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## Article

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# Performance of modified greenhouse dryer with thermal energy storage



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## ABSTRACT

In this attempt, the main goal is to do annual performance, environomical analysis, energy analysis and exergy analysis of the modified greenhouse dryer (MGD) operating under active mode (AM) and passive mode (PM). Thermal storage is being applied on the ground of MGD. It is applied in three different ways namely barren floor, floor covered with black PVC sheet (PVC) and Black Coated. Experimental study of dryers in no-load conditions reveals that floor covered with a black PVC sheet is more conducive for drying purpose than other floors. The MGD under AM is found to be more effective as compared to PM for tomato and capsicum, which are high moisture content crops. For medium moisture content crop (potato chips), both dryers show relatively similar drying performance. Crops dried inside the greenhouse dryer are found to be more nutrient than open sun dried crops. The payback period of the modified greenhouse dryer under passive mode is found to be 1.11 years. However, for the active mode of the modified greenhouse dryer is only 1.89 years. The embodied energy of the passive mode of the dryer is a 480.277 kWh and 628.73 kWh for the active mode of the dryer. The CO<sub>2</sub> emissions per annum for passive and active mode greenhouse dryers are found to be 13.45 kg and 17.6 kg respectively. The energy payback time, carbon mitigation and carbon credit have been calculated based type of crop dried. The range of exergy efficiency is 29%–86% in MGD under PM and 30%–78% in the MGD under AM. The variation of Heat utilization factor (HUF) for MGD under PM is 0.12–0.38 and 0.26–0.53 for MGD under AM. The range of co-efficient of performances (COP) for MGD under PM is 0.55–0.87 and 0.58–0.73 for MGD under AM.

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## 1. Introduction

At the present stage, the stock of precious fossil fuel is depleting at a very high rate. It leads to the rise in the price of the fossil fuel along with energy insecurity in the coming future. The burning of fossil fuel also leads to environmental pollution that is the one the primary concern of the world. Hence, researchers and scientists are looking to find the alternate energy sources, which fulfil the energy demand with low-cost along with environmentally friendly. In the present scenario, solar power emerges as an alternative option to provide the energy security. Since significant amount of energy is being used in the field of drying, hence by the use of solar energy, it can reduce up to 27%–80% of precious non-renewable energy (Prakash and Kumar, 2013a). Solar dryer can be used for

the low temperature drying. Many researchers have applied this concept and dryer various agricultural produce such as red chilli, fenugreek, jaggery, tomato, onion (Fudholi et al., 2014; Shrivastava and Kumar, 2015; Kumar and Tiwari, 2006a,b; Kumar and Tiwari, 2007; Prakash and Kumar, 2014a). A detailed review on the solar drying by the use of various existing solar dryers in the different part of the globe is being done by the researcher (Kumar et al., 2014).

From a long time, the greenhouse is being used for the purpose of cultivation of the crops. It works on the principle of the greenhouse effect. It is found that crop cultivated in the greenhouse is better developed as compared to the open sun grown crops (Kumar et al., 2006). From last two and half decade, greenhouse structure is also being used for the purpose of low temperature drying by the help of solar radiation. The greenhouse dryer (GD) is being operated in the natural convection heat transfer mode (Passive mode) and forced convection mode of heat transfer (active mode). Prakash and Kumar (2014b) have reviewed various existing greenhouse dryer of both modes. Kumar et al. (2013) have done the study

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### Nomenclature

$U$	Overall heat transfer coefficient ( $W/m^2 \text{ } ^\circ C$ )
$A_i$	Area of the wall where $i = 1-5$ in $m^2$
$T_r$	Room temperature ( $^\circ C$ )
$T_a$	Ambient temperature
$I_g$	Global radiation in $W/m^2$
$A$	Effective area of dryer tray in $m^2$
$N$	Number of air exchange per hour
$V_e$	The velocity of exhaust air in $m/s$ .
$\sigma$	Standard deviation
$X'_i - X'$	Deviation from the mean
$N$	Number of sets
$N_0$	Number of observation in each set.
$T_{gd}$	Ground temperature in $^\circ C$
$T_{rm}$	Temperature of inside modified greenhouse dryer in $^\circ C$
$T_a$	Ambient temperature in $^\circ C$ .
$T_t$	Total moisture content at any given time
$T_o$	Initial moisture content prior to drying
$T_e$	Equilibrium moisture content.
$p_1$	Number of repressors
$n_1$	Sample size
$Y_p$	Predicted value
$Y_e$	Experimental value
$Dr_c$	Dryer cost
$d$	Rate of interest
$f$	Rate of inflation
$W_m$	Mass of water removed
$E_m$	Embodied energy in kWh.
$n$	Life span of dryer which is 35 years
$D$	Exchange rate of carbon credit based international policy
$E_{cha}$	Input energy in the chamber
$m_o$	At zero moisture content time
$M_{initial}$	Initial moisture content
$M_{final}$	Final moisture content
$L$	latent heat of vaporization in $kJ/kg$
$I$	Solar intensity in $W/m^2$ .

over GD under passive mode (PM) and active mode (AM) of the roof even span type in the monsoon season in no-load conditions. The result shows that GD under AM is comparatively better thermal performance than PM of the GD due to lower inside humidity.

