J Ther Eng, Vol. 10, No. 3, pp. 811–825, May, 2024

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000833

Research Article

Drying Solanum lycopersicum (Tomatoes) in greenhouse solar dryer: An eco-environmental study

Pringal M. PATEL[1,*], Vikram P. RATHOD[1], Divyesh PATEL[2]

[1]*Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, 395007, India*
[2]*The 727 Solar Food Products, Navsari, Gujarat, 396427, India*

ARTICLE INFO

Article history
Received: 20 May 2023
Revised: 23 July 2023
Accepted: 30 August 2023

Keywords:
Agriculture; Carbon Emission; Embodied Energy; Greenhouse; Life-cost; Payback; Solar Dryer

ABSTRACT

Fruits and vegetables are an important part of human diet. In the present study, the thermal performance of a solar greenhouse dryer for drying Solanum lycopersicum (Tomatoes) was analyzed. The drying pattern at various locations of the drying chamber and different levels of the dryer was evaluated. The life cost analysis for drying the tomatoes in the dryer for 25 years of service was evaluated. The greenhouse solar dryer was developed with a structure base of galvanized iron pipes and a covering of a 2 mm thick polycarbonate sheet. The experiment was carried out for drying the tomatoes at various locations in the dryer using the trays and trolley system. The maximum thermal efficiency of the dryer is 26.66 % while drying out 5.8 kgs of tomatoes in one day. The economic analysis of the greenhouse solar dryer shows that the payback period of such a system can be attained in only 1.6 years which terms the dryer feasible and economically viable in the current agro-drying market. The embodied energy for the dryer was calculated at 3154.71 kWh for the system. The CO_2 emission for the greenhouse solar dryer was found to be around 6.62 tonnes for a lifespan of 25 years. The net CO_2 mitigation was calculated at around 41.62 tonnes which would generate an earning from 46766 INR to 62355 INR worth of carbon credits.

Cite this article as: Patel PM, Rathod VP, Patel D. Drying Solanum lycopersicum (Tomatoes) in greenhouse solar dryer: An eco-environmental study. J Ther Eng 2024;10(4):811–825.

INTRODUCTION

Constant food production is not possible for various reasons, but the food can be produced in adequate quantity and stored for future demand. Still, the extra amount of the food produced starts to deteriorate as soon as it is harvested. Almost 1/3rd of the harvested agro products are wasted in India due to a lack of storage facilities [1]. Drying food products is very popular for the storage of food. The conventional drying processes are heavily energy-driven, a significant concern as the traditional energy sources add huge amounts of carbon footprints [2]. The increase in carbon footprint will directly affect the environmental cycle.

Solanum lycopersicum (Tomatoes) are a great source of vitamin A and one of the most consumed vegetables in the Indian market [3]. The overproduction of tomatoes in the harvesting season and their abundance in the market results

***Corresponding author.**
*E-mail address: pringalsvnitphd006@gmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey
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in a decrease in the price of tomatoes. The post-harvesting losses can be significantly reduced by the drying of the tomatoes. Dried tomatoes have a large economic and application market with use in various salads, pizzas, ketchup, soups and other dishes [4].The various scientific research on the drying of tomatoes suggests that heat treatment of the tomatoes does not affect their nutritional value while sometimes also increasing the level of lycopene content and antioxidant property [5]. The major problem with free sun drying is that it is prone to dust contaminations, bird excrement, and rainfall, which would indefinitely deteriorate the product's quality and appearance [6]. Chamber-based solar drying and storage systems evolved from these primary problems. The concept of chamber-based or greenhouse-based solar drying of food particles is suitable for developing nations, as farmers can utilize it directly without requiring any technical knowledge [7]. The material used in the drying arrangement is also readily available in the surrounding market at cost-effective rates. The significant advantages of a greenhouse drying system are that it consists of no moving parts and it has an almost negligible maintenance cost, and the initial cost of development is also low [8,9] dried 80 kg of chillies in a tunnel-type solar dryer, and the results suggest that the solar-dried chillies had a premium colour and astringency consistency compared to open sun-dried chillies. The pre-treatment of the products helped in shortening the drying time. The same tunnel dryer was also used to understand the drying kinetics of meat and peppermint plants [10]. The investigation of drying tomato pomace through a solar tunnel greenhouse dryer was carried out in a chamber built as a half cylinder with a plastic lid. The continuous use of exhaust fans increased the drying rate in the dryer [11]. The greenhouse solar dryer with polycarbonate sheets with 70% transmittance covered on the ceiling and three sides of the chamber with an angled roof and side loading entrance is used to dry out tomato pomace. The rear wall of the chamber was insulated with black polystyrene, and the product trays were kept inside the dryer; it took around 5 hours to dry the product at the temperature range of 40-to-58 degrees Celsius [12]. offered a somewhat alternative greenhouse solar dryer design. The concrete base of the dryer was replaced with two layers of solar collector. A solar module was provided to operate the exhaust fan. The coefficient of convective heat transfer increased due to the addition of the solar collector in the base, and the analytical finding suggests that the heat consumption factor, energy and exergy efficiency of the dryer is also more compared to the dryer without the solar collector. The dried is proposed to use for crop drying at temperatures ranging from 40°C to 70°C. A large-sized parabolic drying chamber greenhouse solar dryer was fabricated to dry 300 to 1000 kg of chilli. It consisted of nine ventilation fans which are operated with three 50 W solar cell modules. The drying time for 500 kg chilli was decreased from 5 days to 3 days when compared to open sun drying, with the chilli having initial moisture of 74% (wet basis) [13]. The performance comparison was carried out in the greenhouse drier with thermal storage and without thermal storage for drying red pepper in the drying system. The drying time was reduced to 30 hrs for the dryer with thermal storage, which was found always higher about 5-19°C compared to ambient conditions. The drying time reduces to 55 hrs in the dryer without thermal storage when compared to 75 hrs of open sun drying [14]. The performance analysis of the thermal storage material calcium hexahydrate as PCM was investigated, which suggest that varying the thickness of the PCM in the north wall from 2-5 cm varies the amount of heat stored in the drying chamber. The thickness of 4 cm was found best with the increased temperature of around 6-12°C inside the dryer in the nighttime while used in passive mode [15]. the solar air heater was coupled with the greenhouse drier to power the PCM unit inside the dryer, the average exergy and energy efficiency were found to be 4.2% and 74.3% respectively [16]. The combination of various salt was used as PCM for minimizing the formation of frost in the greenhouse dryer during cold climatic conditions; two different heat exchangers were used to keep the floor and air inside the dryer heated up. The heat exchange with sub-surface configuration was used to raise the temperature of the floor, and a water-air heat exchanger was used for the air inside the greenhouse dryer. An average increment of 4–6 degrees Celsius was reported compared to the atmospheric condition. The combination of thermal storage systems allows the drying of both during day and night for the products [17,18]. Various researchers have been working on the development of various types of solar greenhouse dryer technology to increase productivity and decrease the drying time for various types of agriculture products; the active and hybrid systems show up great potential and can be scaled up for farmers. The various application of thermal energy storage is also applied to making the dryer work for around 24 hours. The scaling up of various potential designs of dryers would lead us to practical and edible agro products in the market. The actual and marketable agro products or dried products need to be homogenous in consistency. The big batches of products need to be dried up equally with the same drying rate to achieve such consistency. The application of medium and large-scale dryers will lead us to non-homogenous drying around various points in the drying chamber. As the utilization of chamber-based drying system is increasing exponentially in developing countries, more research needs to be focused on the spatial variation of the drying rate in the chamber, which affect the quality of the final product.

