CHAPTER 5

ENERGY, EXERGY, ECONOMIC AND ENVIRONMENTAL ANALYSIS OF PCM BASED SOLAR DRYER

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5.1 Introduction

India currently has one of the world's most rapidly growing economies. It produces 259 million metric tonnes of fruits and vegetables annually, making it the world's second-largest agricultural producer altogether. The United Nations reports that India wastes nearly 30% of its food supply. Worrying statistics show that 22% of the population is undernourished despite all the wasted food. Therefore, it is important to develop ecologically safe techniques of preserving food to ensure that its nutritional value is maintained. About 4.6%-15% of all fruits and vegetables are wasted every year because of outdated harvesting methods, inadequate storage space, and outdated technologies. Approximately 2% of available capacity is allocated to processing fruits and vegetables. Only 20% of India's agricultural output is processed, with the remaining 80% without processing goes directly from the farm to the consumer through intermediate supply chain [1,2]. In the existing food crisis, most developing nations are dealing with food losses caused by inefficient post-harvesting processes account for approximately half of fruits and vegetables and one quarter of food grains. Standard driers as well as cold storage facilities is expensive, the rise in the cost of petroleum only served to worsen the situation. Farmers in rural areas do not have access to cold storage. One of the primitive approaches for minimising post-harvest losses is solar drying. Solar-powered drying devices are cost-effective for food drying. TESS eliminates the uneven sunlight characteristics in solar drying operation. For good quality drying of food items, a solar drying combined with TES material facilitates an uninterrupted consistent temperature drying practise at 50 °C.

The TES materials utilised in the solar dryer absorbs heat throughout the day and distributes it during the off-sunshine period [3,4]. The energy required for drying is estimated by the total amount of moisture that needs to be extracted from an item. Many conventional and nonconventional energy sources are available for dehydrating processes applications. Unconventional sources, on the other hand, must be preferred due to their desirable and long-term benefits. As a result, solar energy is widely used unconventional or alternative energy source for drying processes. [5,6]. Solar drying methods are more efficient dehydrating practises than open air sun drying because moisture is removed at higher temperatures with relatively lower humidity. The appropriate temperature range for drying of various agricultural products are determined to be within 45 to 60 ºC [7]. However, the major issues here are the unpredictable and unreliable nature of solar radiation. Because of these doubts, these energy sources are not as flexible as they could be. As a result, storing energy is essential to keep the gap between supply and demand as small as possible. This allows us to lower our energy consumption. [8,9]. A solar dryer using TES could provide a viable option for drying agriculturally based products during periods of low radiation or insufficient energy supply. It improves the efficiency and reliability of the energy facilities resulting in advancing the energy industry. The increasing need for sustainable sources of energy has brought attention to the importance of TES [10,11]. Depending on different suggested technologies and specific weather circumstances, solar dryers had been found to reduce around 12.5 and 87% of the drying period when in comparison to open air sun drying [12-14].

Energy analysis is a quantitative whereas exergy analysis is a qualitative approach of examining the design system. The 1st thermodynamics law concerning the total energy balance of the design systems inlet and outflow is energy analysis. However, energy analysis has difficulty identifying the precise characteristics of a system and fails to differentiate energy quality. On the other hand, exergy is a crucial tool for assessing and optimizing a system's energy efficiency since it describes the huge quantity of work produced via movement of a working fluid (air), heat, or mechanical work in equilibrium by its surroundings [15]. Solar dryers are popular due to their reliability, availability, and eco-friendliness. Solar dryers can be easily made in rural locations. However, to fabricate a sustainable solar dryer, it is essential to have a thorough understanding of its performance elements, such as energy, exergy, economic, environmental and product quality. These analyses are attempted many times. However, the data is one-dimensional and does not indicate solar dryer behavior. Therefore, a detailed examination of the 3E parameters - energoeconomic, exergoeconomic, and enviroeconomic study is carried out. This study investigates the influence of solar drying on the quality of goods (Q) parameters. Analysing the solar dryer from an energy, exergy, environmental, economic, energoeconomic, exergoeconomic, and enviroeconomic perspective, as well as a quality perspective (7E+Q), can help make solar dryer more functional [16].

As a result, the developed PCMSAH from the previous Chapter is studied in detail in this Chapter by integrating a drying chamber to develop a phase change material based solar dryer (PCMSD). Finally, the performance of the developed PCMSD is evaluated by conducting tomato drying experiments with three different PCMs (paraffin wax, stearic acid, and acetamide). The drying characteristics of tomatoes are studied in detail. The energy and exergy analyses of collector and drying section of PCMSD are performed. The PCMSD's economic analysis is conducted using the annualized cost technique and payback period, while the environmental analysis is conducted using embodied energy, energy payback period, yearly CO_2 mitigation, and carbon credit to determine its feasibility for technology transfer to end users such as farmers and other beneficiaries.

5.2 Materials and Methods

5.2.1 System description

The PCMSD system developed in Department of Energy, Tezpur University, India comprises of PCMSAH connected to drying chamber supported by the support stand. The representation of the PCMSD system shown in Fig. 5.1 describes the structure of the arrangement of the system like the cold air inlet to the collector, hot air outlet of the collector and immediate inlet hot air to the drying section and finally out of the drying section.

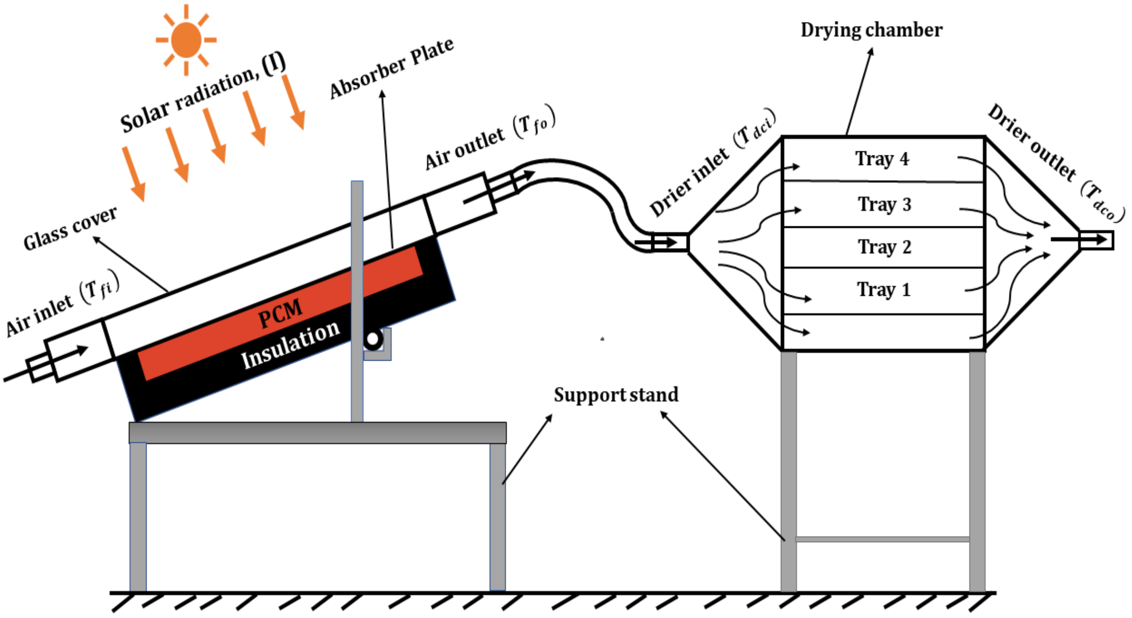


Fig. 5.1: PCMSD schematic diagram

The detailed components and material used in the development of PCMSD are presented in Table 5.1. The materials for development of the PCMSD are all procured from the local market of Tezpur, Assam, India. The PCMs used in the study are commercial grade which are procured from online source (IndiaMART).

Table 5.1: Components and material used in PCMSD

S.No.	Components of PCMSD	Materials used
1	Absorber plate	Aluminium sheet
2	Collector body frame structure	Wood
3	Glass cover	Glass
4	Glass cover frame	Aluminium
5	Outer covers	Aluminium sheet
6	Drying Chamber	Mild steel
		Hollow iron rod
7	Coatings	Black paint
8	Drying trays	Wood
		Aluminium mesh
9	Total Insulation	Thermocol
10	Stand support	Mild steel
11	Fittings (nuts, bolts, screw, and rivets)	Steel
12	Divergent duct	Mild steel
		Plastic pipe
13	Blower	Plastic
		Copper wire
14	PCMs	Paraffin wax
		Stearic acid
		Acetamide

The following equation is employed to find out the drying bed area by neglecting the loading void fraction [17].

$$A_d = \frac{m_t}{x\,\rho_t\,\zeta} \qquad (5.1)$$

where A_d is the drying bed area (m^2), m_t is the mass of the product (tomato) (5 kg), x is the drying bed thickness or aluminum wire mesh thickness (0.00543 m), ρ_t is the bulk density of the product (tomato) (710 kg/m^3) [18], ζ is the porosity of the tray (80 %). Substituting all the values in the Eq. (5.1) we can estimate the drying bed area as 1.62 m^2. The drying bed area was further divided into 4 trays of (0.637 m x 0.637 m) area.

The specifications of PCMSD system which includes solar collector and the drying chamber connected through a flexible insulated pipe as shown in Fig. 5.1 and presented by Table 5.2.

Table 5.2: Specifications of PCMSD

Sl. No.	Components	Dimensions
1	Absorber plate area	1.57 m^2
2	Air vent area	0.1 m^2
3	Glass cover area	2 m^2
4	Glass to absorber plate distance	0.1 m
5	Total area of the drying bed	1.62 m^2
6	Size of the drying trays	(0.637 m x 0.637 m)
7	Total number of trays	4
8	Distance between two consecutive trays	0.10 m
9	Distance between the tray and wall of the drying chamber	0.1807 m
10	Mass flow rate of fluid (air), $\dot{m}$	0.028 kg/s
11	Drying capacity	5 kg (tomato)

5.2.2 Experimental procedure

5.2.2.1 Determination of initial moisture content of tomato

To determine the initial moisture content on a wet basis, 100 g of tomato (Solanum lycopersicum) slices are distributed uniformly as a thin layer (0.003 m thickness) onto a stainless-steel tray and then dried in a Relitech's RT-150 hot air oven at 105 ºC for 24 hours. This is done when the weight of the tomato reaches three constant weights. In order to calculate the average value of the initial moisture content, the procedure was carried out three times using fresh tomatoes weighing 100 g each.