Kumar and Tiwari (2006a,b) have dried jaggery in the roof even span type greenhouse dryer under passive and active mode. The thermal model predicted the important drying parameters such as jaggery temperature, jaggery mass and room temperature. The result shows that the thermal model can predict with fair accuracy. Kumar and Tiwari (2007) have studied the effect mass of onion flakes to the convective mass transfer coefficients in three different ways of drying—open sun drying, greenhouse drying under forced convection and greenhouse dryer under natural convection. The study reveals that the convective mass transfer coefficients strongly depend upon mass of the onion flakes in tray. The result shows that for high moisture content crop, greenhouse dryer under AM is found to be more efficient and for low moisture content crop, greenhouse dryer under passive mode is found to be more effective. For the medium moisture content crop, both dryers' shows almost similar drying effect. Kumar and Tiwari (2006c) have studied the effect of various shapes and size of jaggery to the convective mass transfer coefficient of the roof even span type greenhouse dryer of both modes. Study shows that for the larger pieces of jaggery, greenhouse dryer under active mode was found to be high convective mass transfer coefficients than passive mode dryer.

Researchers have applied the novel soft-computing prediction models to predict the important drying parameters for the greenhouse dryer such room temperature, room relative humidity, ground temperature (Prakash and Kumar, 2013b, 2014c,d,e). The model was able to predict with high-level accuracy which far superior to a thermal model. To make greenhouse dryer more efficient, some modification is being incorporated in the conventional greenhouse dryer. Two significant thermal losses take place in the greenhouse dryer namely through the north wall and ground of the greenhouse. In order to minimize the ground loss, Study is being carried out in different floor conditions for the greenhouse dryer and opaque mirror is applied in the north wall of the greenhouse to minimize the thermal losses from the north wall (Prakash and Kumar, 2014f,g,h). Result shows the significant improvement in system efficiency as compared to the traditional greenhouse dryer. The study of the modified greenhouse dryer under AM in the load condition is being conducted for the tomato flakes drying (Prakash and Kumar, 2014a). An experiment was carried out simultaneously in the open sun drying as well as in the dryer. Environmental analysis and mathematical modelling were being performed for the same dryer. The study has shown that this dryer is more efficient than all other existing greenhouse dryers.

The objectives of this research are to perform: (i) annual performance of the both dryers in the three different floor conditions (barren concrete floor "BCC", floor covered with double layer of black PVC sheet with holes in upper layer "BPVC" and black painted concrete floor "BPCF") (ii) drying simultaneously in all three modes for three different crops and compares its biochemical properties (iii) cost and energy analysis of the both dryers.

## 2. Materials and methods

Both modified greenhouse dryer is being made by the aluminium frame due its light in weight and other important technical properties. The frame was enveloped with the transparent polycarbonate sheet except north wall. The opaque mirror is applied in northern wall of the dryer. The dimension of length, width and side height is 1.5 m, 1.0 m and 0.5 m respectively. The roof top of the dryer is the even span and inclination is the  $23.5^\circ$  because this angle is the latitude of the Bhopal. The exhaust fan of the active mode of the dryer is powered by the 6 W of solar panel with battery backup. The mass flow rate is found to be  $0.0375 \text{ m}^3/s$  in the modified greenhouse dryer under active mode. Experimental observations were taken in hourly basis. To measure the weight of the crop, top weighing machine—model no TTB 10, Wensar weighing Scales Limited, India, of capacity 10 kg were used. The hygrometer by Lutron (HT-305) was used to measure temperature and relative humidity. For measuring the crop and ground temperature, Mini Temp portable infrared thermometer were used and solar power meter was used to measure the global solar radiation.

After fabrication of the both dryers, these were tested round the year in the no-load conditions to evaluate its thermal performance. Experiments were conducted from October 2012 to May 2103 in no-load condition except June–September 2013 due to rainy season. Every month from 15th to 17th observation were taken in the three different floor conditions for both dryers from 9:00 am to 5:00 pm. First day dryers were kept on the BCC, second day on the BPVC and on the third day, dryers were kept on the BPCF. After testing of the dryer in no-load conditions, three different crops of 3500 gm namely tomato flakes, potato chips and capsicum flakes were dried in the three different modes simultaneously from 20th to 25th October 2013 in the Department of Energy (Energy Centre), Maulana Azad National Institute of Technology, Bhopal, India as shown in Fig. 1. All crops were purchased in local market of Bhopal. Capsicum and tomato did not require any pre-treatment except washing and removing any foreign impurities on the surface of

the crop. After cleaning and removal all possible impurities, crop were cut into thickness of 3–5 mm slices. However, potato drying needs some pre-treatment process. Potato chips required some pre-treatment so after cut in to 1.28 cm thick then two process is required. Firstly blanching for 7–9 min in steam and secondly cool for 6–7 min in cool water. After pre-treatment, the potato chips were spread in the drying tray without overlapping of chips. Same amount of 3500 gm of potato chips were dried in the open sun drying mode separately and at the same time (Fig. 1). Experimental uncertainty analysis were done for most sensitive drying parameter to ensure the instrumental competency (Prakash and Kumar, 2015). After drying of all crops, the dried crop was converted into powder form and examined the various biochemical properties in the Indian Agricultural Research Institute (IARI).