The objective of the current study is to analyze the thermal performance of the greenhouse solar dryer for drying tomatoes and a novel approach to depict the spatial drying performance of the drying chamber. Estimate the embodied energy and carbon credits for the current greenhouse drying system. Analyze the life cycle cost of the current system and its economic sustainability for tomato drying.

MATERIAL AND METHODS

Process

The solar radiation penetrates the transparent sheet of polycarbonate and is absorbed by the food products. The reflected infrared radiations are trapped due to the polycarbonate sheet, which creates a greenhouse effect. Due to the greenhouse effect, the content in the dryer is heated up, and the air inside is circulated through the product due to density difference; thus, the drying of the product is carried out. Through the outlet aperture, wet air emerges, taking the moisture the product released with it. The removal of this moisture is the primary phenomenon involved in drying. Agro products consist of diverse nutrient combinations, with varying degrees of heat resistance in their constituent bond chains. Consequently, it is crucial to apply heat for moisture removal within specific limits to avoid nutrient damage, thereby ensuring the preservation of the dried product's quality [19].

The phenomenon of drying can be bifurcated into three parts, which would include pre-drying process, The drying process, and Post-drying process. In the pre-drying section, the material is processed through some treatment, which helps them to retain some nutrient properties or may help in the actual drying process. In the second part of drying comes the use of the equipment and variables for controlling the amount, direction, and time for which the product is exposed to heat energy used for removing the moisture content.

The post-drying process is followed up at last to bring the product into thermodynamic equilibrium or consumable state [20]. The evaluation of the drying system is characterized by various parameters like thermal efficiency, energy efficiency and specific heat consumption. Generally, specific heat consumption and energy efficiency have been mainly analyzed for dryer performance. Figure 1 shows how the analysis of energy consumption is performed in an indirect convective dryer system [21]. Solar radiation, the ambient temperature, and the specific humidity are also a matter of concern while designing the solar drying system, and all the environmental variables will directly affect the performance of the dryer [22, 23].

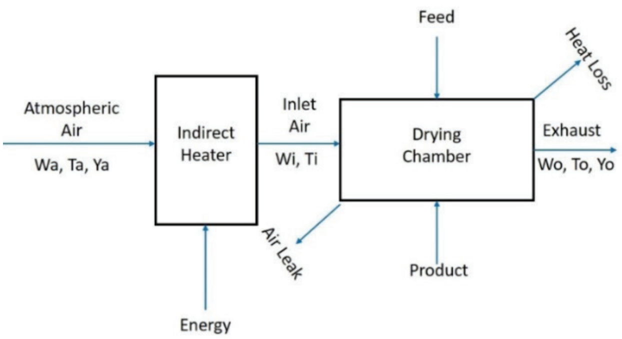

Figure 1. Schematic representation of an indirect drying process.

Experimental Apparatus

The experimental setup consists of a greenhouse solar dryer (GHSD) which was developed on the premises of the company "727 Solar Food Products" at Navsari, Surat, Gujarat, with the global co-ordinate of 20.76°N, 73.05°E. The greenhouse solar dryer is a structure that directly traps solar energy in a restricted environment to transform it into thermal energy [24]. As shown in Figure 2, the developed GHSD was constructed using a galvanized iron (GI) box pipe with a foundation support of hardwood plywood with black colour thermal paint to absorb the maximum amount of heat from the surrounding [25]. The dryer's structure consists of four walls and a roof that is angled at a 21° angle. The sides are covered with two mm-thick, clear polycarbonate sheets with a 70% transmittance value to allow the maximum amount of radiation to pass through, and they are also lightweight which makes the system much more accessible [26, 27]. The polycarbonate sheet was chosen to be the dryer's transparent cover because it has a high transmittance of shortwave solar radiation and a low transmittance of infrared radiation, which causes the dryer to produce a greenhouse effect [28, 29]. The moist air was evacuated using the fan positioned on the upper

Figure 2. Experimental setup of greenhouse solar dryer.

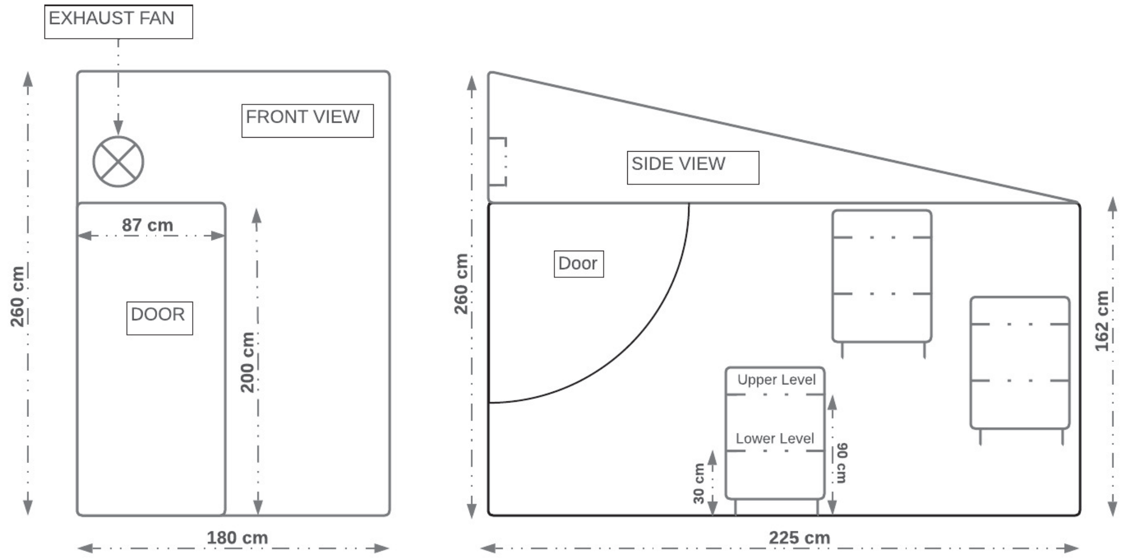

Figure 3. Schematic diagram of the dryer with measurement details.

side of one wall. The dryer is operated under force convection to increase its effectiveness [30]. The placement of exhaust fans is kept on the top of the chamber as the hot air always rises due to a decrease in density, and it is necessary to remove the saturated hot air for proper circulation and homogenous drying. Another reason for placing the exhaust fan at the top is to avoid dust particles and contamination from the surrounding, which generally settle down near the ground. The detailed specifications of the dryer are shown in the schematic diagram (Fig. 3). The product to be dried is placed in the three carts; each cart consists of two trays one placed at an upper level and the other one at the lower level. The size of each tray is 80 cm by 40 cm and is made of food-grade aluminium material.