5.2.2.2 Tomato drying in PCMSD and open sun dry

The experimental set-up is carried out in a developed PCMSD to investigate the performance throughout the day. The temperatures at different points in PCMSD are measured with K-type thermocouples with ± 2.2 ºC/ ± 0.75 % error as shown in Fig. 5.2 and explained in Table 5.3. The solar radiation is measured with global solar radiation meter Kipp and Zonen, CMP6 with measuring capacity up to 2000 W/m^2 and relative error of ± 5 W/m^2. Centrifugal blower, Forte' with 220 V/50 Hz voltage/frequency, no load speed of 0–13,000 rpm, power 600 W and blowing rate 0–2.8 m^3/min is used to give a forced draft to the PCMSD. The mass flow rate of 0.028 kg/s is maintained by blowing air of 0.24 m/s velocity measured by anemometer (testo 417) considering the density of air at 25 ºC as 1.184 kg/m^3 at the entrance of air vent area (0.1m^2) supplied towards of PCMSD. However, the actual power required to operate the blower by air mass flow rate of 0.028 kg/s during the experiment is measured by power analyser as 250 W. Temperature data logger, Personal Daq/56TM is used for retrieving all the temperature data from the K-type thermocouples.

Drying experiment of tomato is caried out with PCMSD including three different PCMs viz., acetamide, stearic acid and paraffin wax and open sun drying on three different days of December 2022. Freshly harvested tomatoes are procured from the neighbouring market and thoroughly examined for discarding the spoiled ones. 2 kg for each day of experiment with three different PCMs are weighed using the electronic weighing balance where the tomato is sliced into 3–5 mm and dried 1kg on PCMSD and 1kg on open sun dry as shown in Fig. 5.3. The drying experiment on PCMSD is carried out on 8th (paraffin wax), 10th (stearic acid) and 14th (acetamide) of December 2022 with the air mass flow rate of 0.028 kg/s starting from 07:30 AM to 16:30 PM. Throughout the experiment, temperatures of the air at several PCMSD points and solar radiation are recorded every 30 min. The weight of the tomato of open sun dry and the tomato from inside the chamber is measured at every 30 min until the solar radiation drops till 0 W/m^2. All the thermocouples placed in required locations are organised in Table 5 and solar radiation is recorded throughout the day with an interval of 30 min.

Fig. 5.2: Thermocouple locations in PCMSD

Table 5.3: Thermocouple locations in PCMSD

Thermocouple name	**Location in PCMSD**
T1	Inlet to collector
T2	Outlet from collector
T3	PCM temperature
T4	Glass temperature
T5	Absorber plate
T6	Ambient
T7	Inlet to drying chamber
T8	Outlet from drying chamber

The mass shrinkage ratio is the most significant structural alteration observed on crops as a function of weight loss. Tomato mass shrinkage ratio (*SR*) is the ratio of original mass (m_i) to ultimate or final mass (m_f) after drying [19]. Initially 1kg of tomato for PCMSD and 1kg for open air sun drying is considered for experiment on each day and the final mass of the tomato is recorded at the end of the experiment to determine mass shrinkage ratio with all the three PCMs respectively.

$$SR = \frac{m_i}{m_f} \tag{5.2}$$

(a) PCMSD drying (b) Open sun drying

Fig. 5.3: Tomato drying in PCMSD and open sun drying

5.2.3 Energy analysis of PCMSD

5.2.3.1 Energy analysis of PCMSD collector

The heat energy received or absorbed by the PCMSD collector is given [20].

$$Q_A = A \times I \times \tau_g \times \alpha_g \tag{5.3}$$

where A is the PCMSD collector's absorber plate area, I is the solar radiation, τ_g is the transmittivity of glass cover and α_p is the absorptivity of the absorber plate.

PCMSD Collector actual heat output, or heat supplied, is calculated as [21].

$$Q_u = \dot{m} \times C_p \times (T_{co} - T_{ci}) \tag{5.4}$$

The energy efficiency of the PCMSD collector is given by.

$$\eta_c = \frac{Q_A}{Q_u} \tag{5.5}$$

5.2.3.2 Energy analysis of PCMSD drying chamber

The amount of energy required by the PCMSD to dry tomatoes is the absorbed heat by the PCMSD collector in the given time interval [22].

$$E_{in} = Q_A \times t \tag{5.6}$$

where *t* is the length of time interval for the tomatoes that are assigned to dry.

The drying efficiency or overall energy efficiency (η_d) of the PCMSD is given by [22].

$$\eta_d = \frac{m_w L_w}{E_{in}} \quad (5.7)$$

where m_w is the total amount of moisture removed from tomato during experiment and the latent heat of vaporisation of water is denoted by L_w.

Specific energy consumption (*SEC*) (kWh/kg) of the PCMSD is determined from tomato drying experiment [23] and the specific moisture extraction rate (*SM*) (kg/kWh) [24] of the PCMSD is also estimated to determine how much water is removed from each kg of tomato slices and how much energy is used to do so.

$$SEC = \frac{E_{in}}{m_w} \quad (5.8)$$

$$SM = \frac{m_w}{E_{in}} \quad (5.9)$$

5.2.4 Exergy analysis of PCMSD

Exergy analysis can be used to determine the efficiency of energy transition systems. Exergy can be defined as the majority of useful work performed by a system that demonstrates the utility of energy.

The exergy of incoming solar radiation as energy input is affected by optical losses, absorber surface absorptivity, thermal emissions to the environment, and heat transfer rate into the working fluid (air).

5.2.4.1 PCMSD collector exergy analysis

In a steady-state scenario, the exergy balance for the PCMSD collector could be represented as below [24].

$$\sum \mathrm{Ex}_{\mathrm{in\_c}} - \sum \mathrm{Ex}_{\mathrm{out\_c}} = \sum \mathrm{Ex}_{\mathrm{loss\_c}} \quad (5.10)$$

where $\mathrm{Ex}_{\mathrm{in\_c}}$ is the exergy inflow, $\mathrm{Ex}_{\mathrm{out\_c}}$ is the exergy outflow, and $\mathrm{Ex}_{\mathrm{loss\_c}}$ is the exergy loss of the PCMSD collector, respectively.

Exergy inflow of the PCMSD collector is given by the expression as mentioned below [25].

$$\sum \mathrm{Ex}_{\mathrm{in\_c}} = \left[1 - \frac{T_a}{T_r}\right] Q_A \quad (5.11)$$

where T_r is the temperature of the sun (6000 K) and Q_A is collectors total absorbed energy.

Exergy outflow and exergy loss of the PCMSD collector are evaluated using the expression below [25].

$$\sum \mathrm{Ex}_{\mathrm{out\_c}} = \dot{m}\, c_p \left[(T_{co} - T_{ci}) - T_a \ln\left(\frac{T_{co}}{T_{ci}}\right) \right] \tag{5.12}$$

$$\sum \mathrm{Ex}_{\mathrm{loss\_c}} = T_o S_{gen} = \left[1 - \frac{T_a}{T_r}\right] Q_A - \dot{m} c_p \left[(T_{co} - T_{ci}) - T_a \ln\left(\frac{T_{co}}{T_{ci}}\right) \right] \tag{5.13}$$

The exergy efficiency of the PCMSD collector is calculated using the expression below [25].

$$\eta_{Ex\_c} = \frac{\sum \mathrm{EX}_{\mathrm{out\_c}}}{\sum \mathrm{EX}_{\mathrm{in\_c}}} \tag{5.14}$$

5.2.4.2 Exergy analysis of the PCMSD drying chamber

The exergy of the PCMSD drying chamber can be computed using the basic concept of exergy balance, which is represented as an exergy loss equal to the difference between exergy inflow and exergy outflow; thus,

$$\sum \mathrm{Ex}_{\mathrm{in}\_d} - \sum \mathrm{Ex}_{\mathrm{out}\_d} = \sum \mathrm{Ex}_{\mathrm{loss}\_d} \tag{5.15}$$

where subscript *d* is drying chamber, while exergy inflow and outflow of the drying chamber [25] can be calculated as.

$$\sum \mathrm{Ex}_{\mathrm{in}\_d} = \dot{m}\, c_p \left[(T_{di} - T_a) - T_a \ln\left(\frac{T_{di}}{T_a}\right) \right] \tag{5.16}$$

$$\sum \mathrm{Ex}_{\mathrm{out}\_d} = \dot{m}\, c_p \left[(T_{do} - T_a) - T_a \ln\left(\frac{T_{do}}{T_a}\right) \right] \tag{5.17}$$

where T_{di} and T_{do} denotes the input and exit temperatures of the PCMSD's drying section, respectively.

The exergy efficiency of the PCMSD drying section can be calculated by dividing exergy outflow by exergy inflow of the drying section [22, 25].

$$\eta_{Ex\_d} = \frac{\sum \mathrm{EX}_{\mathrm{out}\_d}}{\sum \mathrm{EX}_{\mathrm{in}\_d}} \tag{5.18}$$

5.2.5 Economic analysis of PCMSD

The cost of a solar dryer can be reduced and its popularity among consumers raised through careful economic planning. The primary goal for all the solar dryers design should be to lower the energy price for production of hot air. The major parameters to be studied when analysing the economic evaluation of a solar drying device are capital cost (*P*), annual cost (*AC*), and payback period over the complete operational life cycle.

5.2.5.1 Annualized cost method

The following equation is used to compute the first annual cost (*FAC*) of PCMSD for the first year [26].

$$FAC = CRF \times P \tag{5.19}$$

where *P* represents the capital cost and *CRF* represents the capital recovery factor for PCMSD.

The *CRF* of PCMSD is expressed by [26].

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{5.20}$$

where *i* represents the yearly interest rate and *n* is the number of years over which PCMSD is expected to operate (10% and 15 years, respectively).

