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Experimental and exergy evaluation of a PCM integrated active indirect solar dryer for Turkey berries with economic and environmental assessment

K. Senthil Kumar¹, R. Vasanthi², Mahdi Sh. Jaafar³, Arunkumar Munimathan^{4,6}, Manoj Kumar Shanmugam⁴, Mamdooh Alwetaishi⁵, Asif Afzal⁷, Parvathy Rajendran⁸✉ & It Ee Lee⁹✉

The research was investigated Turkey Berries drying capability using Active Mode Indirect Solar Dryers at Kovaipudur in Coimbatore, India. The conic-shaped Thermal Energy Storage (TES) covered the solar collector selectively and photovoltaic (PV) panels used to power divergent ducts equipped with DC blowers to enhance the AMISD. An energy analysis revealed meaningful distinctions between the AMISD systems equipped with TES and those operated without TES. The implementation of Thermal Energy Storage brought about a 89.6% collector efficiency rate that exceeded the results commonly reported in related PCM-based solar drying platforms. The proposed combination of a conic-shaped PCM module and a PV-powered diverging duct serves as the main cause behind this performance gain by supporting heat retention and enhancing airflow distribution. The solar dryers achieved better overall efficiency when using TES because they reached 15.23% efficiency compared to 14.8% without TES. The TES system increased the Energy Utilization Ratio up to 29.31 from its initial value of 28. Without TES AMISD used 1384 W of energy but with the implementation of TES it only needed 1268 W to function properly. The information about energy output demonstrates TES produces maximum energy consumption efficiency both with and without Phase Change Material (PCM). The PCM integration in the Specific Collector Area (SAC) improved its energy efficiency from 6.84 to 7.1%. The Sustainability Index scores achieved 8.1 when PCM was included in the experiments while the baseline scores remained at 8.01 without PCM application. Regardless of positive findings the actual experimental data fell short of projecting greenhouse dryer service expectancy to last for 35 years. The study demonstrates that using AMISD with PCM works effectively with improved energy performance while diminishing environmental influence and decreasing operational costs. Based on present circumstances in the region Turkey Berries drying with these specifications appears feasible and sustainable.

Keywords Phase change material, Indirect solar dryer, Energy storage, Energy analysis, Economics, Energy efficiency, Environmental impact, And economic feasibility

¹Department of Mechanical Engineering, Sri Krishna College of Technology, Coimbatore 641042, Tamilnadu, India.

²Department of Agricultural Engineering, KIT-Kalaigarkarananidhi Institute of Technology, Coimbatore 641402, Tamil Nadu, India. ³Department of Chemical Engineering and Petroleum Industries, College of Engineering, Al- Mustaqbal University, Hilla 51001, Iraq. ⁴Department of Mechatronics Engineering, Hindusthan College of Engineering and Technology, Coimbatore 641032, Tamilnadu, India. ⁵Department of Civil Engineering, College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia. ⁶Department of Mechanical Engineering, University Centre for Research & Development, Chandigarh University, Gharuan, Mohali, Punjab, India. ⁷Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura 140401, Punjab, India. ⁸School of Aerospace Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300 Pulau Pinang, Malaysia. ⁹Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor D. E., Malaysia. ✉email: aeparvathy@usm.my; ieleee@mmu.edu.my

Abbreviations

AMISD	Active mode indirect solar dryer
PCM	Phase change material
TES	Thermal energy storage
PV	Photovoltaic
SAC	Solar air collector
EUR	Energy utilization ratio
SI	Sustainability index
WER	Waste exergy ratio
IP	Improvement potential
EIF	Environmental impact factor
η	Efficiency
η_{ex}	Exergy efficiency
CO ₂	Carbon dioxide
db	Dry basis