Data Collection

The various parameters like the temperature at the surface of various trays, atmospheric temperature, wind velocity, exhaust fan velocity, solar radiation and relative humidity were measured in various instances to relate the effect of each with the drying phenomenon. The temperature at the upper layer and lower layer trays in the trolley along with the temperature outside the dryer were measured using the RTD sensors connected with the data logger cum indicator. The manual readings of the temperatures were also recorded every 15 minutes to verify any instrumentation errors. The relative humidity was measured using a digital thermometer and humidity meter inside and outside the dryer at 15-minute intervals. The solar radiation inside the drying chamber and in the outside atmosphere was measured using a solar meter at an interval of 10 min during the experiment. The wind velocity was measured at a similar instance using the digital anemometer at the exhaust of the drying chamber and outside atmosphere. The detailed specifications of the different instruments used are in Table 1.

Drying Kinetics

The observation of the mass of the drying tomatoes is one of the important parameters to understand the drying rates. During the drying operations, the mass of the tomatoes was measured every hour in different trays. The moisture content was calculated using the expression given below [31],

Table 1. Specification of the instruments used in the experiment

Instruments	Accuracy	Range	Product Code
Solar power meter	+/- 10 W/m^2	0-2000 W/m^2	Tenmars (TM-207)
Anemometer	+/-5%	0 to 30 m/sec	Anemometer (GM8908)
RTD sensors	+/- 0.2 °C	-50 to +250 °C	PT-100
Eight-channel universal temperature scanner logger	+/- 0.1 °C for PT100	-100 to +600 °C	Countronics (CT708)
Humidity and Temperature meter	+/- 3.5% RH	0 to 100 % RH	HTC (HT-306)

$$M_t = \frac{W_i - W_d}{W_i} \times 100 \quad (1)$$

Where W_i denotes the product's starting weight, W_d denotes its bone-dry weight at time t, and M_t denotes its moisture content (%dB) at that same time. The moisture ratio (MR) can be used to indicate the moisture content (%dB) as a function of drying time.

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

Where MR is the moisture ratio, M_t is the moisture content at time t, M_o is the initial moisture content (%dB) and M_e is the equilibrium moisture content at time t which can be determined using the relative humidity around the surrounding. The equation can be simplified as below to eliminate the effect of frequently changing relative humidity levels in the surrounding.

$$MR = \frac{M_t}{M_o} \quad (3)$$

The moisture ratio was monitored to understand the drying dynamics of the product. The difference in the moisture ratio for the product at various location points was analyzed to understand the effect of shading and air flow circulation on the drying rates. The drying rates for various trays were compared to find out best location for optimum drying in the drying chamber.

Experimental Procedure

Fresh tomatoes were purchased from the local market to ensure the best quality and freshness. The experiments were conducted in April 2021 at Navsari, Gujarat, India. The drying of tomatoes started at 8:00 am. The drying was stopped at around 5:00 pm for the day. The evaluation of the moisture content removed from the products was carried out from the weight loss analysis. The tomatoes were weighed and sliced over the tray in a thin layer through which air could pass in order to increase the drying rate. The tomatoes were distributed into six trays which weighed around 1 kg in each tray, to analyze the effect of the position and location of drying product in the dryer. The final combined mass of the product and tray was noted down before putting the tray in the dryer to monitor the water removal rate of the product accurately. The mass of the tray was measured every hour with a weight balance having an accuracy of 1 g.

RESULTS AND DISCUSSION

Solar Radiation

The solar radiation intensity over the greenhouse chamber and in the atmosphere directly affects the drying of the product (Tomatoes). The direct solar radiation intensity measurements were recorded just outside the solar dryer and inside the drying chamber to mark the difference of direct solar radiation falling on the drying product after passing through the polycarbonate sheet. The measurement was noted every 10 mins during the experimentation (9 hr). The maximum intensity measured was around 1185 W/m^2 at 12:30 pm in the atmosphere and 925 W/m^2 inside the drying chamber. The proceeding of solar intensity throughout the experiment is shown in Figure 4. The variation in the solar radiation intensity at some points may be due to clouds covering the area at that time. The average solar radiation is found to be 689 W/m^2 for the day.

Temperature Profile

The temperature measurement at various locations was noted down in the drying chamber during the experiment. The specific temperature profile was created for the drying tray placed at six different locations to understand the dynamics of drying in the chamber. The arrangement of various trolleys in the GHSD is shown in Figure 5. The temperature profile for the various trays at different locations in the drying chamber is plotted in Figure 6. The temperature profile generally follows the solar radiation data patterns

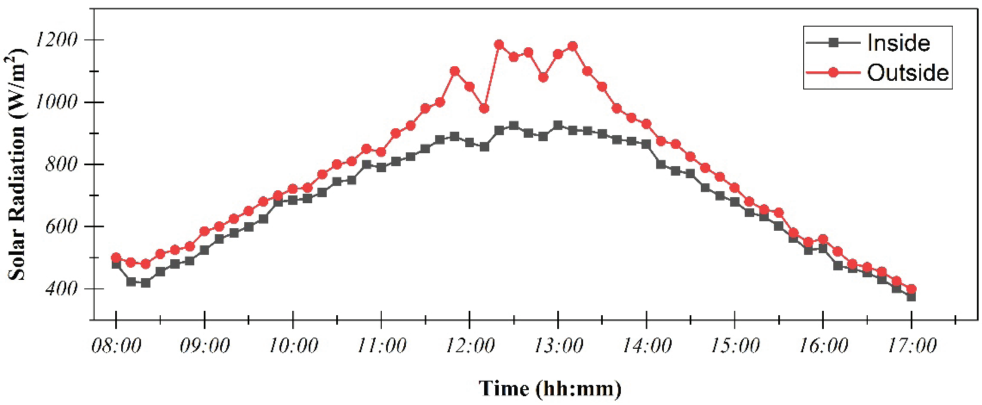

Figure 4. Solar radiation intensity variation over the day.

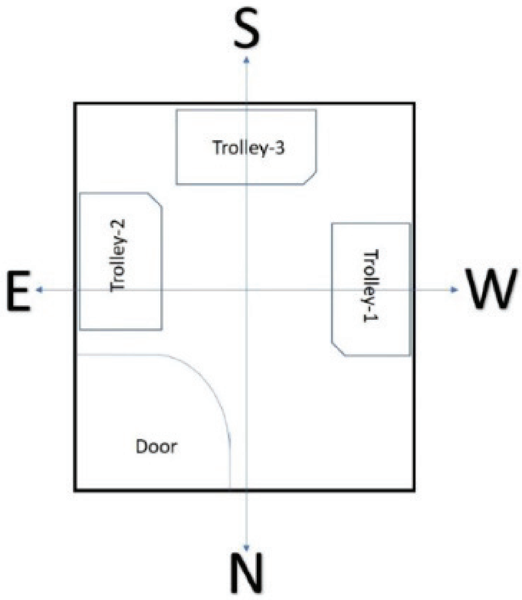

Figure 5. Arrangement of trolleys in the drying chamber.