### 3. Numerical computation for performance analysis

#### 3.1. Thermal performance analysis

##### 3.1.1. Characteristic curve in no-load condition

The characteristic curve is being drawn for both modified dryer in all three floor conditions. It was drawn according to the Prakash and Kumar (2015) with instantaneous thermal loss efficiency factor ( $\eta_i$ ) verse  $\frac{T_r - T_a}{I_g A}$ .

The instantaneous thermal loss factor for passive dryer is

$$\eta_i = \frac{U' \sum A_i (T_r - T_a)}{I_g A} \quad (1)$$

For active mode dryer is

$$\eta_i = (0.33N V_e (T_r - T_a)) / (I_g A). \quad (2)$$

##### 3.1.2. Heat utilization factor (HUF): (Sayyad et al., 2010)

$$HUF = \frac{(T_{gd} - T_{rm})}{(T_{gd} - T_a)}. \quad (3)$$

##### 3.1.3. Co-efficient of performances: (Sayyad et al., 2010)

$$COP = \frac{(T_{rm} - T_a)}{(T_{gd} - T_a)}. \quad (4)$$

##### 3.1.4. Specific energy consumption

Specific Energy Consumption for the drying of crops is evaluated by following equation (Fudholi et al., 2013):

$$SEC = \frac{E_{cha}}{W_m} \quad (5)$$

where,  $W_m$  is the mass of water removed that is evaluated by the equation which is given as:

$$W_m = \frac{m_0 (M_{int} - M_{final})}{100 - M_{final}}. \quad (6)$$

Drying efficiency of the system is calculated from following relation (El-Sebaili and Shalaby, 2012):

$$\eta = \frac{W_m l}{I_g A_{ch}} \quad (\text{For passive mode}) \quad (7)$$

$$\eta = \frac{M_w l}{I_g A_{ch} + P_t} \quad (\text{For Active mode}). \quad (8)$$

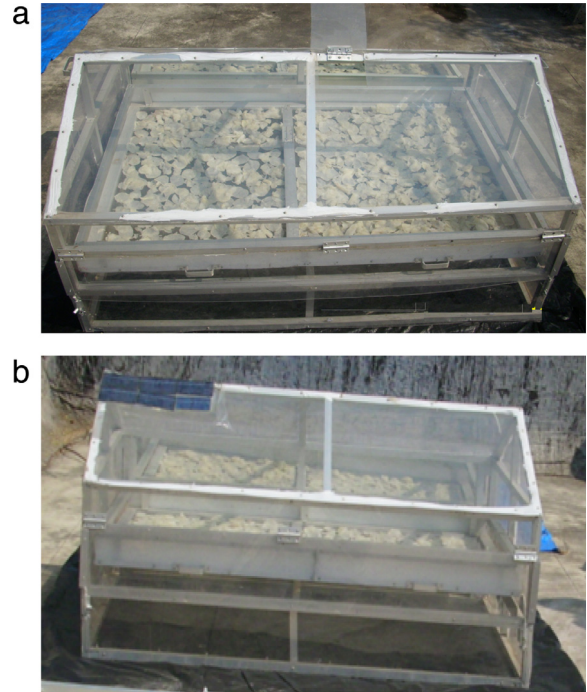


Fig. 1. Photographs for modified greenhouse dryer under passive mode (a) and active mode (b) for potato chips drying.

#### 3.2. Environmental analysis

##### 3.2.1. Embodied energy

The total energy required to produce any items, things or services is called embodied energy. Table 1 presents the embodied energy of the materials which is being used in the development of the active mode and dryer under passive mode respectively.

##### 3.2.2. Energy payback time (EPBT)

It is the time required to pay back the embodied energy of the product and calculated as (Prakash and Kumar, 2014a):

$$\text{Energy Payback Time (EPBT)} = \frac{\text{Embodied Energy}}{\text{Annual Energy Output}}. \quad (9)$$

##### 3.2.3. CO<sub>2</sub> emission

The CO<sub>2</sub> emission per year can be calculated as (Prakash and Kumar, 2014a):

$$\text{CO}_2 \text{ emissions per year} = \frac{\text{Embodied energy} \times 0.98}{\text{Lifetime}}. \quad (10)$$

##### 3.2.4. CO<sub>2</sub> mitigation and earned carbon credit

The CO<sub>2</sub> mitigation per kWh of the dryer would be (Prakash and Kumar, 2014a):

$$Z = \frac{1}{1 - L_a} \times \frac{1}{1 - L_{td}} \times 0.98 = 2.01 \text{ kg/kWh}.$$

The CO<sub>2</sub> mitigation in throughout the life of the system

$$= E_m \times Z. \quad (11)$$

The net mitigation of CO<sub>2</sub> over lifetime (kg)

$$= \text{Total CO}_2 \text{ mitigation} - \text{Total CO}_2 \text{ emission} \\ = [E_a \times n \times Z - E_m] \text{ kg} \quad (12)$$

where,  $n$  is life span of dryer which is 35 years.