The agricultural and biomass industries rely heavily on the widespread drying technology for preservation purposes. The removal of moisture occurs through heat-based procedures including conduction, convection and radiation. Solar drying emerges as a sustainable energy-efficient method that employs solar radiation to heat air for achieving biomass and food dehydration¹. The capacity to dry materials depends heavily on four main factors including dimension, starting wetness levels and settings for heat temperatures together with air flow properties². The main purpose remains to boost quality while prolonging shelf stability while decreasing deterioration and optimizing post-harvest processing and storage practices. Different drying innovations have appeared throughout the past decades including both infrared and microwave technologies together with advanced spray dryers³. Enhanced drying rates with better product quality exists in these systems but they present high initial costs and substantial power usage alongside maintenance needs which result in using up to 12% of industrial energy demand⁴. High solar energy potential areas generate increasing interest toward solar drying solutions due to existing technological boundaries. Two categories of solar drying technology exist namely passive systems and active systems⁵. The popularity of Active Mode Indirect Solar Dryers (AMISDs) continues to rise because they control airflow and heat through solar-powered blowers which increases operational performance⁶. Solar dryers become more reliable through the addition of Phase Change Materials (PCMs) and Thermal Energy Storage (TES) materials because these elements help keep temperatures stable and increase drying time despite changing solar irradiance. Researchers have conducted tests which demonstrate the advantages of solar dryers that include Phase Change Materials for different agricultural products⁷. The implementation of TES systems that use paraffin enhances drying operation efficiency through improved energy collection while simultaneously lowering energy inputs and increasing sustainability⁸. The combination of solar technologies in hybrid dryers establishes superior performance compared to natural convection methods when considering energy consumption and environmental effects. Research on solar drying of fruits has dominated the field but lacks investigations into Turkey Berries which represents a short-lived nutritional crop⁹. Rate-discharge PCM applications in solar drying systems exist but researchers have not fully documented innovations for collector geometry or airflow optimization. Scientists have failed to conduct extensive research on the combination of PV-driven divergent ducts and conic-shaped PCM devices that potentially optimize both thermal capacity and airflow management and power generation¹⁰. The enhancement of 0.95% in exergy efficiency for the Solar Air Collector (SAC) represents substantial thermodynamic improvement even if it shows small numerical change from 6.84 to 7.1%. The exergy efficiency of solar drying systems has a high sensitivity to collector losses but demonstrates improved energy utilization through the increased exergy efficiency. The integration of conic PCM and active air flow management allows the present system to achieve greater exergy performance results compared to the standard range of 5–6.5% observed in similar studies¹¹. The current study analyzes an Active Mode Indirect Solar Dryer equipped with Thermal Energy Storage capability which incorporates paraffin-based PCM in a conic-shaped configuration. The system incorporates divergent ducts operated by photovoltaic power to enhance drying uniformity as well as thermal performance. Real-time experimentation enabled the study to measure multiple dryer performance characteristics particularly regarding energy and exergy efficiency together with drying kinetics and economic efficiency and environmental sustainability. The study will produce applicable results to build efficient and cost-effective environmental solar drying technologies for Turkey Berries alongside other agricultural products in sunny climates.

Experimental setup description

The Active Mode Indirect Solar Dryer (AMISD), which is depicted in Fig. 1, integrates a drying chamber and solar air collector. Its compartment measures 30 cm in length, 30 cm in width, and 90 cm in height. The compartment is divided into three sections. The system has a DC powered blower that draws 0.25 A at 12 V and is powered by solar energy. The purpose of this design is to improve the drying chamber's atmospheric air circulation. The widely described experimental methodology includes the employment of particular instruments to measure different parameters. Because each instrument has specified measurement ranges and accuracy levels, accurate data gathering is ensured for assessing the effectiveness and performance of the AMISD.

Direct solar dryer (DSD)

Direct Solar Dryer is known as a greenhouse or cabinet consists of a transparent box covered with glass or polycarbonate sheeting. The translucent cover lets sunlight fall on food slices, diminishing their colour. Large-