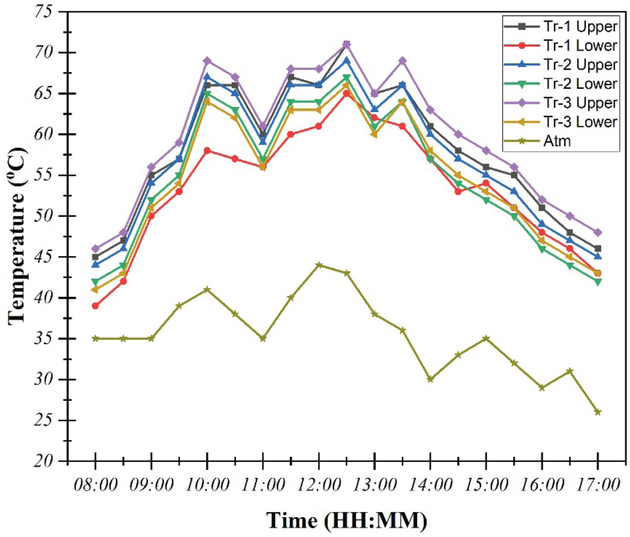

Figure 6. Temperature profile at various locations in the drying system.

as it has directly affected the amount of heat concentrated at a location in the drying chamber. To prevent objects from overheating, it is necessary to monitor any process that involves heat dissipation and temperature distribution using advanced probe sensors [32]. The abrupt changes in the data points during the experiments result from clouds covering the atmosphere at different times. The variation in the temperature profile at various locations of the tray is caused due to airflow variation in the drying chamber and, in addition to that the varying location of the sun in the open sky.

The difference in localized temperature is a major concern while drying out large batches of product, as the drying time is fixed for a batch. However, we still get different quality of dried product at each location of the drying chamber and different moisture ratios at different drying levels. The difference in the temperature over different trolleys at the upper-level and lower-level trays is plotted down in Figure 7. The plots indicating the variation in the temperature during the experiment in the upper and lower layer depict that the upper layer of the drying tray is always exposed to higher levels of solar radiation. The difference in temperature between the two layers also varies according to the location of the trolley; the difference between the two layers of the tray tends to be more in the trolley (TR-1) compared with the trolley (TR-2) and trolley (TR-3). The different temperature level suggests the importance of the location of the drying trays inside the drying chamber. The trolley (TR-1) is near to north side wall and due to the shading effect of the upper tray, the amount of heat gained at the lower level has a greater difference. The trolley (TR-3) is kept in the due south wall, so it is exposed to an adequate amount of solar radiation throughout the day; thus, the difference in the temperature gain is pretty less but still, both trays have a slight difference due to shading effect of the upper tray on the lower tray.

Moisture Ratio

The actual drying process is a combination of multiple simultaneous processes involved between the different layers of the drying product and the atmosphere. The two major processes are heat and mass transfer which evaporates the moisture content from the tomatoes. The generalized form of the drying curve consists of 3 parts; the first phase of drying is the warming-up phase which is followed by the constant drying rate phase, after which it is concluded by the decreasing drying rate phase as the moisture content comes to an equilibrium state [33].

The moisture ratio reduction for various drying locations according to drying trays placed in the various trolleys is plotted in Figure 8. After a single day of drying experiments, the final moisture content reduces to around 20% to 7%. The moisture ratio reduction is directly proportional to the amount of temperature attained at the location during the experiment. The drying rate is higher in the upper level of drying trays than in the lower ones. The shading due to the upper tray is a possible reason for the effect. The upper drying tray in trolley-3 shows a maximum moisture reduction from 95% to 7%, while the lower tray in trolley-1 shows a minimum reduction from 95% to 20%.

The different drying curve for individual trolleys is shown in Figure 9. The difference in the drying rate can be easily spotted in the graph according to various drying locations in the drying chamber. The results show that the effect of saturation of incident solar radiation and the effect of layering in the drying chamber can be a major factor affecting the drying phenomenon.

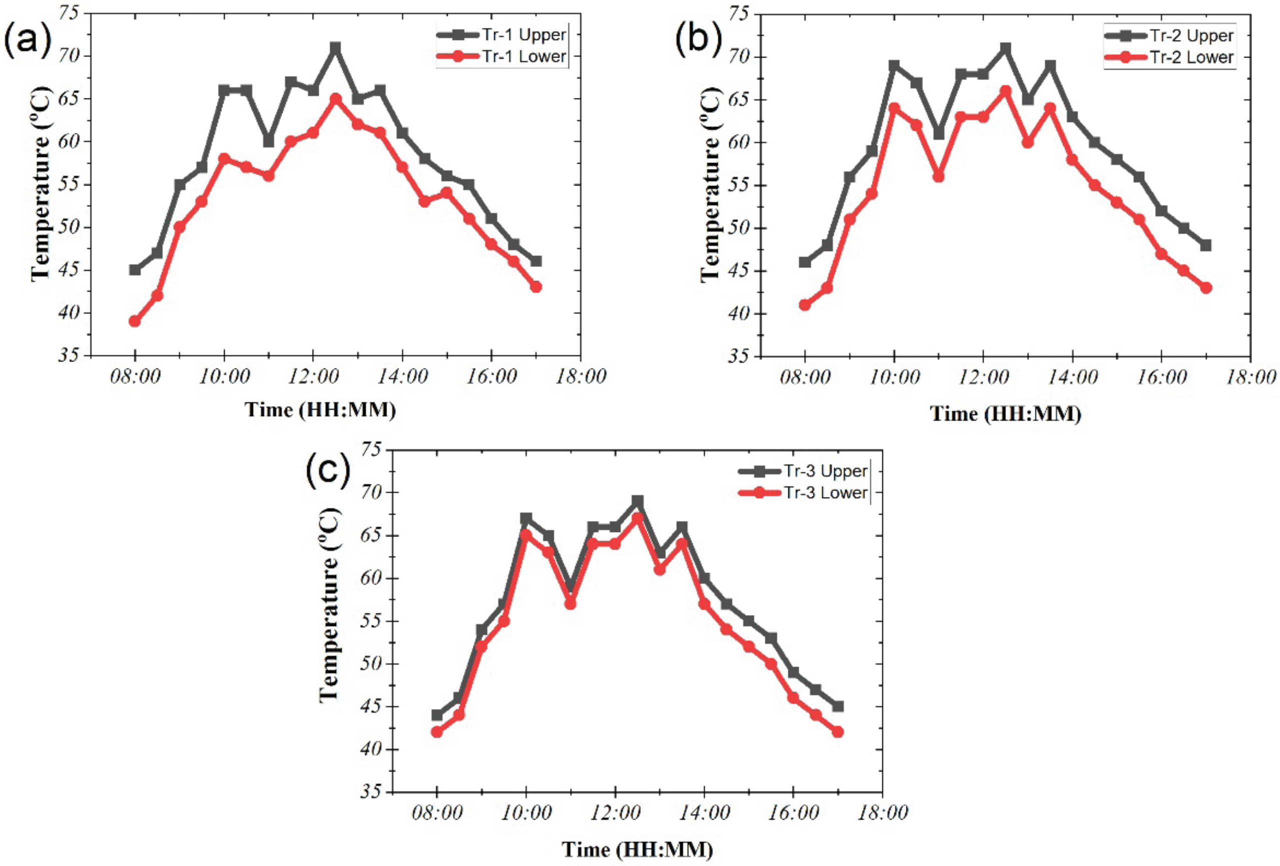

Figure 7. Variation in temperature at different levels with time for (a) trolley -1, (b) trolley-2 and (c) trolley-3.