The earned carbon credit would be

$$= \text{net mitigation of CO}_2 \text{ in life span (tones)} \times D \quad (13)$$



**Table 1**  
Embodied energy for the fabrication of modified Greenhouse dryer (Prakash and Kumar, 2014a,b).

S.no.	Material	Quantity	Embodied energy coefficient	Total energy for active dryer (kWh)	Total energy for passive dryer (kWh)
1	Polycarbonate sheet	15.600 kg	10.1974 (kWh/kg)	159.0794	159.0794
2	Glass	5.400 kg	7.2800 (kWh/kg)	39.3120	39.3120
3	Silver coating	0.750 m <sup>2</sup>	0.2780 (kWh/m <sup>2</sup> )	0.2085	0.2085
4	Black PVC sheet	0.325 kg	19.4400 (kWh/kg)	6.3180	6.3180
5	Wire mesh steel tray	0.700 kg	9.6700 (kWh/kg)	6.7690	6.7690
6	Aluminium section				
	(i) 1"X1 mm section	3.590 kg	55.2800 (kWh/kg)	198.4552	198.4552
	(ii) 4"X1 mm section	0.820 kg	55.2800 (kWh/kg)	45.3296	45.3296
	(iii) 1"X3 mm angle	0.080 kg	55.2800 (kWh/kg)	4.4224	4.4224
7	Fitting				
	(i) Hinges/Kabja	0.200 kg	55.2800 (kWh/kg)	11.0560	11.0560
	(ii) Kundi (door lock)	0.025 kg	55.2800 (kWh/kg)	1.3820	1.3820
	(iii) Handle	0.100 kg	55.2800 (kWh/kg)	5.5280	5.5280
	(iv) Steel screw	0.250 kg	9.6700 (kWh/kg)	2.4175	2.4175
8	DC fan				
	(i) Plastic	0.120	19.4400 (kWh/kg)	2.3328	–
	(ii) Cooper wire	0.050	19.6100 (kWh/kg)	0.9805	–
9	Polycrystalline solar cell	0.059 m <sup>2</sup>	1130.6000 kWh/m <sup>2</sup>	66.1378	–
10	Battery		148.4515	46.0000	–
11	Solar charge controller			33.0000	–
<b>Embodied energy (kWh)</b>				<b>628.7287</b>	<b>480.2776</b>

where,  $D$  varies from \$5–20/tones of CO<sub>2</sub> mitigation and at present 1\$ equal to almost 60 INR (Prakash and Kumar, 2014a).

### 3.2.5. Cost analysis

The payback period of the dryer is being calculated as (Prakash and Kumar, 2014a)

$$N = \frac{\ln\left(1 - \frac{D_{fc}}{S}(d-f)\right)}{\ln\left(\frac{1+f}{1+d}\right)} \quad (14)$$

### 3.3. Exergy analysis

The exergy of dryer is evaluated based on first law of energy balance equation. In the steady flow, the exergy equation of system is like this (Fudholi et al., 2013):

$$E_x = m_{d\text{ amb.}} C_{pd\text{ amb.}} \left[ (T - T_{amb.}) - T_{amb.} \ln \frac{T}{T_{amb.}} \right] \quad (15)$$

At the inlet of the system where ambient air enter the system, the exergy equation is like this (Fudholi et al., 2013)

$$E_{x_{dci}} = m_{d\text{ amb.}} C_{pd\text{ amb.}} \left[ (T_{dc\text{ inlet}} - T_{amb.}) - T_{amb.} \ln \frac{T_{dc\text{ inlet}}}{T_{amb.}} \right] \quad (16)$$

At the outlet of the system where inside air goes out from the system, the equation of exergy is like this

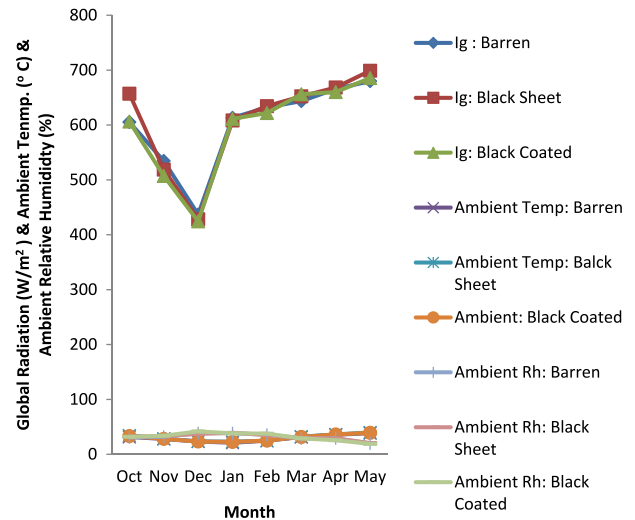
$$E_{x_{dco}} = m_{d\text{ amb.}} C_{pd\text{ amb.}} \left[ (T_{dc\text{ outlet}} - T_{amb.}) - T_{amb.} \ln \frac{T_{dc\text{ outlet}}}{T_{amb.}} \right] \quad (17)$$

Exergy losses during the process of drying can be calculated as follow (Fudholi et al., 2013):

$$E_{x_{loss}} = E_{x_{dci}} - E_{x_{dco}} \quad (18)$$

Exergy efficiency may be defined as that “the ratio of exergy use in the drying of the product to exergy of the drying air supplied to the system” (Akbulut and Durmus, 2010). Therefore, the equation of exergy efficiency is: (Fudholi et al., 2013)

$$\eta_{Ex} = \frac{E_{x_{dco}}}{E_{x_{dci}}} = 1 - \frac{E_{x_{loss}}}{E_{x_{dci}}} \quad (19)$$



**Fig. 2.** Variation of global solar radiation, ambient temperature and ambient relative humidity during no-load experimentation.