PCMSD's yearly salvage value (*ASV*) is calculated as [26].

$$ASV = SFF \times S \tag{5.21}$$

where *SSF* and *S* stand for the sinking fund factor and the salvage value of PCMSD, respectively. Salvage value is estimated to be worth 10% of the first-year expense. For SSF, we have [26].

$$SFF = \frac{i}{(1+i)^n - 1} \tag{5.22}$$

It is estimated that 15% of the initial annual cost will go towards PCMSD annual maintenance cost (*AMC*) [26].

$$AMC = 0.15 \times FAC \tag{5.23}$$

Annual power cost (P_c) is given by.

$$P_c = t \times D_y \times W \times P_{e/kWh} \tag{5.24}$$

where t = time of operation per day (8 h), D_y = Total number of active sunshine days per annum for PCMSD operation (230 days), W= power consumed by electric blower (250 W), $P_{e/kWh}$ = Price of the electricity per unit (Rs 10 /kWh)

Annual cost (AC) of PCMSD is given by [27].

$$AC = FAC + AMC + P_c - ASV \tag{5.25}$$

The following is a calculation of PCMSD's annual useful energy (AUE) [27].

$$\begin{aligned} &Annual\ useful\ energy\ (AUE) = \\ &\quad The\ average\ of\ total\ solar\ incident\ radiation\ on\ the\ tilted\ surface\ of\ the\ SAH \times \\ &\quad absorber\ area\ \times\ efficiency\ \times\ approximate\ number\ of\ sunny\ days\ \times \\ &\quad number\ of\ operating\ hours\ per\ day \end{aligned} \tag{5.26}$$

5.2.5.2 Economic payback period

The economic payback period ($EcPBP$) for PCMSD considering i_d = 10 % (rate of discount) and i_f = 5.51 % (rate of inflation) is estimated using [25].

$$EcPBP = \frac{\ln\left(1 - \frac{P}{AI}(i_d - i_f)\right)}{ln\left(\frac{1+i_f}{1+i_d}\right)} \tag{5.27}$$

where AI is the annual income from PCMSD dried tomato given by [25].

$$AI = Q_{dry}P_{dry} - Q_{fresh}P_{fresh} - Q_{dry}C_d \tag{5.28}$$

where the capacity of dryer per day is 5 kg per batch, total number of drying day annually is 230 days, Q_{dry} is the quantity of dry tomato produced annually taking 18.28 % as a final moisture content of the tomato (289.80 kg/year), P_{dry} (Rs 500) is the price of the dried tomato per kg, Q_{fresh} is the quantity of fresh tomato to be dried annually (5 kg × 230 days = 1150 kg for all the PCMs), P_{fresh} (Rs 50) is the price of the fresh tomato per kg and the drying cost per kg of dried tomatoes, denoted as C_d, is calculated as.

$$C_d = \frac{AC}{Q_{dry}} \tag{5.29}$$

5.2.6 Environmental analysis of PCMSD

5.2.6.1 PCMSD energy payback period

Energy payback period (*EnPBP*) is the time it takes for PCMSD construction materials to earn back the Embodied energy (E_{emb}) used in their production. This time is calculated as [28].

$$EnPBP = \frac{E_{emb}(kWh)}{E_{AO}(kWh/year)} \tag{5.30}$$

PCMSD annual thermal energy output (E_{AO}) is calculated by [28].

$$E_{AO} = E_{DO} \times D_y \tag{5.31}$$

where D_y represents the assumed annual total number of daylight suitable for PCMSD operation (230 days).

The PCMSD's daily thermal energy production (E_{DO}) can be estimated by [28].

$$E_{DO} = \frac{m_w \times L_w}{3.6 \times 10^6} \tag{5.32}$$

where m_w is the daily moisture removed from fresh tomato during drying (3.74 kg/day) and the latent heat of evaporation of water (L_w) is 2260000 J/kg.

5.2.6.2 Carbon dioxide (CO_2) emission

For every kilowatt-hour (kWh) of electricity produced by a coal power station, 0.98 kg of carbon dioxide are released into the atmosphere. The annual emission of carbon dioxide is then determined by [29].

$$Yearly\ CO_2\ emission = \frac{0.98 \times E_{emb}}{n}\ kg/year \tag{5.33}$$

where E_{mb} is the embodied energy

Any practical process in typical appliances incur transmission losses (L_t) and internal losses (L_i). Then, we can modify Eq. (5.33) as shown below [29].

$$Yearly\ CO_2\ emission = \frac{E_{emb}}{n} \times \frac{1}{1-L_t} \times \frac{1}{1-L_i} \times 0.98\ kg/year \tag{5.34}$$

Assuming 40% and 20% for L_t and L_i [27], we get the following expression for Eq. (5.34).

$$Yearly\ CO_2\ emission = \frac{E_{emb}}{n} \times 2.042\ kg/year \tag{5.35}$$

5.2.6.3 Carbon dioxide (CO_2) mitigation

The CO_2 mitigation of PCMSD is calculated using the expression below [15].

$$CO_2\ mitigation = ((E_{AO} \times n) - E_{emb}) \times 2.042\ kg \tag{5.36}$$

where n is the lifetime of the PCMSD as 15 years.

5.2.6.4 Carbon credit potential

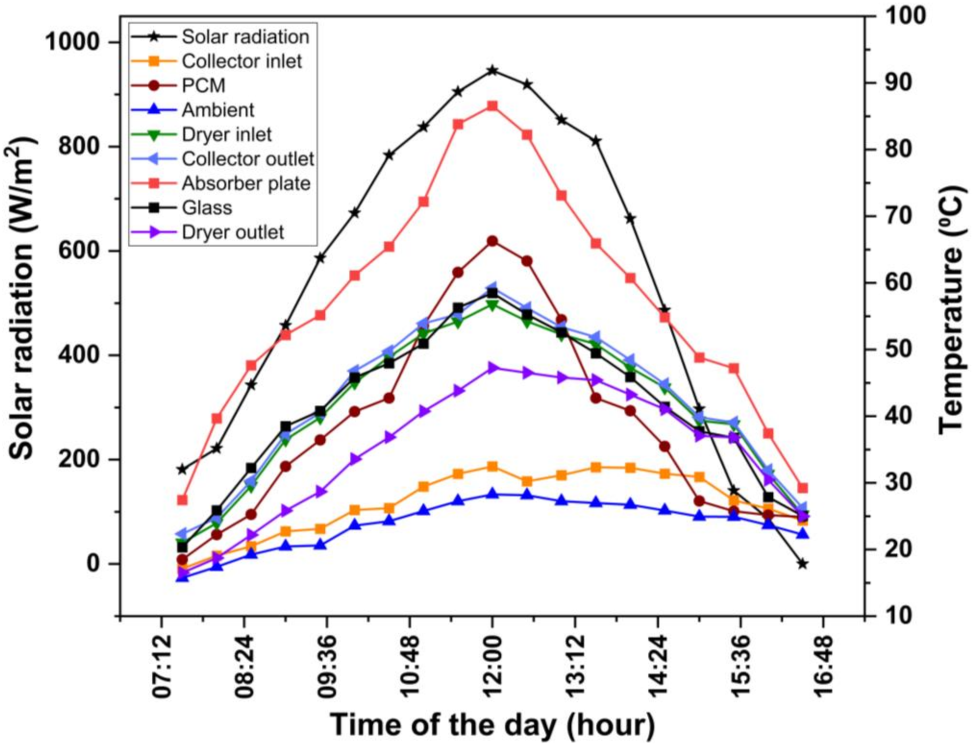
The price of offsetting one metric tonne of carbon emissions is equal to one carbon credit. The following expression can be used to determine how many carbon credits are earned in a given year [15].

$$Carbon\ credit\ earned = yearly\ CO_2\ mitigation \times Price\ per\ tonne \tag{5.37}$$