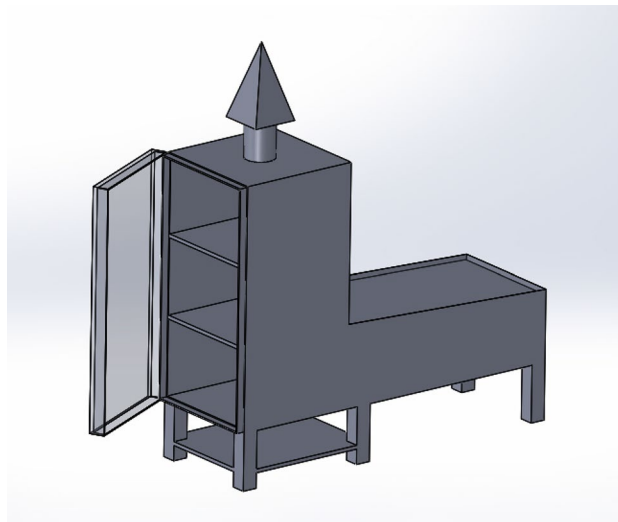


Fig. 1. Experimental design.

scale drying applications frequently use this kind of direct drier, and research is being done to determine how Phase Change Material (PCM) affects thermal performance¹³.

Indirect solar dryer (ISD)

To shield food goods from direct sunlight, warm air is produced externally using solar air collectors (SAC) in indirect solar dryer (ISD) as shown in Fig. 2. The outcome of drying of an ivy gourd-specific natural convection ISD with a paraffin wax Thermal Energy Storage setup was designed and assessed¹².

Experimental procedure

The experiment was carried out from morning 8:00 AM to evening 6:00 PM on October 20–26 in Kovaipudur, Coimbatore and the equipment availed during this experiment is listed in the Table 1 with its ranges and accuracy rate. Table 2 shows the properties of paraffin wax with its properties. The Turkey Berries, which had an initial moisture level of 85.5%, were split into two equal parts. Four kilograms of the berries were subsequently separated into three equal sections for each trial, and they were then placed in trays within the Open Sun Drying (OSD) setup and the drying chamber. Testing took place for nine hours a day, from morning 8:00 AM till evening 6:00 PM¹⁴. A weighing balance was used to record the hourly mass measurements of the samples in the drying chamber and OSD. The initial moisture content of the Turkey Berries was determined using a hot air oven. The results of the experiment were assessed under full load conditions in terms of Energy, Exergy, Economic, and Environmental criteria, offering a thorough grasp of the drying process and its related variables¹⁵.

A set of Testo 184 G1 Thermometer and RB-WT10000 Hygrometer measured ambient temperature and humidity values during drying trials which spanned from 8:00 AM until 6:00 PM. The ambient climate starting from 29.2 °C at dawn rose to its highest point of 36.8 °C before dropping to 30.1 °C in the evening. The humidity levels had a reverse reaction during the day starting from 65% before declining to 42% in the middle of solar exposure and recovering to 58% by 6:00 PM. These environmental factors had a substantial impact on drying behavior and their measurement served to maintain test day consistency.

Drying kinetics of Turkey berries

Turkey berry drying properties were evaluated in the AMISD experiment. For analysis, the dry basis (db) initial moisture content (MC) of Turkey Berries was ascertained¹⁶.

$$MC (db) = \frac{m_{ip} - m_{fp}}{m_{fp}} \quad (1)$$

Where m_{ip} —initial dried mass of the samples. m_{fp} —dried mass of the samples at the end in g, of AMISD.

ISD energy analysis

In the Indirect Solar Dryer (ISD), solar intensity falls on the Solar Air Collector (SAC) and it is taken into account as the system's energy input. Heat released from the drying cabinet and SAC enclosures as well as the energy carried by the air at the chimney exit are examples of energy outputs. The dryer and SAC are assumed to have SSF (steady-state flow) in the analysis. The Energy Efficiency Analysis (EEA) can be conducted more easily since a constant mass flow rate ($\dot{m}_{ai}$ and $\dot{m}_{ao}$) of air is assumed when applying the conservation of mass principle¹⁵.