## 4. Result and discussion

### 4.1. No-load condition

After fabrication of the system, both dryers were tested in the no-load condition in order to evaluate its thermal performance. Experiments were conducted from October 2012 to May 2013. For three different floor conditions, three different days were selected in a month. On 15th both dryers were kept on the barren concrete floor, on 16th both dryers were kept on the floor covered with double layer of black PVC sheet and on 17th both dryers were kept on the black painted floor. In all three days of the month, all-most similar weather conditions were there, hence variation in the global solar radiation, ambient temperature and relative humidity was very low as it is shown in Fig. 2.

The ground temperature, inside room temperature and inside room relative humidity are responsible to create favourable drying atmosphere inside the greenhouse dryer. The variation of these three parameters during experimentation is presented in the Figs. 3 and 4 for both dryers. Greenhouse room temperature is found to be always higher than ambient temperature. The room and ground temperature is found to the highest when dryer is

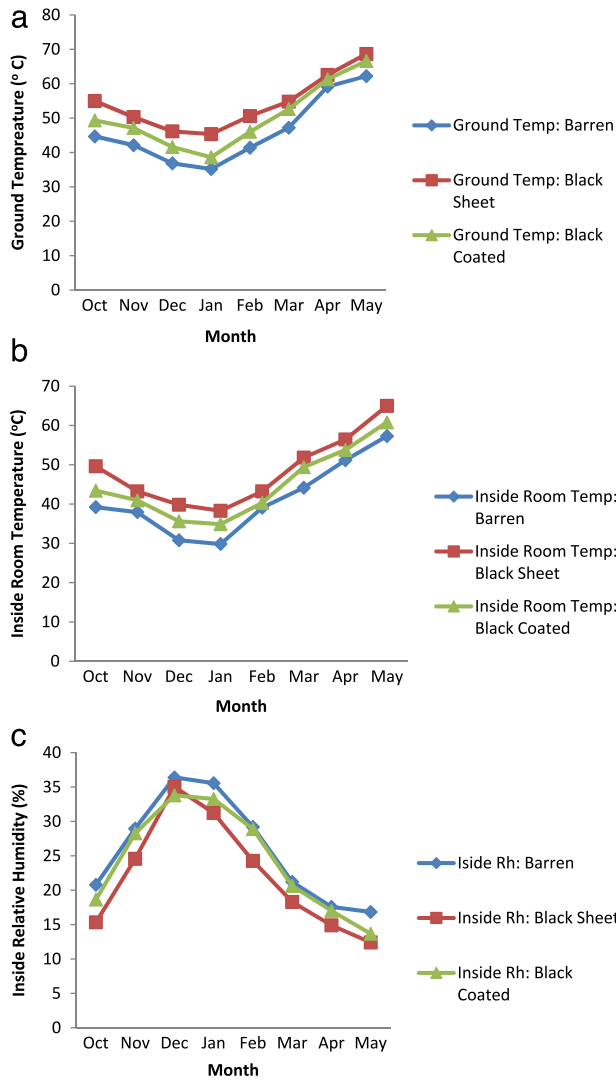


Fig. 3. (a–c). Variation of greenhouse dryer under passive mode (a) ground temperature (b) inside room temperature (c) inside relative humidity.

kept on the BPVC and the lowest in the BCC. For passive mode of dryer, the average monthly temperature difference between greenhouse and ambient air varies from 7.6 to 18.77 °C in case of BCC, however for BPCF varies from 10.21 to 20.67 °C also for dryer is kept on the floor covered with black PVC sheet, it varies from 15.11 to 25.23 °C. Due to constantly removal of humid air, the inside temperature is lower than passive mode of the dryer. The raise of temperature for both ground temperature and room temperature is found to be highest when dryer is kept in the concrete floor covered with BPVC and lowest in the BCC. Hence, heat energy accumulation inside the greenhouse is higher in the case of BPVC. It is due to minimization of conductive losses to the ground. The covered double layer black PVC sheet have fine holes in upper layer. These black PVC layers act as solar air heating devices or system for the dryer. The relative humidity of inside air is always found to be lower than ambient relative humidity due to heat accumulated inside dryer. For active mode dryer, the monthly variation in ground temperature of the barren floor varies from 35.20 to 68.90 °C, 41.60 to 66.60 °C in black colour concrete floor conditions and 46.10 to 68.20 °C when dryer is kept on PVC covered concrete floor. Fig. 6 represents the variation of HUF and COP for both dryer. The variation of Heat utilization factor (HUF) for MGD under PM is 0.12–0.38 and 0.26–0.53 for MGD under AM. The range of co-efficient of performances (COP) for MGD under PM is 0.55–0.87 and 0.58–0.73 for MGD under AM.