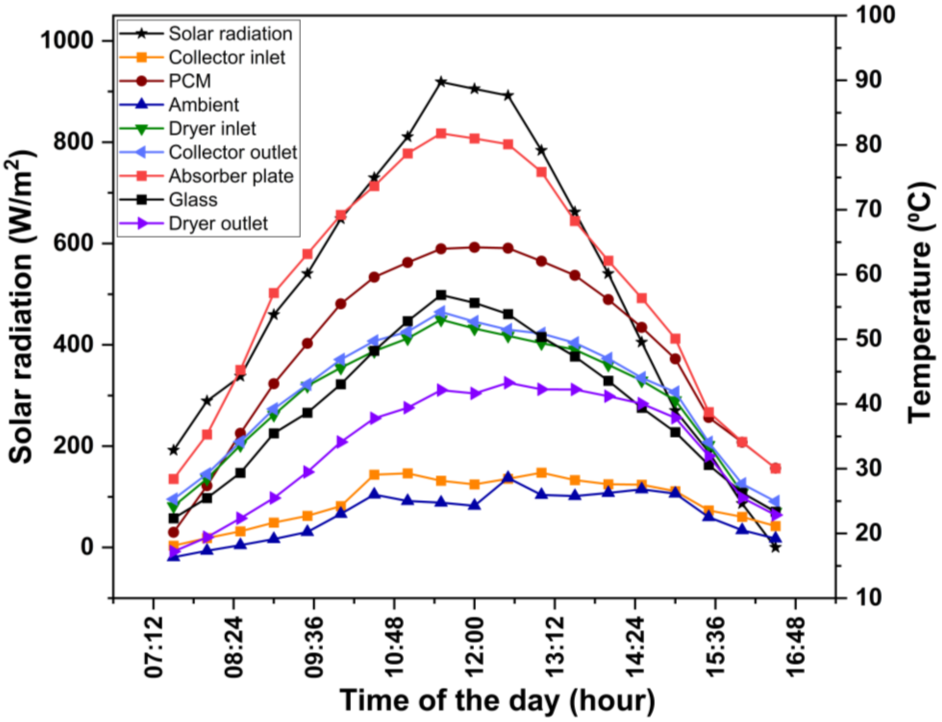
5.3 Results and Discussions

5.3.1 Performance analysis of PCMSD

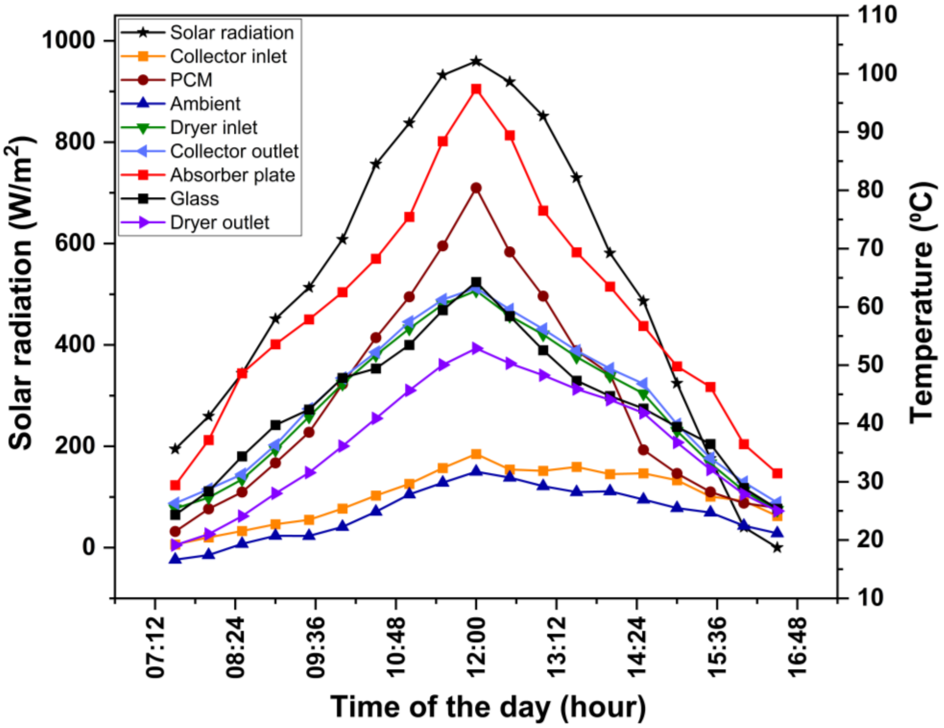
The temperature data retrieved from different thermocouples placed in different locations of PCMSD during the drying experiment are illustrated in Fig. 5.4 for three different PCMs respectively. The different experimental data such as solar radiation, ambient temperature, temperatures in different locations of PCMSD and moisture loss of the tomato are employed in determining the performances of PCMSD by means of drying energy and exergy analysis in the following study.



(a) Paraffin wax



(b) Stearic acid

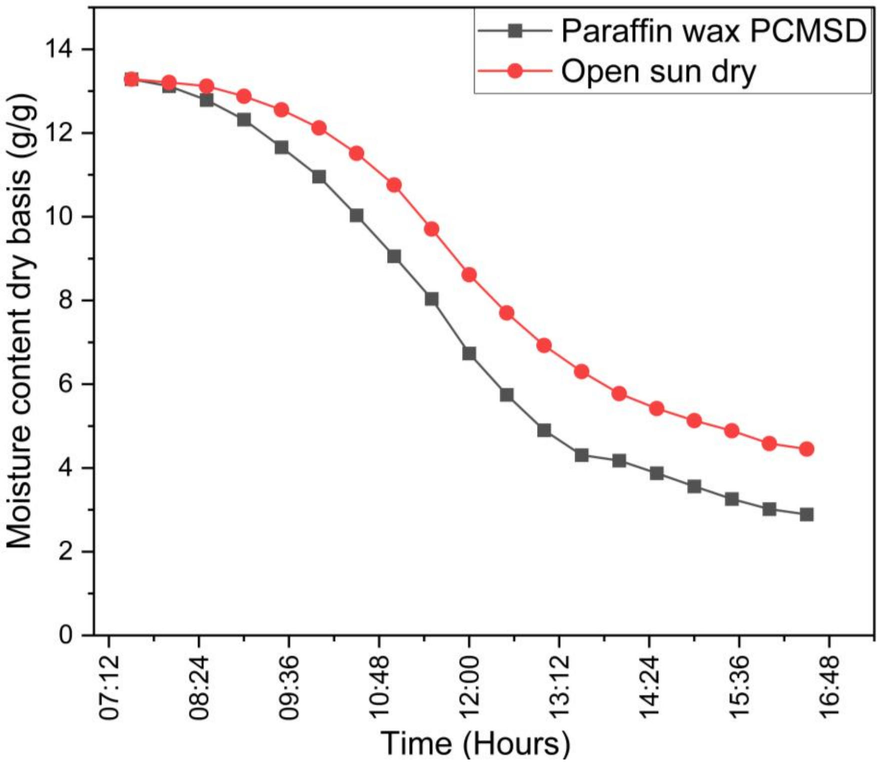


(c) Acetamide

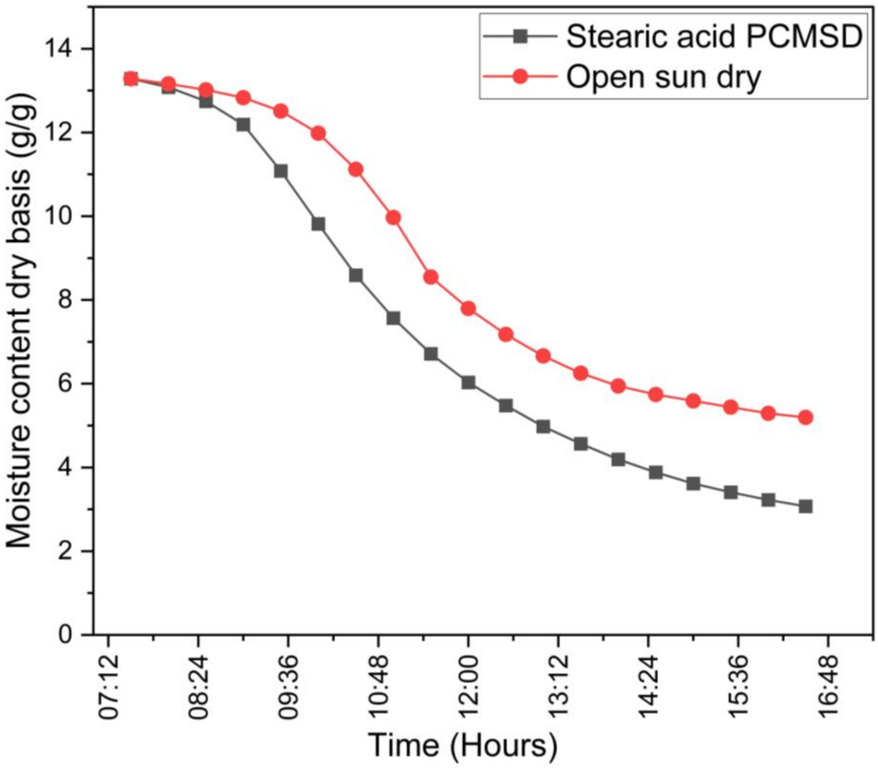
Fig. 5.4: Input parameters of the PCMSD from the experiment

5.3.2 Drying analysis of tomato in PCMSD and open sun dry

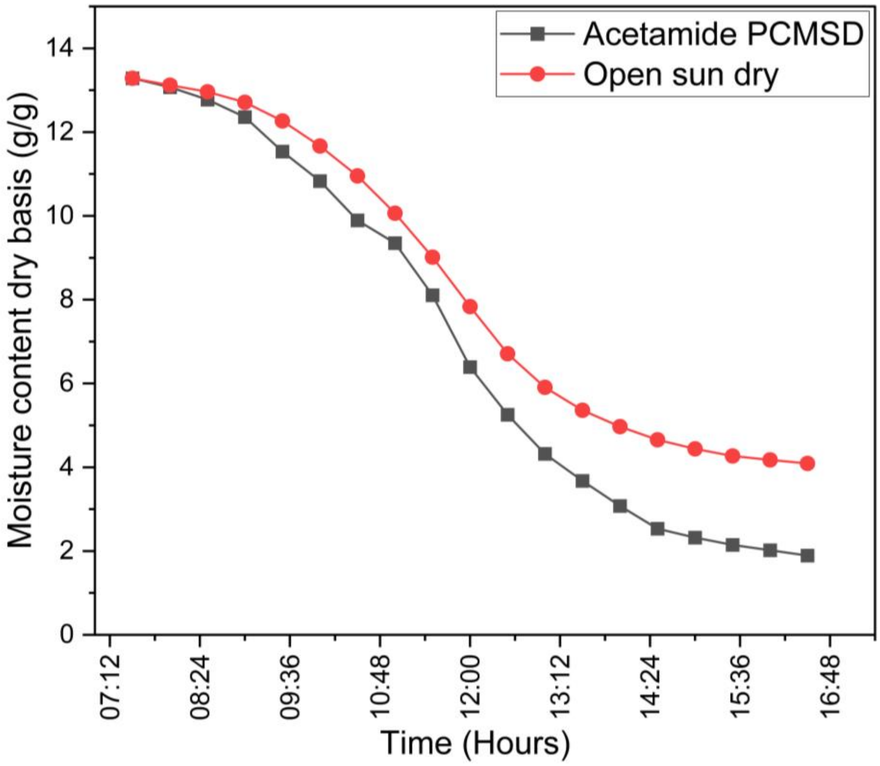
Tomatoes dried in PCMSD over the course of several days with three different PCMs are shown in Fig. 5.5, which shows how their moisture content (db) changed as they are dried. The mean value of the tomato's initial moisture content (wb) is measured to be 93% or 13.29 (db). Ideally the safe moisture content (wb) of the dried tomato is 18.28 % [30]. During the experiment of 8 h, the moisture content (db) of tomato dried in the PCMSD changed from (13.29 to 2.89 g/g) for paraffin wax and (13.29 to 4.45 g/g) for open sun drying, (13.29 to 3.07 g/g) for stearic acid and (13.29 to 5.19 g/g) for open sun drying, and (13.29 to 1.89 g/g) for acetamide and (13.29 to 4.09 g/g) for open sun dry respectively. A definite exponential trend is visible in all the graphs, as moisture content descending with the increase drying time. The moisture removal in the case of PCMSD is consistent and not affected by intermittent clouds or other weather conditions. As the tomato moisture reduces with time, the moisture removal rate decreases, and open sun dry is not efficient enough to remove moisture completely without external input. The drying time recorded for reducing the moisture content of tomato is 8 h for PCMSD and open sun drying. The proposed PCMSD effectively removes the moisture of tomatoes faster than the open sun dry.



