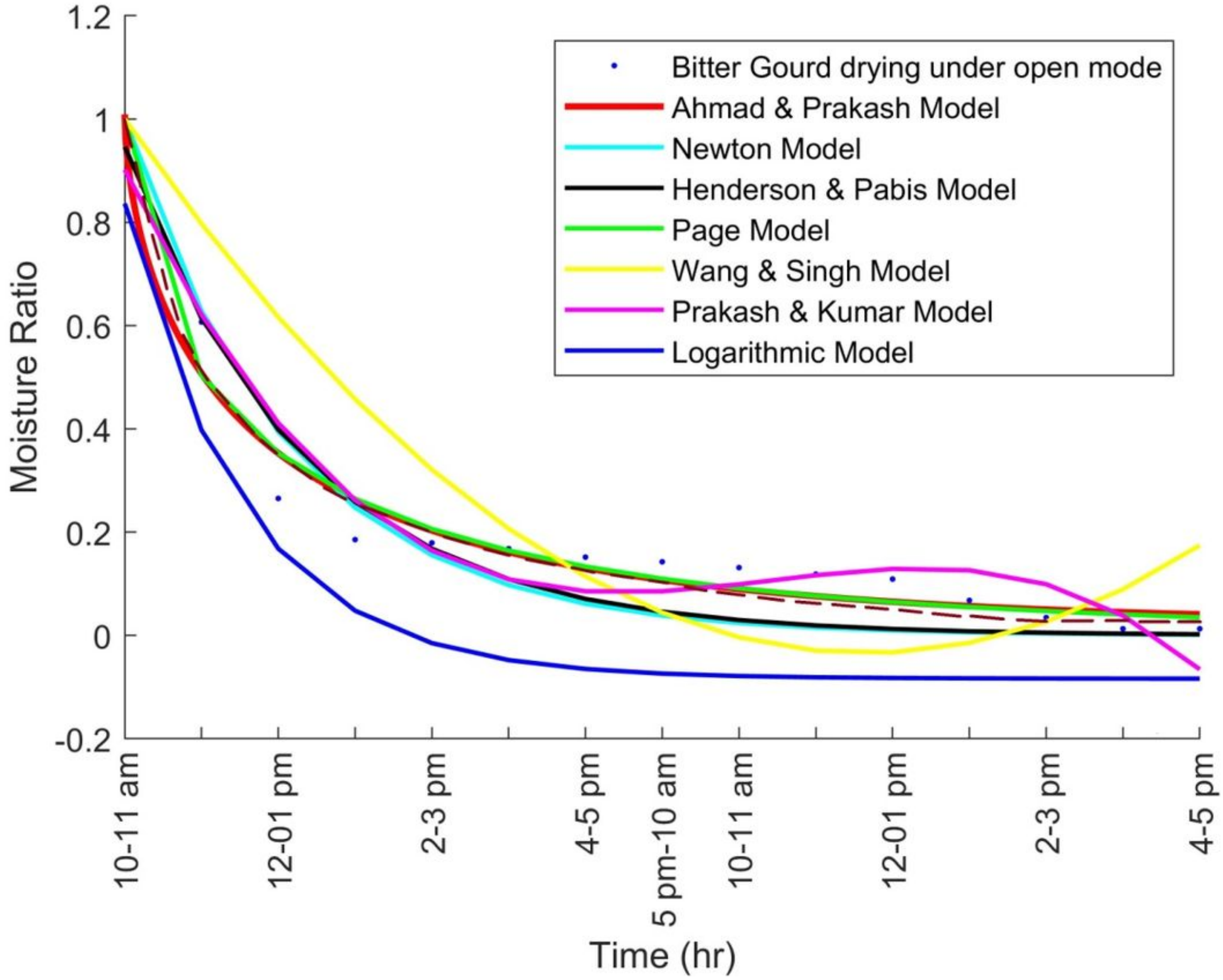

Figure 12

Variation of Prediction & Experimental Value of Moisture ration for different Mathematical Model in Open Mode

Supplementary Files

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- BittergourdTable.pdf