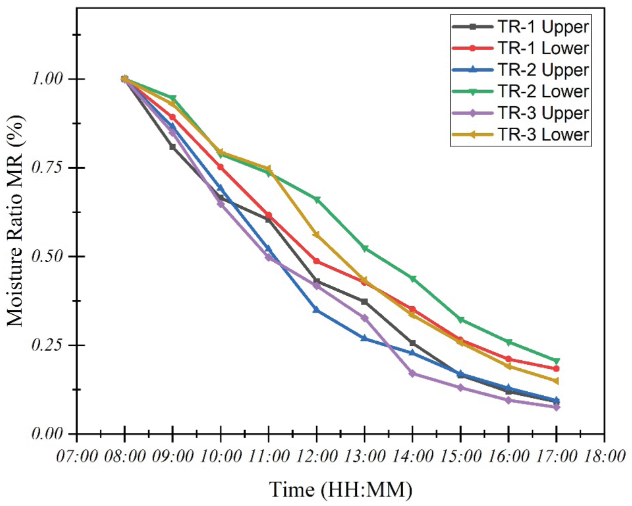

Figure 8. Plots for moisture ratio v/s time at various locations in the drying chamber.

Convective Mass Transfer Coefficient (hm)

The estimation of drying behaviour often relies on a significant parameter known as h_m, which represents the surface properties of the materials. This parameter plays a crucial role in comprehending the underlying physics of the drying process. Employing moisture ratio (MR), the h_m values at different locations of the drying chamber of various products can be calculated, enabling an assessment of their drying characteristics [34].

$$h_m = \frac{V}{A_m t}\ln(MR) \tag{4}$$

In Eq. (4), V is the volume of the material, A_m is the surface area of the material. The shape of tomato slices is cylindrical. The average size of the tomato slices was 4.5 cm in diameter and 3 cm thick, and the moisture ratio was calculated for different trays as per Eq. (3). The mass transfer coefficient for various trays during the experimental process is shown in Figure 10. The convective mass transfer coefficient for the upper trays in all the locations always seems to have a greater value than the lower-level tray. The mass transfer coefficient values keep on increasing as time increases. The average mass transfer coefficient for the drying chamber during the experiments is found to be 0.005 m/s.

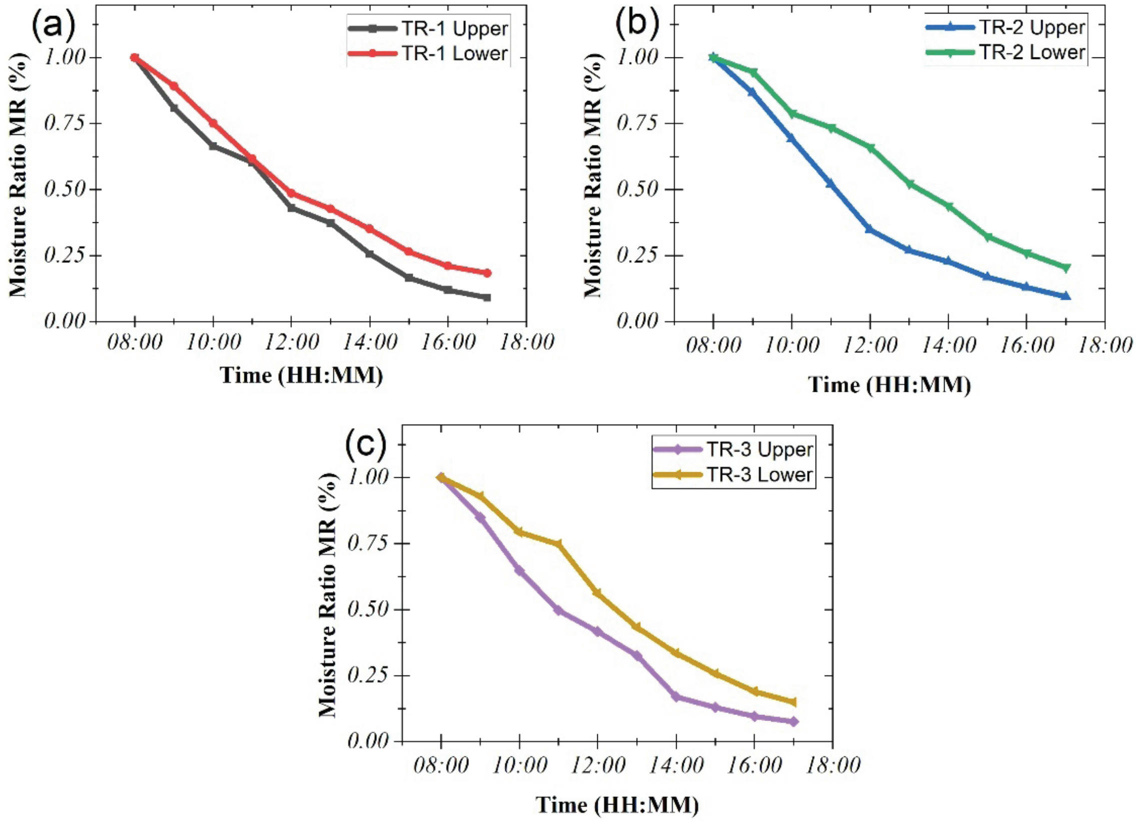

Figure 9. Variation in moisture ratio at different levels with time for (a) trolley -1, (b) trolley-2 and (c) trolley-3.