(a) Paraffin wax



(b) Stearic acid



(c) Acetamide

Fig. 5.5: Moisture removal rate of tomato by PCMSD and open sun dry

The mass shrinkage ratio *(SR)* of the tomato after drying with three different PCMs and open sun dry is tabulated in Table 5.4. It is found that tomato dried in PCMSD with all the PCMs showed better mass shrinkage ratio as compared to open sun dry.

Table 5.4: Mass shrinkage ratio of PCMSD and open sun dry

PCM	PCMSD	Open sun dry
Paraffin wax	0.27	0.38
Stearic acid	0.29	0.43
Acetamide	0.20	0.36

5.3.3 Energy efficiency of PCMSD

The primary inputs for PCMSD energy analysis, actual heat absorbed (Q_A) from solar radiation and useable heat received by collector (Q_u) for three PCMs analysed during tomato drying experiments using Eqs. (5.3) and (5.4), are displayed in Fig. 5.6, also provides the variation in them over the time.

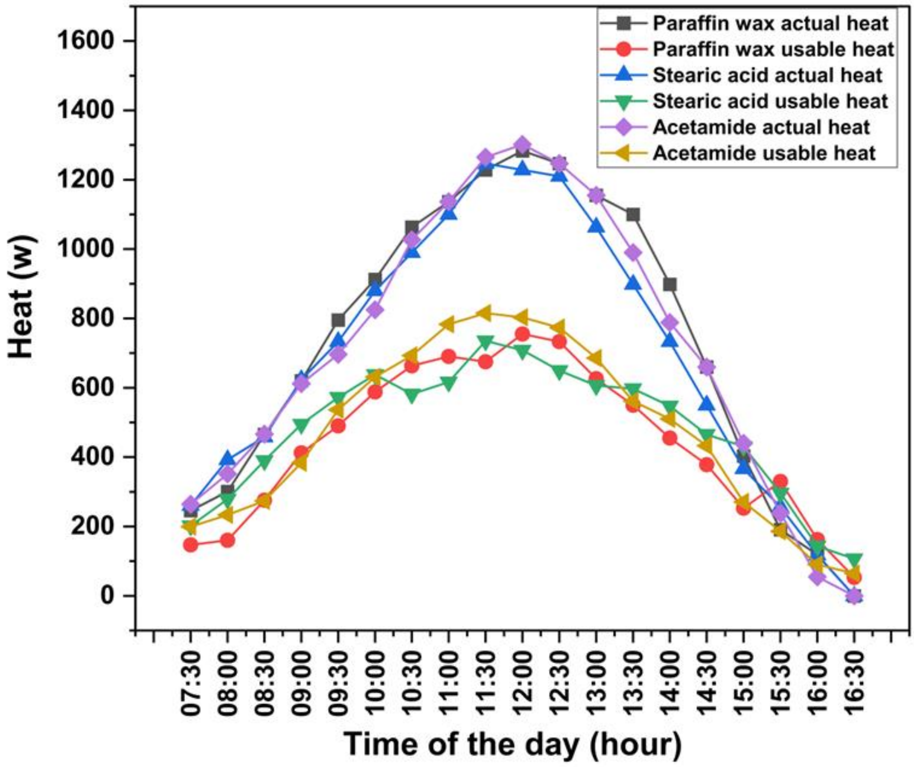


Fig. 5.6: Collector actual heat received, and usable heat gained

Fig. 5.7 depicts the collector energy efficiency of PCMSD with regard to time of operation for three distinct PCMs. The energy efficiency of collectors varies between 50.02 and 66.45% for paraffin wax, 53.02 and 85.09% for stearic acid, and 58.77 and 78.21% for acetamide. The collector's efficiency increased after 2:30 PM due to PCM heat storage, which sustained the temperature variations between the input and output air temperature. This resulted in the collector's useful heat energy exceeding the heat energy absorbed by the PCMSD collector. The current investigation's PCMSD collector efficiency is found to be in good accord with past work, where the collector energy efficiency ranged from 52.46 to 93.94 % for forced convection and 41.75 to 76.65% for natural convection [22].

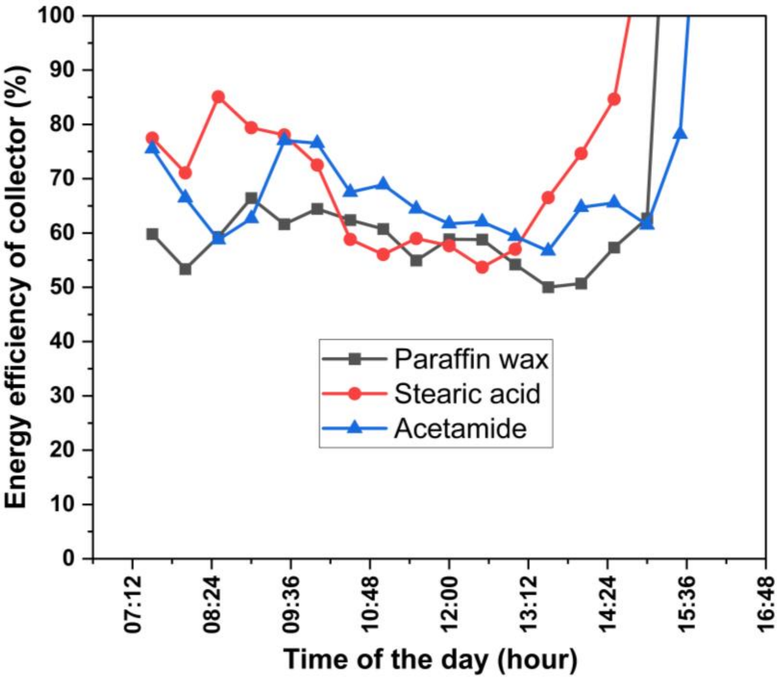


Fig. 5.7: Energy efficiency of collector

Fig. 5.8 depicts the dryer energy efficiency with three different PCMs. The overall energy efficiency of PCMSD drying chamber is 6.61 % for paraffin wax, 6.85 % for stearic acid, and 7.40 % for acetamide. As the moisture removal rate increased, the dryer's energy efficiency increased from the beginning of the drying process until 9:30 AM. The dryer energy efficiency curve fluctuates between 09:30 AM and 3:00 PM as moisture removal continues and the PCMs entirely melt. Due to the heat produced from the PCM during the discharge time, the dryer's energy efficiency increases drastically after 3:00 PM.

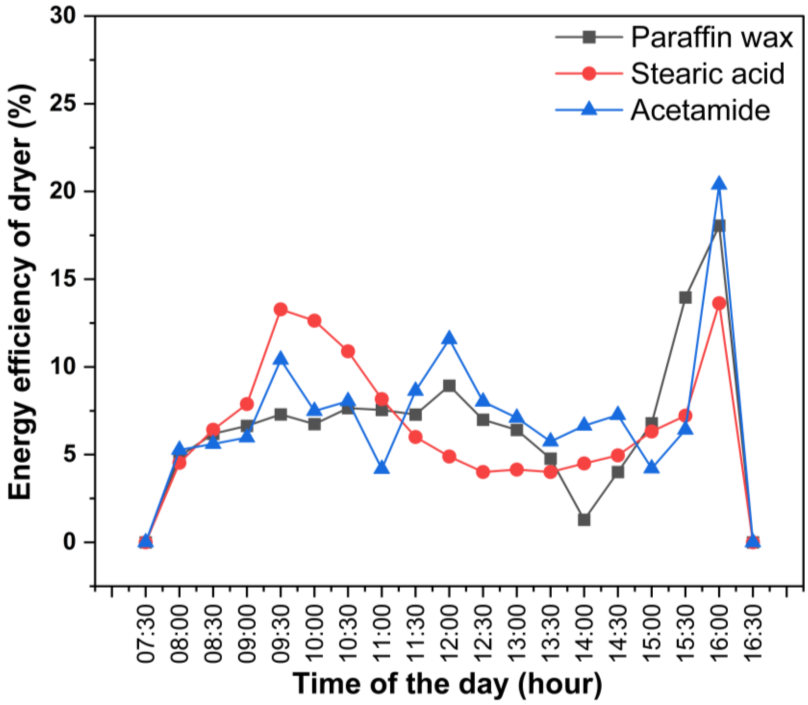


Fig. 5.8: Energy efficiency of dryer

The specific energy consumption (*SEC*) is the quantity of energy needed to eliminate 1 kg of moisture from the food product, while the specific moisture extraction rate (*SM*) is the rate at which moisture is extracted from the food product. Table 5.5 shows the *SEC* and *SM* of the PCMSD with three different PCMs. *SEC* is found lowest with acetamide followed by stearic acid and paraffin wax while *SM* is found highest with acetamide followed by paraffin wax and stearic acid respectively.