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \quad (2)$$

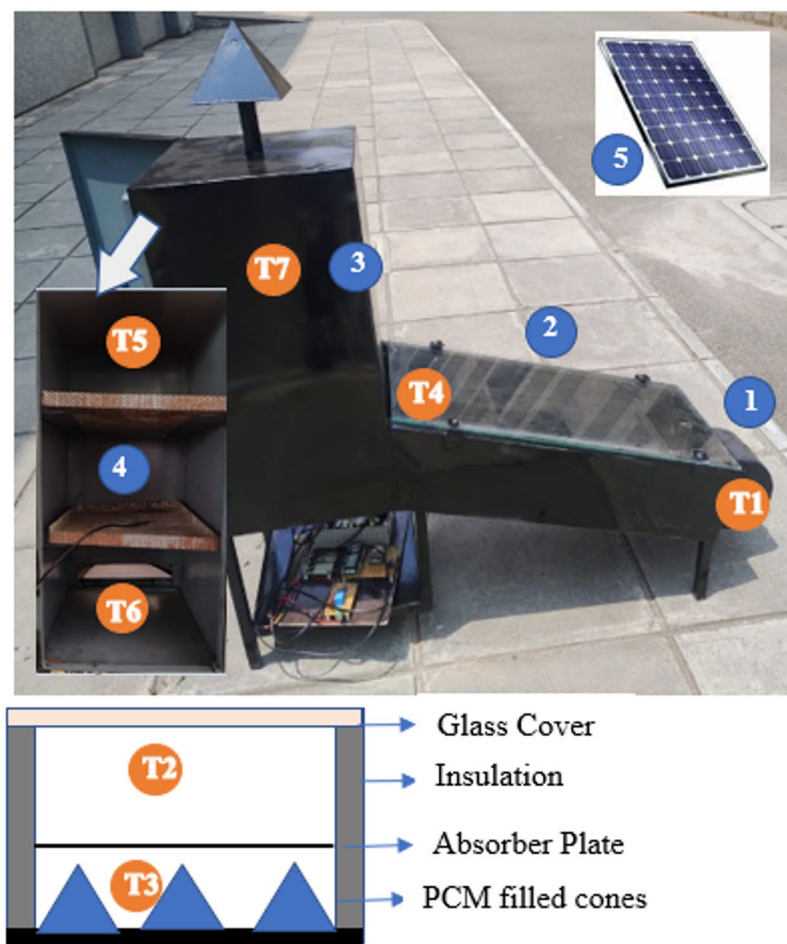


Fig. 2. Experimental setup.

Instruments	Ranges	Accuracy
Reference cell	2000 W/m ²	± 0.5%
Digi-sense data logging vane anemometer	0–25 m/s	± 3%
Ebro EBI 310	– 30 to 85 °C	± 5%
RB-WT1000 anemometer	0–40 m/s	± 4%
Testo 184 G1	– 30 to 100 °C	± 1%
RB-WT10000 hygrometer	– 40 to 80 °C	± 2%

Table 1. Equipment's used for drying according to specifications.

Refs.	TES material ¹⁰	Melting temperature (T _m) °C	Density (ρ) in kg/m ³	Heat of fusion (h _f) in kJ/kg	Specific heat (C _p) in kJ/kgK	Thermal conductivity (k) in W/mK
15	Paraffin wax	56–60	775(Liquid), 850 (Solid)	214.4	3.890, 2.940	0.21
14	Paraffin wax	35–54	786.14(Liquid), 833.60 (Solid)	196.05	2.44, 2.35	–
6	Paraffin wax	56–58	778(Liquid), 861 (Solid)	200–220	–	0.15, 0.4
5	Octacosane	55	803	254	1.9	0.23

Table 2. PCMs and their properties used for agricultural products drying.

According to the theory of steady-state energy conservation.

$$\dot{Q} - \dot{W} = \sum \dot{m}_{ao} \left(h_{ao} + \frac{v_{ao}^2}{2} + z_o g \right) - \sum \dot{m}_{ai} \left(h_{ai} + \frac{v_{ai}^2}{2} + z_i g \right) \quad (3)$$

SAC energy analysis

The SAC-applicable steady-state principles of mass and energy conservation.