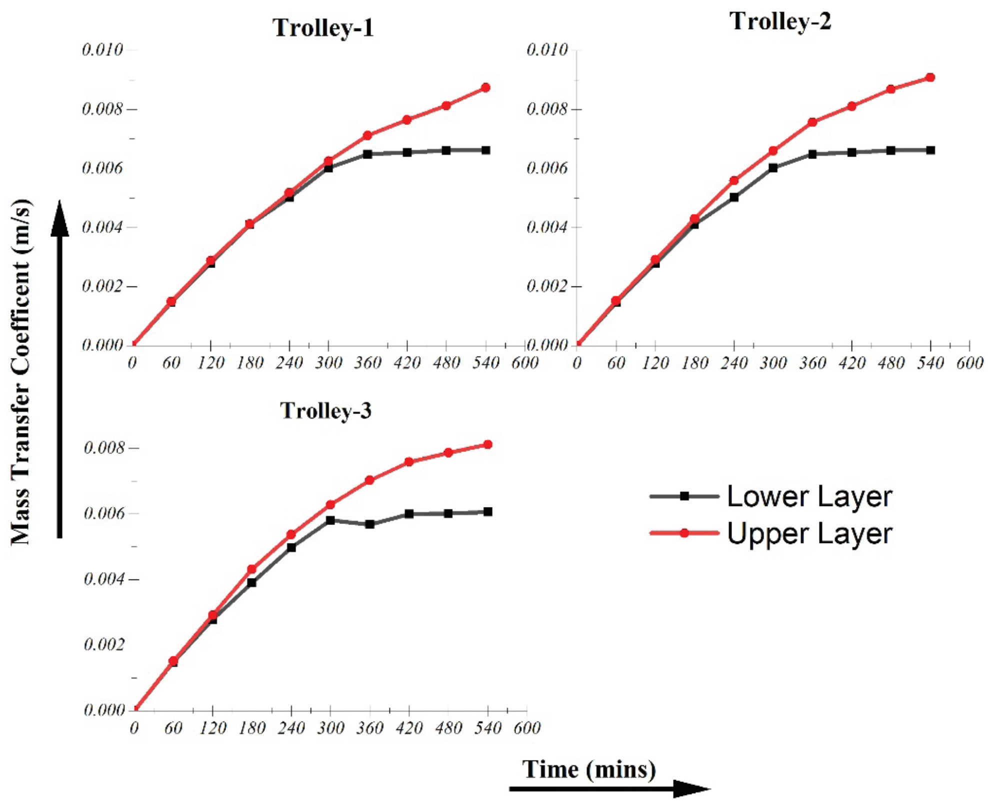

Figure 10. Mass transfer coefficient (h_m) for various trays locations during experiments.

Dryer Performance

Efficiency variables can be used to describe dryer performance. The solar greenhouse dryer's daily drying efficiency can be written as [35]:

$$\eta_{di} = \frac{M_{ev} \times \lambda}{I(t) \times A} \times 100 \quad (5)$$

Where M_{ev} is the quantity of evaporated moisture (in kilogrammes), λ is the latent heat of evaporation (in joules per kilogramme), $I(t)$ is the average solar radiation incident on the dryer (in watts per square metre), A is drying area used in the dryer (in square metres). From the 5.8 kg of tomatoes drying in 1 day, the removal of 5.1 kg moisture was obtained.

Hence, the dryer's average daily thermal output can be determined as follows:

(Q_u) = moisture evaporated (kg) x Latent heat of evaporation x (J/kg)

Hence, the thermal output of the dryer annually [35],

$$E_{out} = \text{Daily output of the dryer (kWh)} \times \frac{number\ of\ sunshine\ days}{Time\ taken\ to\ dry\ one\ batch} \quad (6)$$

Input Energy (E_{in})[35] = ($I(t)$* No. of sunshine hours * Drying time * Area * 10^{-3}) kWh

Thus, daily drying efficiency[35],

$$\eta_{di} = \frac{output\ energy}{input\ energy} \times 100 \quad (7)$$

Thus, with a drying tray area of 1.94 m^2 with a median solar intensity of 689 W/m^2, the daily drying efficiency for the dryer mentioned above over one day (9 hours of sunshine) was calculated as 26.66% which is in the range of the previous research reported by [31, 36]. The various data used and calculated are shown in Table 2.

Economic Analysis of Greenhouse Solar Dryer

The solar dryer can become an essential tool for the agricultural community and the farmers. The economic viability of the dryer needs to be studied before deployment of the dryer in the practical application. The economic analysis of the solar dryer depends upon the final product obtained from the dryer. The equations (7-19) are derived from [36]. The current study focuses on tomato drying, a popular and viable product after drying. The economic analysis is performed by considering the total mass of dried tomatoes in the dryer annually (M_{pa}) can be found out by:

$$M_{pa} = \frac{M_{pd} \times D}{D_b} \quad (8)$$

Where D_b is the time taken to dry one batch of product, D is the number of operation days, and M_{pd} is the amount of tomatoes dried in one batch. The total capacity of the current solar dryer is around 6 kg per batch and the drying time concluded from the experiment is one day per batch (9 h). Each batch's fresh product mass is indicated by M_f, and C_{fp} is the average cost for procurement of 1 kg of fresh product. The cost of fresh product per kg of dried can be calculated by:

$$C_{fd} = \frac{C_{fp} \times M_f}{M_{pd}} \quad (9)$$

The cost of drying the product using the dryer (C_{ud}) can be obtained by estimating the yearly cost of the dryer (C_{an}) which can be found using the formula:

$$C_{an} = C_{acp} + C_{mt} - S_v + C_{acf} \quad (10)$$

$$\text{Where, } C_{acp} = C_{cc} \times F_{cp} \quad (11)$$

C_{mt} is the annual maintenance cost which is around 3% of the annual capital cost, and S_v is the salvage value counted as 10% of the annual capital cost. C_{cc} is the capital cost of the dryer, and F_{cp} is the capital recovery factor.

$$F_{cp} = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (12)$$

If N_f is the hours for which the fan runs in a year to remove the moisture from the dryer, C_{ue} is the charge for electricity for one unit and P_f is the rated power for the fan, then the annual operation cost of the fan can be calculated by:

$$C_{acf} = N_f \times P_f \times C_{ue} \quad (13)$$

The cost of drying per kg of material (C_u) is given by,

$$C_u = \frac{C_{an}}{M_{pd}} \quad (14)$$

Table 2. Thermal analysis data for greenhouse solar dryer

Available Data	Values	Calculated Terms	Values
I_{mc}	95%	Q_u	3.20 kWh
F_{mc}	13%	E_{aout}	960 kWh
W_i	5.8 kg	E_{in}	12 kWh
λ	226 * 104 J/kg	η_{di}	26.66%
N	300		
T	1 day (9 hours)		
M_{ev}	5.1 kg		
A	1.94 m^2		
$I(t)$	689 W/m^2		

$$Thus,\ C_{ud} = C_{fd} + C_u \tag{15}$$

If we consider SP_{dp} as the per kg market price of the dried product, then the saving obtained drying per kg of product in the dryer can be calculated by:

$$S_{kg} = SP_{dp} + C_{ud} \tag{16}$$

The drying of any product in the dryer is done in batches, so to calculate the saving obtained per batch (S_b) in the solar dryer can be given as

$$S_b = S_{kg} \times M_{pd} \tag{17}$$

The solar drying process is generally stopped after a full day of drying as we have already concluded that the amount of moisture removed is adequate according to the final product we need to obtain. The saving of the dryer per can be obtained by:

$$S_d = {}^{S_b}/_{D_b} \tag{18}$$

The annual saving in the Kth year obtained from the solar dryer can be concluded as follows:

$$S_k = S_d \times D \times (1 + R_{if})^{k-1} \tag{19}$$

Here, R_{if} is the rate of inflation.