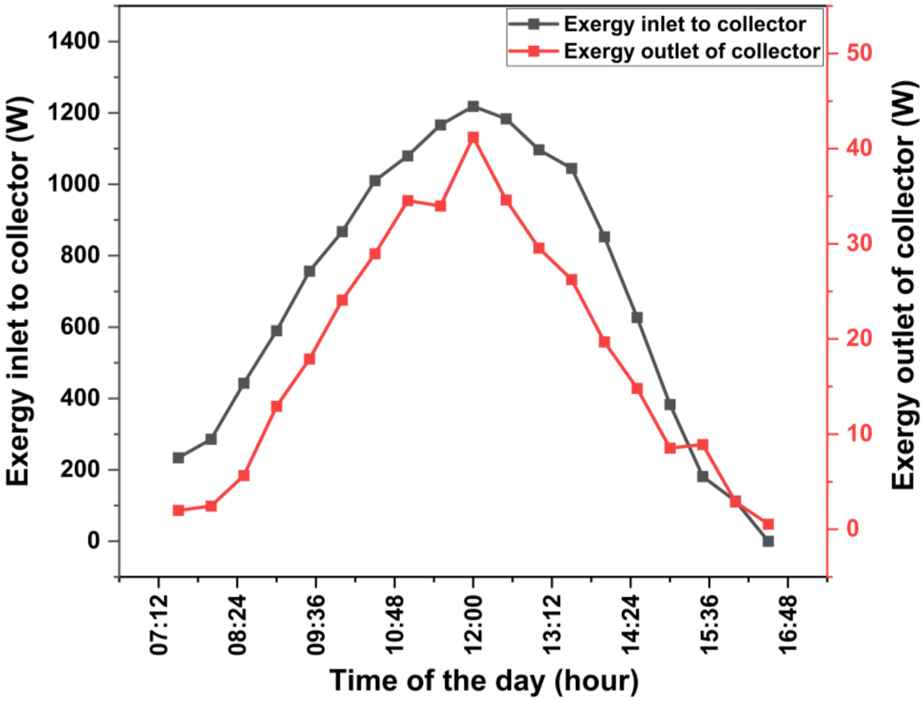
Table 5.5: Average SEC and SM during tomato drying in PCMSD

PCM	**Paraffin wax**	**Stearic acid**	**Acetamide**
Specific energy consumption, *SEC* (kWh/kg)	11.94	10.62	9.56
Specific moisture extraction rate, *SM* (kg/kWh)	0.09	0.09	0.10

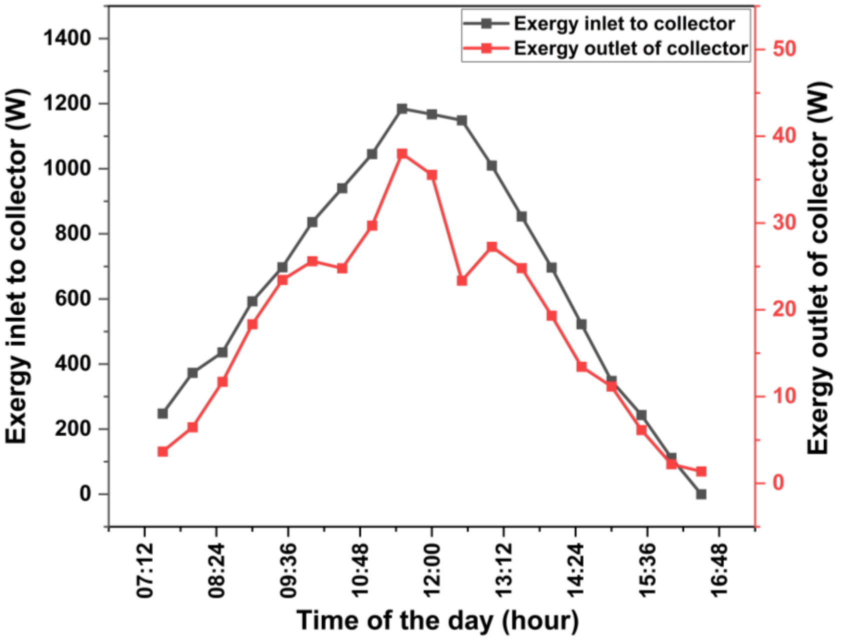
5.3.4 Exergy efficiency of PCMSD

5.3.4.1 Exergy inflow and outflow of the PCMSD collector

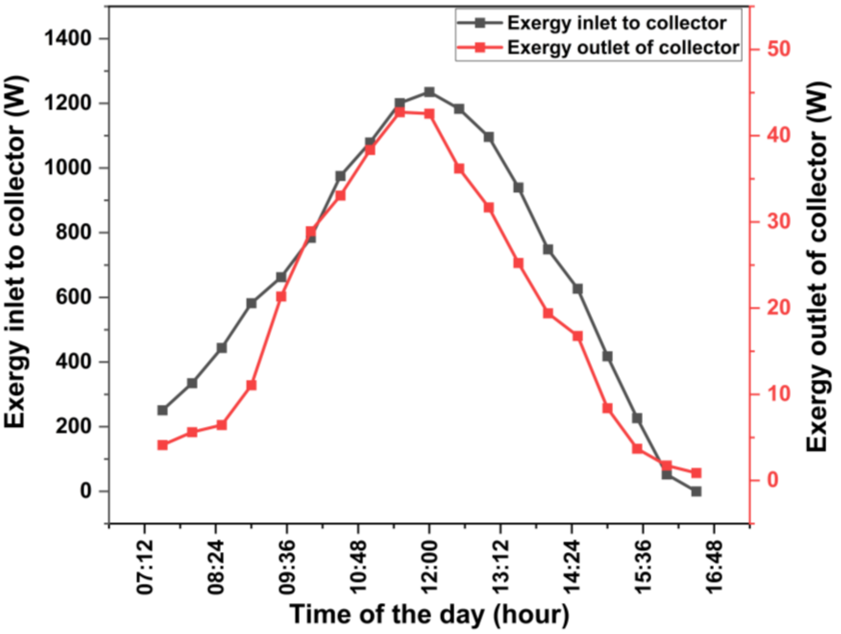
The PCMSD collector input and output exergy during the drying experiment with three PCMs are evaluated using Eqs. (5.11) and (5.12) and represented in Fig. 5.9. The amount of exergy produced depends on several factors, including the absorber plate area, mass flow rate, solar intensity, and the ambient air temperature. The tomato drying experiment data are used for the exergy inflow and outflow analysis of the PCMSD collector. Maximum values of collector exergy inflow and exergy outflow are observed during midday, when solar radiation is highest for various PCMs, as 12:00 PM for paraffin wax, 11:30 AM for stearic acid, and 12:00 PM and 11:30 AM for acetamide, respectively. The minimum, average, and maximum values of exergy inflow and exergy outflow of PCMSD collectors for paraffin wax are (112.45 W, 691.35 W, and 1218.72 W) and (1.99 W, 18.40 W, and 41.21 W), stearic acid (111.65 W, 655.63 W, and 1184.63 W) and (1.38 W, 18.23 W, and 38.01 W), and acetamide (52.28 W, 675.92 W and 1235.39 W) and (0.89 W, 19.91 W and 42.74 W) respectively. The trend of the exergy input and outlet is observed to rise at an increasing rate before reaching a maximum value, and then to progressively decrease with the solar intensity. This is because the collector's exergy inflow and outflow are dependent on the ambient air temperature, collector outlet and inlet temperature, which falls during the off-sun period and at noon. However, the exergy outlet trend appeared to fluctuate at different times of the day, and by the end of the experiment, the exergy outlet is found higher than the exergy inlet, which is due to the PCM latent heat storage effect that raised the exergy outlet.



(a) Paraffin wax



(b) Stearic acid



(c) Acetamide

Fig. 5.9: Exergy inflow and outflow of collector

Three processes mostly contribute to the destruction of exergy within the collector. Throughout the process of absorbing solar energy, the absorber plate unfortunately experiences exergy losses. Additionally, exergy destruction occurs as a result of heat escaping from the collector and during the energy transfer from the absorber plate to the fluid (air) [31]. The destruction of exergy inside the PCMSD (consisting of intermediate conduit and drying chamber) is attributed by different thermal losses in the conduit and the drying chamber including inefficiency of transfer of heat and mass during dehydration the product. In the current study little attention was given to the product (tomato) specific design of the drying chamber which might be the cause for exergy destruction. Further, inadequate provision of moisture migration from the drying chamber might be another concern. The product specific design accompanied by the measures for prevention of thermal heat losses (insulation and optimum convection) are some of the suggested areas of improvement.

Exergy efficiency of collector of PCMSD with paraffin wax, stearic acid and acetamide is estimated by using Eq. (5.14) as shown in Fig. 5.10. The overall exergy efficiency of collector with paraffin wax is 2.66 %, stearic acid is 2.78 % and acetamide is 2.94 %, respectively. The corresponding values of exergy efficiency are in the range of 0.85–4.91 % for paraffin wax, 1.48–3.36 % for stearic acid and 1.63–3.69 % for acetamide, respectively. The exergy efficiency of the collector of the present study agrees with the findings in previous investigations, as they are in the range of 0.21 - 5.12% [22] and 0.81% [32] respectively.

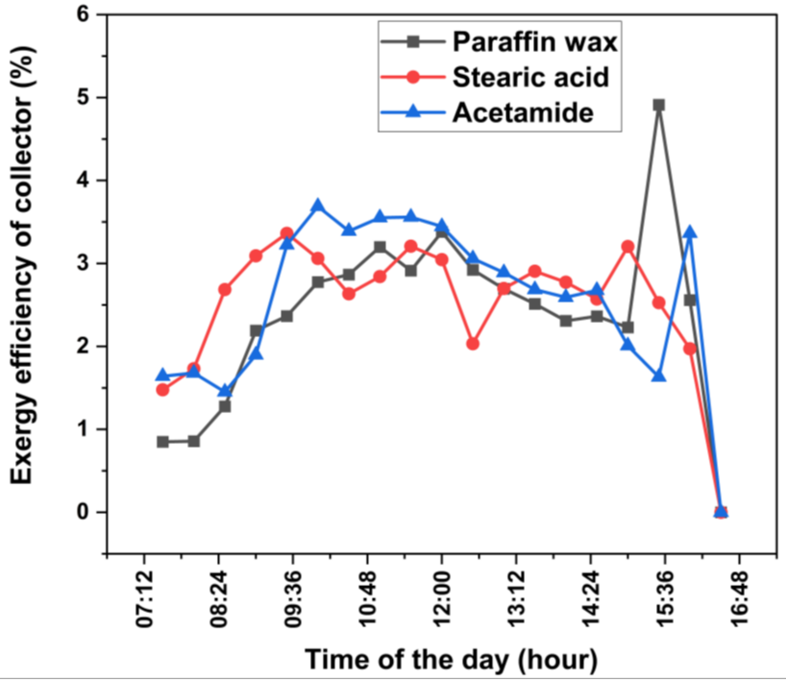
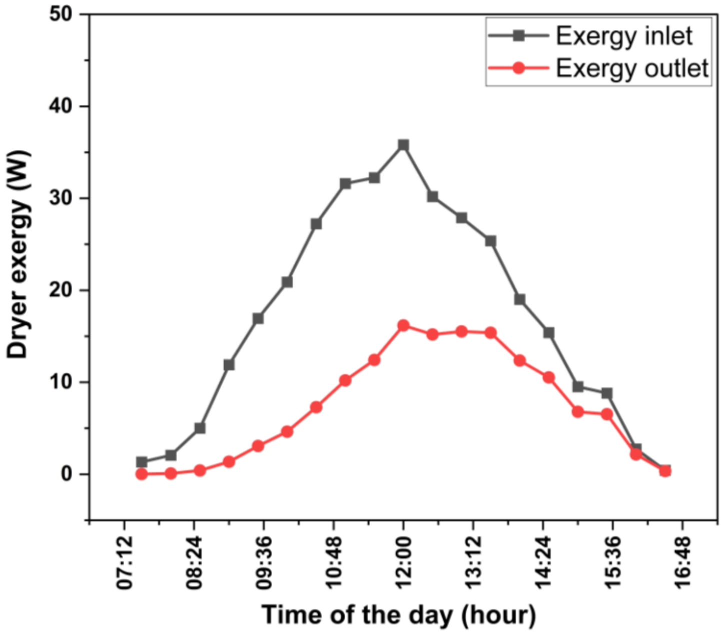