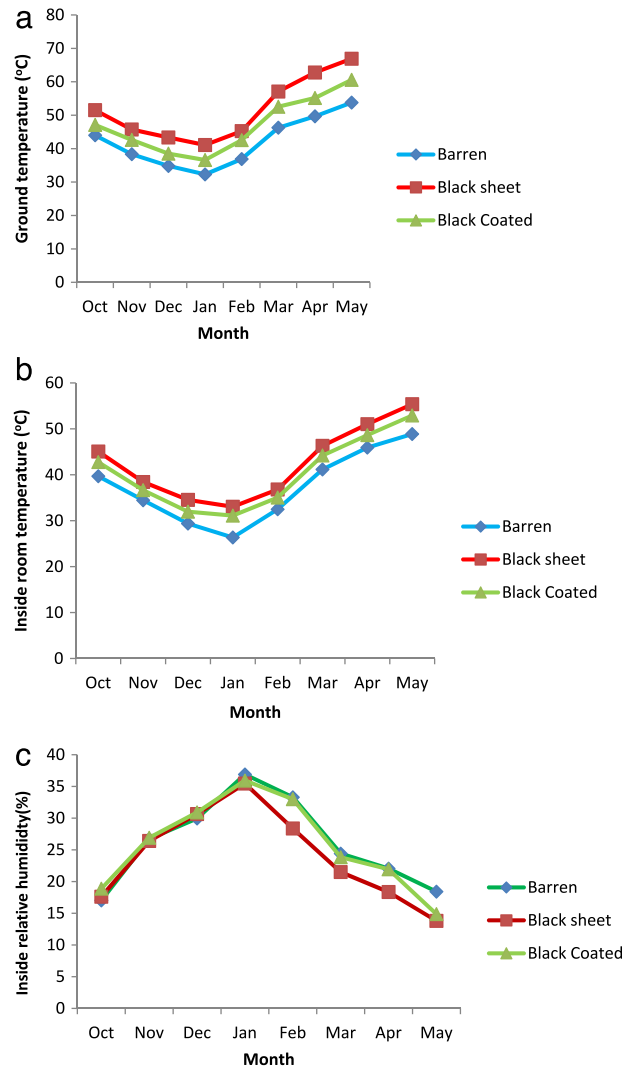


Fig. 4. (a–c). Variation of greenhouse dryer under active mode (a) ground temperature (b) inside room temperature (c) inside relative humidity.

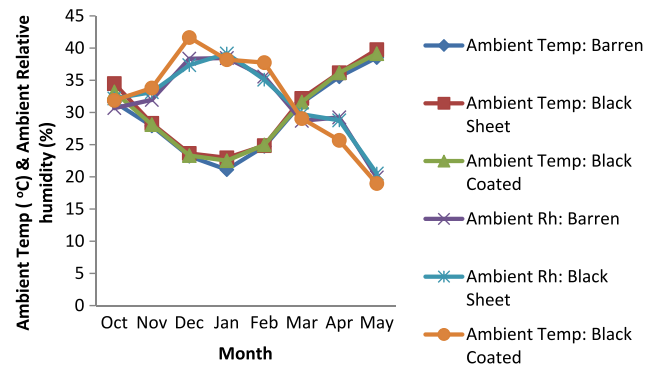


Fig. 5. Variation of ambient parameters during experimentation in load conditions.

#### 4.2. Load condition

The variation of ambient parameters was found to be almost similar during experimentation in load conditions as presented in Fig. 5. Each crop was dried for two consecutive days. Both day clear sky conditions were there. Due to this drying experiment was conducted smoothly. Drying of all three crops (tomato flakes, capsicum flakes and potato chips) of conducted in all three modes simultaneously. For all three crops, the drying performance of

**Table 2**  
EPBT of the dryer, net carbon dioxide mitigation and earned carbon credit in various conditions.

S. No.	Parameters	Units	Drying materials											
			Potato				Capsicum				Tomato			
			Active		Passive		Active		Passive		Active		Passive	
1	EPBT	Years	1.51	1.16	1.24	1.01	1.14	0.94						
2	CO <sub>2</sub> mitigation	Tones	28.65	28.69	35.01	33.36	38.06	35.36						
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
3	Earned carbon credit	INR	9456.59	37,826.37	9470.45	37,826.37	11,555.71	46,222.84	10,904.84	43,620.07	12,561.70	50,245.49	11,669.91	46,680.95

**Table 3**  
Fabrication materials and its cost.

S. No.	Materials	Material used	Cost per unit (INR)	Total cost (INR) for passive dryer	Total cost (INR) for active dryer
1	Polycarbonate sheet	3.25 (m <sup>2</sup> )	1748	5683.0	5683.0
2	Mirror	1.50 (m <sup>2</sup> )	733	1100.0	1100.0
3	Black PVC sheet	3.00 (m <sup>2</sup> )	27	81.0	81.0
4	Aluminium angle and channel	5.00 kg	200	1000.0	1000.0
5	Wire mesh stainless steel	1.15 (m <sup>2</sup> )	70	80.5	80.5
6	Screw			50.0	50.0
7	Labour			1000.0	1000.0
8	DC fan	1.00 no	350	–	350.0
9	Polycrystalline solar cell	6.00	300	–	1800.0
10	Battery	1.00	500	–	500.0
11	Solar charge controller	1.00	1200	–	1200.0
	<b>Total (INR)</b>			<b>8994.5</b>	<b>12844.5</b>