The payback time (P_b) can be estimated from the relation given by the equation:

$$P_b = \frac{ln\left[1 - \frac{C_{cc}}{S_1}(d - R_{if})\right]}{ln\left(\frac{1 + R_{if}}{1 + d}\right)} \tag{20}$$

The experiment was carried out by drying around 5.8 kg of tomatoes in the greenhouse solar dryer, out of which the final dried product obtained was 0.7 kg in one batch after drying and assuming 300 days of full sunshine days in a year with drying time for one batch is around one day. The capital cost for the development of the dryer was around Rs. 1,54,523. The interest rates for long-term capital are estimated at around 8% with the current inflation rate at 6%. The fresh tomatoes were purchased at a rate of 30 Rs per kg and the selling price of the dried tomatoes was around 700 Rs per kg. The annual saving after one year of usage can be estimated at around 81056 INR, and the payback period for the solar dryer would be 1.61 years. The various calculated parameters for the economic analysis are shown in Table 3 below:

Embodied Energy

The extraction, processing, delivery, fabrication, modelling, and making of any products on the site requires some amount of energy and that total amount of energy can be termed as embodied energy for that product. The environmental impact of producing any product can be estimated from the embodied energy. The various types of material add different amounts of CO_2 into the environment which adds to the greenhouse gases ratio in the habitable environment. The embodied energy shows the total effect of the material on the environment during its whole life cycle. Table 4 displays the embodied energy of the various materials used in the solar greenhouse dryer's construction, operation, and maintenance. The percentage distribution of various components of the system in the total embodied energy is shown in Figure 11.

Carbon Credits and Mitigation

The potential for climate change that is connected to the PV power system can be measured by CO_2 mitigation. For comparison with CO_2 emissions from

Table 3. Economic analysis of solar drying tomatoes

Parameters	Value	Parameters	Value
Capital Cost of the Dryer (C_{cc})	Rs. 154523	Capital Recovery Factor (F_{cp})	9%
Interest Rate (d)	8%	Annual Capital Cost (C_{acp})	Rs. 14475.53
Inflation Rate (R_{if})	6%	Annual Maintenance Cost (C_{mt})	Rs. 434.24
Mass of product Dried per Batch (M_{pd})	0.7	Annual Salvage Value (S_v)	Rs. 1447.55
No. of Days taken to dry out one batch of the product (D_b)	1 Day	The operational cost of fan per year (C_{acf})	Rs. 280.80
Mass of Fresh Product per Batch (M_f)	5.8	Cost of 1 Kg of dried product using the dryer (C_{ud})	Rs. 314.01
Cost of 1 Kg of fresh product	Rs. 30	Cost of fresh product per kg of dried product (C_{fd})	Rs. 248.57
Expected life of the dryer (η_{sys})	25 Years	Saving per Kg (S_{kg})	Rs. 386
Selling Price per kg of dried product (SP_{dp})	Rs. 700	Saving per Batch (S_b)	Rs. 270
Electricity cost per unit (C_{ue})	Rs. 5.2	Saving per Day (S_d)	Rs. 270
Rated power of Fan (P_f)	20 W	Saving After 1 year (S_1)	Rs. 81056
No. of sunshine days per year (D)	300	Payback Period (P_b)	1.61 Years

Table 4. Embodied energy of various components in the greenhouse solar dryer

Sr.No.	Material	Quantity (kg)	Energy Coefficient per kg (kWh/kg)	Total energy (kWh)	References
1.	Polycarbonate Sheet	96	10.180	977.28	[37], [38], [39]
2.	Plywood Sheet	9	0.44	3.96	
3.	Perforated Aluminum Tray	12	55.28	663.36	
4.	Galvanized Iron Section				
	a. 25.4 mm x 1 mm Section	150	9.67	1450.5	
	b. 25.4 mm x 3 mm Angel	3	9.67	29.01	
5.	Fitting				
	a. Hinges	0.2	55.28	11.056	
	b. Door Lock	0.1	55.28	5.528	
	c. Steel Screw	0.250	9.67	2.4175	
	d. Handle	0.15	55.28	8.292	
6.	Dc Fan				
	a. Plastic	0.120	19.45	2.334	
	b. Copper	0.050	19.61	0.9805	
Total Embodied Energy				**3154.71**	

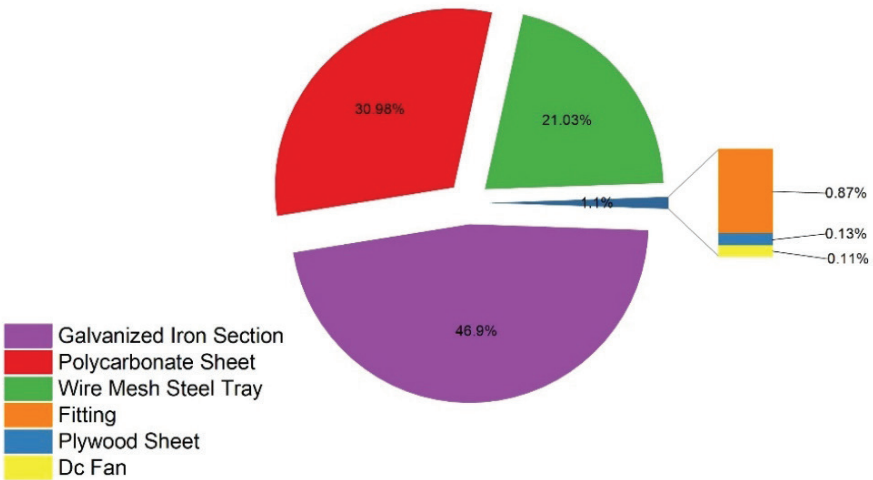

Figure 11. Percentage contribution for embodied energy of various components in the drying system.

alternative power-generating technologies, cumulative CO_2 mitigations per kilowatt hour were also measured. Worldwide efforts to reduce the spike in concentrations of greenhouse gases include the usage of carbon credits [36]. By capping total yearly emissions and allowing the market to trade any deficiency in emissions, they offer a means of reducing greenhouse effect emissions on an industrial scale. Credits can be traded between companies or purchased and sold on global marketplaces at the going rate. Credits can be used to fund carbon reduction initiatives among international trading partners. Numerous businesses sell carbon credits to businesses and clients who want to reduce their carbon impact voluntarily.