Fig. 5.10: Collector exergy efficiency

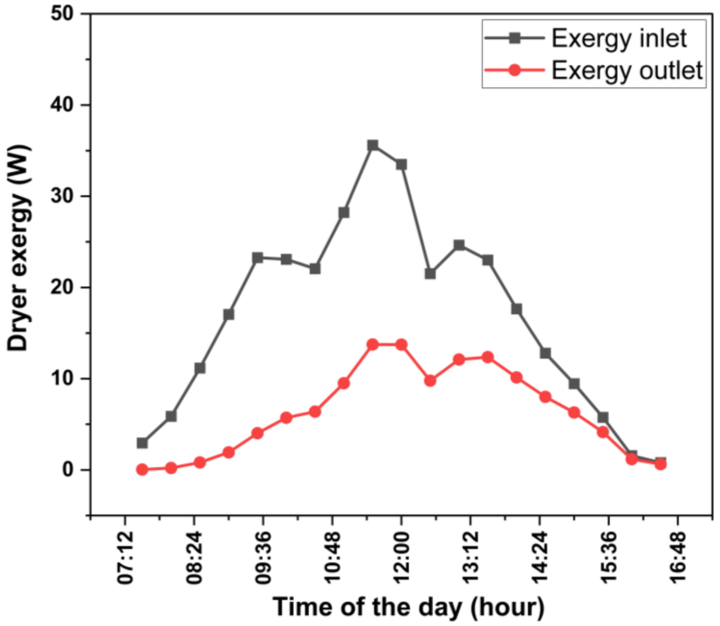
5.3.5 Exergy efficiency of PCMSD drying section

5.3.5.1 Exergy inflow and outflow of PCMSD drying section

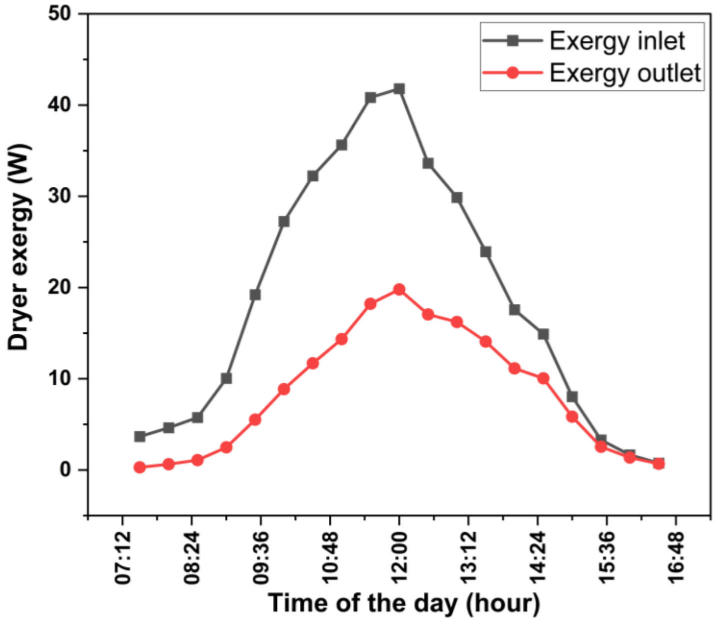
Fig. 5.11 represents the exergy inflow and outflow of the drying section with time for different PCMS viz., paraffin wax, stearic acid and acetamide. The exergy inflow and the exergy outflow of the drying section is a function of the difference between outlet and inlet temperatures of the drying section. As indicated in the Fig. 5.11 the exergy inflow and the exergy outflow of drying section is seen to be similar to the trend of solar radiation variation. The LHS maintains the temperature during discharging after the peak sunshine hour. The minimum, average, and maximum exergy inflow, and exergy outflow of the drying section for paraffin wax is (0.43, 17.07, 35.82 W) and (0.03, 7.40, 16.18 W), stearic acid is (0.81, 16.85, 35.60 W) and (0.04, 6.36, 13.75 W) and acetamide is (0.76, 18.67, 41.80 W) and (0.30, 8.52, 19.80 W), respectively.



(a) Paraffin wax



(b) Stearic acid



(c) Acetamide

Fig. 5.11: Exergy inflow and outflow of dryer chamber

The drying section's exergy efficiency is primarily impacted by the drying chamber's exergy outflow and inflow. The fluctuation of exergy efficiency of the drying section with time for three different PCMs is depicted in Fig. 5.12. In Fig. 5.12, the exergy efficiency of the drying section for three distinct PCMs increases with time until the experiment is completed. The evaluated values of exergy efficiency of the PCMSD drying section with paraffin wax range from 2.12-83.47%, stearic acid range from 1.25-78.52%, and acetamide range from 8.15-90.29%, with the overall exergy efficiency of the dryer being 43.33%, 37.74%, and 45.64%, respectively. The current study's exergy efficiency of the drying phase of PCMSD is in good agreement with the previous literature, which reports 9.634 -74.79% [25], 3.7 - 75.15% [32] and 6.34 -94.35% [33].

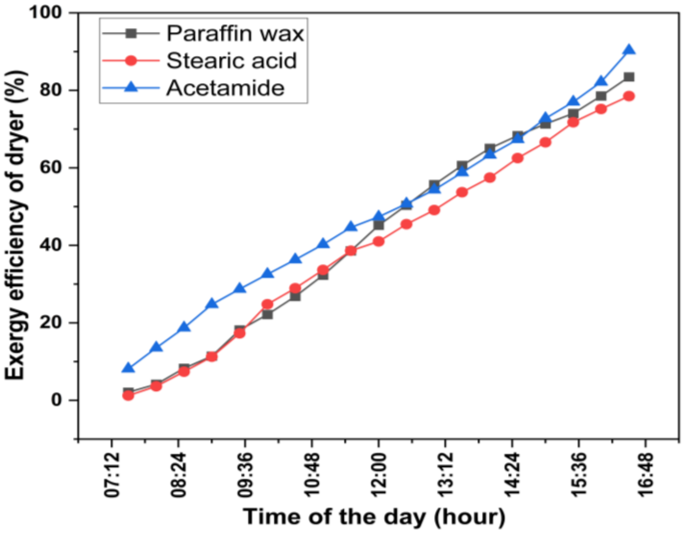


Fig. 5.12: Dryer exergy efficiency

5.3.6 Economic analysis of PCMSD

Capital cost, annual cost, payback period, and annual income earned throughout the complete working lifespan are the primary criteria to assess while evaluating the economic analysis of PCMSD system. The economic analysis of PCMSD is carried out by considering full capacity drying (5 kg), useful lifetime (L_d) of 15 years and all the materials are procured from the market in Tezpur, Assam, India. The capital cost (P) of PCMSD is tabulated in Table 5.6.

Table 5.6: Capital cost of components used in PCMSD

S.No.	Components of PCMSD	Materials used	Required quantity	Rate of the components per unit	Fabrication charges	Total (INR)
1	Absorber plate	Aluminium sheet	2.5 kg	230	300	875
2	Collector body frame	Wooden	10 kg	220	800	3,000
3	Glass cover	Glass	21.5 sq ft	93		2,000
4	Glass cover frame	Aluminium frame	24 ft	90	800	2,960
5	Outer covers	Aluminium sheet	2.5 kg	230	800	1,375
6	Drying Chamber	Mild steel sheet	13 kg	160		
		Mild steel angle	10 kg	180	3,500	9,180
		Hollow Iron rod	15 kg	120		
7	Coatings	Black paint	2 L			1,200
8	4 no. of drying trays	Wooden	1 kg	200	200	400
		Aluminium mesh	1.5 kg	600	500	1,400
9	Total Insulation	Thermocol				2,800
10	Support stand	Mild steel angle	12 kg	180	1,200	3,360
11	Fittings (nuts, bolts, screw, and rivets)	Steel				1,000
12	Divergent duct	Mild steel sheet	9 kg	160	500	1,940
		PVC pipe				320
13	Blower					2,250
14	PCMs	Paraffin wax	11.30 kg	90		1,017
		Stearic acid	12.12 kg	80		969.60
		Acetamide	14.57 kg	300		4,368
15	Total transportation cost					3,000
				Paraffin wax based PCMSD		**38,077.00**
			Capital cost	Stearic acid based PCMSD		**38,029.60**
				Acetamide based PCMSD		**41,428.00**

The economic analysis of tomato drying in PCMSD is performed by evaluating the capital cost, annual cost, savings, and payback period considering the discount rate (i_d = 10 %) and inflation rate (i_f = 5.10 %) and shown in Table 5.7. The capital cost of the PCMSD is 38,077.00 INR (paraffin wax), 38,029.60 INR (stearic acid) and 41,428.00 INR (acetamide) respectively. The capital recovery factor of the PCMSD with all three PCMs is estimated as 0.13, the sinking fund factor as 0.03 and the annual power cost for operation of PCMSD as 4,600 INR respectively. The quantity of dry tomato produced annually considering 18.28 % [30] as a final moisture content of the tomato is estimated as 289.80 kg/year.