**Table 4**  
Properties of the dried crops.

S. No.	Properties	Tomato			Capsicum			Potato		
		Open	Active	Passive	Open	Active	Passive	Open	Active	Passive
1	Moisture (%)	13.04	9.09	10.26	8.19	4.27	6.27	15.04	13.54	13.10
2	Ascorbic acid (mg/100 g)	14.23	29.20	26.70	41.30	51.20	50.90	2.56	5.69	8.54
3	Lycopene (mg/100 g)	24.02	34.63	27.40	1.56	3.54	3.53	0.93	1.24	2.02
4	$\beta$ Carotenoid (mg/100 g)	2.02	2.64	2.32	0.22	0.26	0.25	0.05	0.13	0.12
5	Total Carotenoid (mg/100 g)	4.10	3.14	3.25	0.50	0.40	0.38	0.19	0.13	0.12
6	Nitrogen ( $\mu$ g/100 mg)	10.10	13.10	11.20	9.00	10.30	10.50	5.10	7.70	7.80
7	Reducing Sugar ( $\mu$ g/100 mg)	78.68	80.22	80.47	78.34	75.32	73.55	78.44	77.66	76.17
8	Poly Phenols (mg/100 gm)	78.20	69.14	58.38	84.11	120.25	117.25	9.24	13.37	14.96

**Table 5**  
Experimental percent uncertainties for crops.

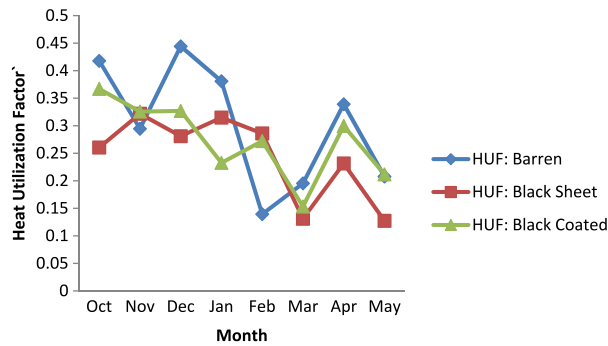
Drying mode	Tomato			Capsicum			Potato		
	I.U. (%)	E.U. (%)	T.U. (%)	I.U. (%)	E.U. (%)	T.U. (%)	I.U. (%)	E.U. (%)	T.U. (%)
Open sun drying	19.20	0.50	19.70	15.08	0.50	15.58	9.64	0.50	10.14
Passive mode drying	20.61	0.50	21.11	18.30	0.50	18.80	9.90	0.50	10.40
Active mode drying	22.46	0.50	22.96	19.07	0.50	19.57	9.78	0.50	10.28

**Table 6**  
Performance of modified greenhouse solar drying of crops and comparative analysis of specific energy consumption and input energy under active and passive mode.

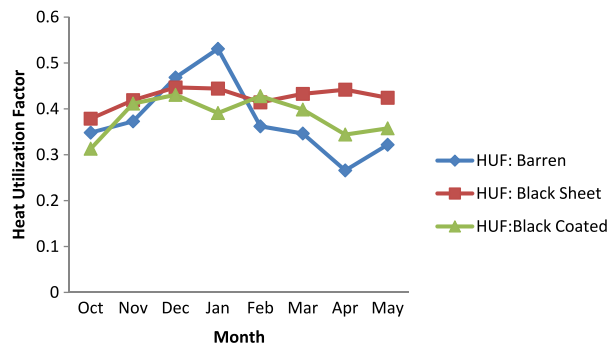
S. No.	Parameters	Units	Crops					
			Potato		Capsicum		Tomato	
			Active	Passive	Active	Passive	Active	Passive
1	Average exergy efficiency	%	78	86	62	31	30	29
2	Average exergy	kW	0.016	0.018	0.017	0.017	0.0069	0.0445
3	Average exergy loss	kW	0.0063	0.0130	0.0073	0.014	0.0120	0.016
4	Inlet energy	kWh	4.559	4.55	4.55	33.16	4.55	4.55
5	Average specific energy consumption	kWh/kg	1.92	1.92	2.99	1.58	4.8	2.58

the open sun drying was found to be the minimum as compared of MGD under active and passive mode. For the high moisture content crop namely capsicum flake and tomato flakes, modified greenhouse dryer under active mode was found to be more efficient and for medium moisture content crop (potato chips), both dryers shows almost equal drying performance. At present