Carbon credit model

Carbon credits are tradable permits that allow companies to emit a certain amount of greenhouse gases. They are often used in cap-and-trade systems, which set a limit on the total amount of emissions that can be released. Companies that emit less than their allotted amount can sell their excess credits to companies that emit more than their allotted amount. This creates a market for carbon credits, which drives up the price of credits and encourages companies to reduce their emissions [40]. If a consumer uses unit power and suffers L_a (i.e., 10%) in losses from substandard household appliances, the amount of power delivered is 1/1-La units. The amount of power that must be produced at the power plant is 1/1- L_a *1/1- L_{td} units if

Table 5. Sustainability parameters for greenhouse solar dryer

Environmental Parameters	Value
Total embodied energy	3154.71 kWh
Moisture evaporated	5.1 kg/day
CO_2 emission over the lifetime	6.62 tons
CO_2 mitigation over the lifetime	48.24 tons
Net CO_2 mitigation over the lifetime	41.62 tons
Max carbon credit earned	62,355.08 INR
Min carbon credit earned	46,766.31 INR

*US$ = 74.91 INR

the transmission and distribution losses are L_{td} (assuming 45%). At the source, the average CO2 equivalent intensity for coal-based energy generation is 0.98 kg of CO_2/kWh.

As a result, the quantity of CO_2 mitigation per kWh for a consumer utilizing a solar system is (1/1- L_a) * (1/1- L_{td}) * 0.98 = 2.01 kg/kWh

The CO_2 Emission per year (kg)

$$= \frac{E_{ei}}{n_{sys}} \times 2.01 \tag{21}$$

The CO_2 Emission over the lifespan of the system (tons) is

$$= \frac{CO_2\ emmision\ per\ year\ \times\ n_{sys}}{1000} \tag{22}$$

The CO_2 mitigation over the lifespan of the system (tons) is

$$= \frac{E_{aout} \times n_{sys} \times CO_2\ emmision\ per\ kWh}{1000} \tag{23}$$

Net mitigation over the lifetime = Total CO_2 mitigation – Total CO_2 emission

Where E_{ei} represents the embodied energy input of the solar greenhouse dryer (kWh), E_{aout} is the dryer's yearly thermal output (kWh), and n_{sys} represents the system's lifetime (taken as 25 years). If CO_2 emissions are traded at \$ per tonne of CO_2 mitigation, the carbon credit is acquired by the system. The carbon credit ranges from \$15-20/ ton of C. Thus, earned carbon credit

$$= \$C\ \times \text{Net}\ CO_2\ mitigation\ over\ lifetime \tag{24}$$

CONCLUSION

The thermal performance of the small greenhouse solar dryer was evaluated to understand the various factors affecting the drying phenomenon. The drying process was evaluated by drying tomatoes inside the dryer. The economic and environmental effect of the solar drying inside the dryer was estimated using Embodied energy analysis. The life cycle cost analysis of drying tomatoes was estimated. The following points are derived from the study:

- The trays placed due south were exposed to proper drying compared to those in the north direction.
- The lower-level tray in the various trolley is always less exposed to direct sun radiation due to the shading effect of the upper tray.
- The convective mass transfer coefficient for the lower-level trays is always lower than the upper-level tray. The average convective mass transfer coefficient is 0.0005 m/s for the drying system.
- Depending on the location of the drying tray in the chamber, the moisture content was reduced to 20% and 7%. The average moisture reduction all over the dryer was around 81%.
- The maximum amount of moisture reduction is seen in the tray located on the upper level placed near the south wall, and the minimum reduction in the moisture was obtained in the tray placed in the lower level placed in the trolley around the north wall.
- The thermal performance of the solar dryer was calculated using the various energy input and the output in terms of drying product output. The thermal efficiency for the day was around 26.66%.
- The embodied energy analysis was also performed to assess the environmental effect of the solar dryer throughout its working life cycle. The Embodied energy for the dryer was estimated to be 3154.71 kWh.
- The amount of CO2 emission for the system is estimated to be 6.62 Tons. The net carbon mitigation for 25 years of the life cycle was estimated to be 41.62 Tons which can earn 46766 INR to 62355 INR based on the carbon credit rates in the future.
- The economic analysis for the GHSD was carried out based on the amount of daily useful product delivered and it was estimated to have Rs 81056 annual earning which concludes the payback period for the system to 1.62 years.

The developed Green House Solar Dryer was found to be environmentally and economically viable to be implemented in the small farming industry for drying tomatoes. The method which can be implemented is continuous drying based on the moisture content of individual trays. The drying tray can be moved around during the drying process based on the moisture content removed and finally removed when the required dryness level is obtained. Meanwhile, introducing new trays in the drying chamber and continuing the drying process while changing the tray's location depending on the dryness level.

NOMENCLATURE

A	Drying area (m^2)
C_{acf}	Annual operation Cost of Fan (INR)
C_{acp}	Annual Capital Cost (INR)
C_{an}	Annual Cost (INR)

C_{cc}	Capital Cost (INR)
C_{fd}	Cost of Fresh Product (INR)
C_{mt}	Annual Maintenance Cost (INR)
C_u	Drying cost for 1 kg material (INR)
C_{ud}	Cost of 1 kg of product dried inside the dryer (INR)
C_{ue}	Electricity Charge for 1 Unit
d	Interest Rate (%)
D	Number of Drying Days per year (days)
D_b	No. of Days taken for drying one batch (days)
E_{aout}	Annual Thermal Output (kWh)
E_{ei}	Embodied Energy Input (kWh)
E_{in}	Input Energy (kWh)
E_{out}	Output Energy (kWh)
F_{cp}	Capital Recovery Factor
F_{mc}	Final Moisture Content (%)
GHSD	Green House Solar Dryer
I_{mc}	Initial Moisture Content (%)
I(t)	Average incident Solar radiation (W/m2)
L_a	Losses due to Appliances
L_{td}	Losses due Transmission and Distribution
M_e	Equilibrium Moisture Content
M_{ev}	Moisture Evaporated (kg)
M_o	Initial Moisture Content (%)
M_{pa}	Total Mass Dried Annually (kg)
M_{pd}	Amount of Product dried in 1 Batch (kg)
MR	Moisture Ratio
M_t	Moisture content at time t
N	No. of Sunshine Hours per Day
N_f	No. of Hours Fan Runs
P_b	Payback Time (years)
P_f	Rated Power of Fan (W)
Q_u	Daily Thermal Output (kW)
R_{if}	Inflation Rate (%)
S_b	Saving per Batch (INR)
S_d	Saving per Day (INR)
S_k	Annual savings in Kth year (INR)
S_{kg}	Saving from drying 1 Kg of Product (INR)
SP_{dp}	Selling Price of Dried Material (INR)
S_v	Salvage Rate (%)
W_d	The bone-dry weight (kg)
W_i	Initial weight of the product (kg)

Greek Letters

λ	Latent Heat of Evaporation (J/kg)
η_{di}	Daily Drying Efficiency (%)
η_{sys}	Lifetime of the System (years)

AUTHORSHIP CONTRIBUTIONS

Pringal M. Patel: Investigation, Data Curation, Formal analysis, Methodology, Writing - Original Draft, Visualization.

Vikram P. Rathod: Conceptualization, Supervision.

Divyesh Patel: Resources, Data Curation.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

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

ETHICS

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

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