The first annual cost, salvage value, yearly salvage value, annual maintenance cost, annual useful energy and annual cost for the operation of PCMSD are shown in Table 5.7. The PCMSD with all the PCMs have almost same annual cost. As shown in Table 5.8, the PCMSD's short payback period (0.54 years for paraffin wax and stearic acid and 0.59 years for acetamide) makes it viable for the transfer of technology for the end users such as farmers and other benefactors.

Table 5.7: Annualised cost of PCMSD with different PCMs

PCM	***FAC (INR)***	***S (INR)***	***ASV (INR)***	***AMC (INR)***	***AUE (kWh/year)***	***AC (INR)***
Paraffin wax	5006.13	500.61	15.76	750.92	8243.98	10341.29
Stearic acid	4999.90	499.99	15.74	749.98	8116.03	10334.14
Acetamide	5446.70	544.67	17.14	817.00	8740.76	10846.56

Table 5.8: Economic payback period of PCMSD with different PCMs

PCM	***P (INR)***	***AI (INR)***	***EcPBP (years)***
Paraffin wax	38,077	77058.71	0.54
Stearic acid	38,029.60	77065.85	0.54
Acetamide	41,428	76553.44	0.59

5.3.7 Environmental analysis of PCMSD

The environmental analysis of PCMSD carried out through the embodied energy as shown in Table 5.9. There are no proper embodied energy data for the PCMs directly. The emissions per unit of electricity are estimated to be in the range of 0.91 to 0.95 kg CO_2 /kWh [34]. The petroleum-based wax has a carbon footprint of 0.609 kg CO_2/kg of wax [35]. So, we can consider the energy density of paraffin wax as 0.66 kWh/kg. Across all oil crop systems, median GHG emissions ranged from 2.49 kg CO_2/kg for rapeseed oil, 3.81 kg CO_2/kg for refined oil and 4.25 kg CO_2/kg for soybean oil [36]. The hydrolysis of these oils can produce stearic acid. Therefore, we can consider the energy density of stearic acid as 2.73 kWh/kg. The power input for acetic acid production and extraction is 9.56 kWh/kg of acetic acid out of which 36% is attributed by the electrochemical extraction

[37]. The production of 1 kg of ammonia requires about 8.3 kWh power [38]. As acetamide can be produced by formal condensation of the acetic acid with ammonia. We can consider the energy density of acetamide as 17.86 kWh/kg. Therefore, the embodied energy in manufacturing of the PCMSD with all the three PCMs are 1357.04, 1382.67 and 1609.81 kWh for paraffin wax, stearic acid and acetamide respectively. The important parameters for the environmental analysis of PCMSD such as yearly CO_2 emission, CO_2 mitigation and range of carbon credit earned for (i) paraffin wax is 184.74 kg/year, 5329.14 kg and $ 26.65 to $ 106.58 (2201.73 INR to 8806.94 INR), (ii) stearic acid is 188.23 kg/year, 5276.80 kg and $ 26.38 to $ 105.54 (2180.11 INR to 8720.45 INR) and (iii) acetamide is 219.15 kg/year, 4812.98 kg and $ 24.06 to $ 96.26 (1988.48 INR to 7953.94 INR) respectively where the cost of carbon credits for indirect solar dryers is estimated to be between $5 and $20 for every metric tonne of CO_2 released [15] and the dollar conversion rate on 07.07.2023 is 82.63 INR. Finally, the energy payback period of PCMSD with different PCMs are estimated as estimated as 2.51 years for paraffin wax, 2.56 years for stearic acid and 2.98 years for acetamide respectively.

Table 5.9 Embodied energy of the components of PCMSD

S.No.	**Components of PCMSD and SD**	**Materials**	**Energy density (kWh/kg) [15, 22, 27]**	**Mass of component (kg)**	**Embodied energy (kWh)**
1	Absorber plate	Aluminium sheet	55.28	2.5	138.2
2	Collector body frame structure	Wooden block	0.66	10	6.6
3	Glass cover	Glass	7.28	7	50.96
4	Outer covers	Aluminium sheet	55.28	2.5	138.2
5	Glass cover frame	Aluminium	55.28	3.5	193.48
6	Drying Chamber	Mild steel	8.89	23	204.47
		Hollow iron rod	6.94	15	104.1
7	Coatings	Black paint	25.11	2.5	62.77
8	Trays	Wood	0.66	1	0.66
		Aluminium mesh	55.28	1.5	82.92
9	Total Insulation	Thermocol	24.61	5	123.05
10	Stand support	Mild steel	8.89	12	106.68
11	Fittings (nuts, bolts, screw, and rivets)	Steel	8.89	1	8.89
12	Divergent duct	Mild steel	8.89	9	80.01
		PVC pipe	19.4	1	19.4

S.No.	Components of PCMSD and SD	Materials	Energy density (kWh/kg) [15, 22, 27]	Mass of component (kg)	Embodied energy (kWh)
13	Blower	Plastic	19.4	1	19.4
		Copper wire	19.61	0.50	9.80
14	PCMs	Paraffin wax	0.66	11.30	7.45
		Stearic acid	2.73	12.12	33.08
		Acetamide	17.86	14.57	260.22
		Embodied energy	Paraffin wax based PCMSD		**1357.04**
			Stearic acid based PCMSD		**1382.67**
			Acetamide based PCMSD		**1609.81**

Summary

In the present Chapter the performance of the developed PCMSD is studied. The mean value of the initial moisture content (wb) of the tomato is examined to be 93 % or 13.29 (db). The moisture content (db) of tomato dried in the PCMSD changed from (13.29 to 3.07 g/g) for stearic acid and (13.29 to 5.19 g/g) for open sun drying, and (13.29 to 1.89 g/g) for acetamide and (13.29 to 4.09 g/g) for open sun dry respectively during the experiments. Tomato dried in PCMSD with all the PCMs showed better mass shrinkage ratio as compared to open sun dry.

The collector energy efficiency is found to be varying from 50.02– 66.45 % for paraffin wax, 53.02–85.09 % for stearic acid and 58.77–78.21 % for acetamide. The overall energy efficiency of the dryer is 6.61 %, 6.84 % and 7.40 % for paraffin wax, stearic acid and acetamide, respectively.

The specific energy consumption *(SEC)* and the specific moisture extraction rate *(SM)* of PCMSD with paraffin wax is (11.94 and 0.06), stearic acid is (10.6 and 20.09) and acetamide is (9.56 and 0.10) respectively.

The minimum, average and maximum values of exergy inflow and exergy outflow of PCMSD collectors are estimated for paraffin wax as (112.45 W, 691.35 W and 1218.72 W) and (1.99 W, 18.40 W and 41.21 W), stearic acid as (111.65 W, 655.63 W and 1184.63 W) and (1.38 W, 18.23 W and 38.01 W) and acetamide as (52.28 W, 675.92 W and 1235.39 W) and (0.89 W, 19.91 W and 42.74 W) respectively. The average exergy efficiency of collector with paraffin wax is 2.38 %, stearic acid is 2.52 % and acetamide is 2.55 %, respectively. The corresponding values of average exergy efficiency are in the range of 0–4.91 % for paraffin wax, 0–3.36 % for stearic acid and 0–3.69 % for acetamide, respectively.

The minimum, average, and maximum exergy inflow, and exergy outflow of the drying section for paraffin wax is (0.43, 17.07, 35.82 W) and (0.03, 7.40, 16.18 W), stearic acid is (0.81, 16.85, 35.60 W) and (0.04, 6.36, 13.75 W) and acetamide is (0.76, 18.67, 41.80 W) and (0.30, 8.52, 19.80 W), respectively. The evaluated values of exergy efficiency of the drying section for the setups with paraffin wax ranged from 2.12–83.47 %, stearic acid ranged from 1.25–78.52 % and acetamide ranged from 8.15–90.29 % and the overall exergy efficiency of drying section are 43.33 %, 37.74 % and 45.64 % for paraffin wax, stearic acid and acetamide, respectively. The destruction of exergy inside the PCMSD (consisting of intermediate conduit and drying chamber) is attributed by different thermal losses in the conduit and the drying chamber including inefficiency of heat and mass transfer during dehydration the product. In the current study little attention was given to the product (tomato) specific design of the drying chamber which might be the cause for exergy destruction. Further, inadequate provision of moisture migration from the drying chamber might be another concern. The product specific design accompanied by the measures for prevention of thermal heat losses (insulation and optimum convection) are some of the suggested areas of improvement.

The capital cost of PCMSD with three different PCMs including material, fabrication and transportation costs are 38,077.00 INR (paraffin wax), 38,029.60 INR (stearic acid) and 41,428.00 INR (acetamide) respectively. The annual cost of PCMSD with three different PCMs are estimated as 10,341.29 INR (paraffin wax), 10,334.14 INR (stearic acid) and 10,846.56 (acetamide) respectively. The annual income from the PCMSD is 77,058.71 INR for paraffin wax, 77,065.85 INR for stearic acid and 76,553.44 INR for acetamide respectively. The economic payback period of the PCMSD with three different PCMs are estimated to be 0.54, 0.54 and 0.59 years for paraffin wax, stearic acid and acetamide respectively which is found to be very short.

The embodied energy of the PCMSD is 1357.04, 1382.67 and 1609.81 kWh for paraffin wax, stearic acid and acetamide respectively. Other parameters for environmental analysis like yearly CO_2 emission, CO_2 mitigation and range of carbon credit earned for (i) paraffin wax is 184.74 kg/year, 5329.14 kg and $ 26.65 to $ 106.58 (2201.73 INR to 8806.94 INR), (ii) stearic acid is 188.23 kg/year, 5276.80 kg and $ 26.38 to $ 105.54 (2180.11 INR to

8720.45 INR) and (iii) acetamide is 219.15 kg/year, 4812.98 kg and $ 24.06 to $ 96.26 (1988.48 INR to 7953.94 INR) respectively. Finally, the energy payback period of PCMSD is estimated as 2.51 years for paraffin wax, 2.56 years for stearic acid and 2.98 years for acetamide respectively.

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