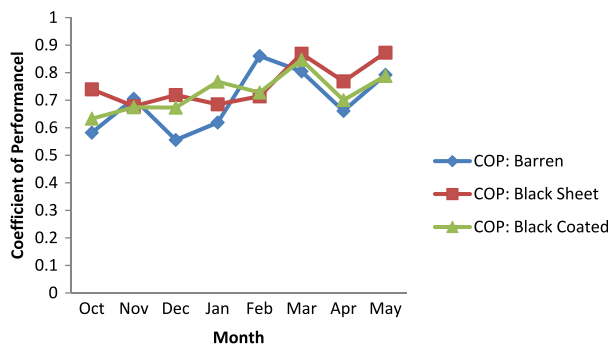
situation it is very important to do energy analysis for the developed system. There are five different energy analysis have been applied to the dryer namely embodied energy, energy pack back time, CO<sub>2</sub> emission, CO<sub>2</sub> mitigation and carbon credit. The details of the material involved in the fabrication of the dryer along with its energy density is presented in Table 1. The embodied



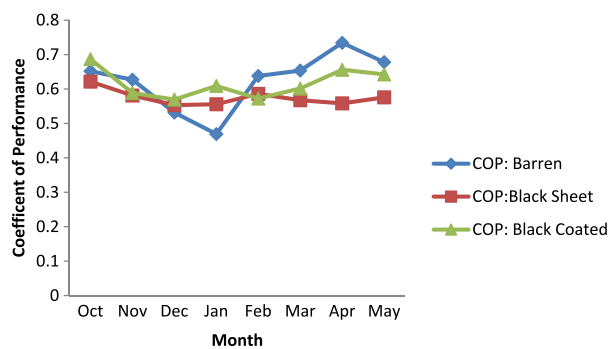
(a) Passive mode.



(b) Active mode.



(c) Passive mode.



(d) Active mode.

**Fig. 6.** (a–d). Variation of HUF and COP of various material modes of greenhouse dryer under active and passive mode.

energy for the passive mode of the dryer is 480.2776 kWh and 628.7287 kWh for the active mode dryer respectively. The energy payback time is calculated based on equations and this is presented in Table 2. For all the crops, EPBT for the passive mode of dryer is found to be low as compared to the active mode dryer due its low

embodied energy. The CO<sub>2</sub> emission per year for the passive mode dryer is only 13.45 kg, however in active mode dryer, it is 17.6 kg.

In order to do economic analysis for the dryer, the payback period by cost of both dryer is being calculated. The detail cost of items and service in the process of fabrication is being presented in Table 3. Due to simple construction in the passive mode dryer, cost incurred is only 8994.5 INR moreover, for active mode dryer it is INR 12844.5. The payback period for passive mode dryer is 1.11 year however for active mode dryer it is 1.89 years.

After drying, each crop is made into powder and several biochemical properties is being evaluated in the Indian agricultural Research Institute, New Delhi and it is given in Table 4. Results show that crop dried in the active mode is found to be more nutritious for the tomato and capsicum flakes however for potato chips both dryers shows almost similar performance. The uncertainty analysis for the moisture evaporation is being calculated. The internal, external and total uncertainty is being presented in Table 5. The performances of modified greenhouse solar dryer and comparative analysis of energy input to system and average specific energy consumption, exergy efficiency, average exergy and exergy loss are presented in Table 6. The average specific energy consumption was found to be 1.92 for both dryer. However for both crop namely tomato and capsicum flakes, MGD under AM is found to be higher average specific energy consumption than passive mode dryer.

It is also analysed in both active and passive mode. The highest value of HUF for Barren, Black Sheet and Black Coated is obtained 0.531, 0.444 and 0.431 respectively on active mode. The COP for Barren, Black Sheet and Black Coated is obtained 0.734, 0.621 and 0.686 respectively on active mode. The variation of COP and HUF is being shown in Fig. 6.

**Conclusion:**

Based on results obtained in this research, concluding remarks are follows:

1. An attempt is made to modify the existing conventional greenhouse dryer to minimize the losses through the north wall and ground.
2. The experimental study has been carried out in the three different floor conditions for modified greenhouse dryer namely barren concrete floor, ground concrete floor covered with black PVC sheet of 0.3 mm thickness and concrete floor coloured by heat resistant black paint. After testing of dryers in no-load condition, PVC covered concrete floor is being recommended for drying in load conditions due to high thermal storage. This leads moderate room temperature of the dryer.
3. Experimental result reveals that for high moisture content crop, modified greenhouse dryer under active mode is found to be better drying performance than modified greenhouse dryer under passive mode and open sun drying.
4. The payback period by cost of MGD was only 1.11 year and payback time by cost for MGDA is slight higher than others because additional costs of other components, which is 1.89 years. The life span of these dryers is considered 35 years.
5. The embodied energy for passive and active dryer are 480.28 and 628.73 kWh, the CO<sub>2</sub> emission in kg per year are 13.45 and 17.6 kg respectively for passive and active mode dryer. The average value of energy payback time, carbon mitigation and earned carbon credit for passive mode of modified greenhouse dryer are 1.04 years, 32.36 tones and INR 26705.00 respectively. However for active mode of the dryer, these parameters are 1.3 years, 33.9 tones and INR 27978.34 respectively.
6. This study would be useful for the scientists and researchers who are working in the field of solar drying and above developed techniques can be utilized for the other designs of solar drying systems for commercial drying.



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