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} = \sum \dot{m}_a \quad (4)$$

$$\dot{Q} = \dot{Q}_{u,} = \dot{Q}_{in} - \dot{Q}_{ls} = \dot{m}_a (h_{ao} - h_{ai}) \quad (5)$$

$\dot{Q}_{u,}$ = Useful heat supplied. $\dot{Q}_{in}$ = Input heat. $\dot{Q}_{ls}$ = Lost heat. $\dot{Q}_{in} = I_{sr} A$. I_{sr} = solar intensity (W/m²).
A = Area of SAC (m²).

$$\dot{Q}_u = \dot{m}_a c_{pa} (T_o - T_i) \quad (6)$$

The experimental efficiency of the collector system amounted to 7.1% based on Eq. (7)¹⁷.

$$\eta = \frac{Q_u}{Q_{in}} = \left(\frac{\dot{m}_a c_{pa} (T_o - T_i)}{I_{sr} A} \right) \quad (7)$$

An examination of the drying cabinet's energy usage.

The efficiency (η_{dry}) is computed using

$$\eta_{dry} = \frac{m_w h_{fg}}{E_{in}} \quad (8)$$

m_w = Total eliminated moisture from the food product in g. h_{fg} = the latent heat (kJ/kg).

$$E_{in} = I_{asr} (A + A_{PV}) t_{dry} \quad (9)$$

where t_{dry} is the total drying time in hours, APV is the area of solar PV modules, and I_{asr} is the average radiation of solar (kW/m²)¹⁸. The cabinet's energy utilization ratio (EUR) can be calculated by dividing the energy needed for drying by the energy obtained from SAC.

$$EUR = \frac{m_w h_{fg}}{\dot{m}_a c_{pa} (T_o - T_i)} \quad (10)$$

The specific amount of energy used in (kWh/kg) is determined using,

$$SEC = E_{in} / m_w \quad (11)$$

The extraction of moisture rate (SMER) (kg/kWh) is computed using

$$SMER = \frac{m_w}{E_{in}} \quad (12)$$

Exergy analysis for ISD

In order to do exergy calculations for every part of the solar dryer, steady flow is assumed. The generic expression for constant flow exergy is applied, disregarding changes in dryer pressure, food product exergy loss, and potential and kinetic energies¹⁷.

$$Ex = \dot{m}_a C_{pa} \left[(T - T_o) - T_o \ln \left(\frac{T}{T_o} \right) \right] \quad (13)$$

SAC Exergy analysis.

SAC Exergy input (Ex_{in})

$$Ex_{in} = \left[T - \frac{T_o}{T_s} \right] Q_{in} \quad (14)$$

where, $T_s = 6000$ K.

Q_{in} represents the energy that solar radiation supplies to the absorber plate and is written as

$$Q_{in} = \alpha I_{sr} A \quad (15)$$

The glass window transmissivity 0.808 and the absorptivity (α) of the plate is 0.939.

SAC Exergy output (Ex_{out}) is exhibited by,

$$Ex_{out} = \dot{m}_a C_{pa} \left[(T_{co} - T_{ci}) - T_o \ln \left(\frac{T_{co}}{T_{ci}} \right) \right] \quad (16)$$

The exergy loss of SAC (Ex_{ls}) depicts the process of irreversibility and is assessed using,

$$Ex_{ls} = I = T_o S_{gen} = \left[1 - \frac{T_o}{T_s} \right] Q_{in} - \dot{m}_a C_{pa} \left[(T_{co} - T_{ci}) - T_o \ln \left(\frac{T_{co}}{T_{ci}} \right) \right] \quad (17)$$

The exergy efficiency calculation of SAC resulted in 55.16% using Eq. (18),

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = 1 - \frac{Ex_{ls}}{Ex_{in}} = 1 - \frac{T_o S_{gen}}{\left[T - \frac{T_o}{T_s} \right] Q_{in}} \quad (18)$$

Analysis of energy use in the drying chamber.

The drying chamber's energy input,

$$Ex_{in} = \dot{m}_a C_{pa} \left[(T_{di} - T_0) - T_0 \ln \left(\frac{T_{di}}{T_0} \right) \right] \quad (19)$$

The drying chamber's energy output¹⁸,

$$Ex_{out} = \dot{m}_a C_{pa} \left[(T_{do} - T_0) - T_0 \ln \left(\frac{T_{do}}{T_0} \right) \right] \quad (20)$$

The loss of exergy is calculated using

$$Ex_{ls} = Ex_{in} - Ex_{out} \quad (21)$$

The exergy efficiency is calculated by,

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = 1 - \frac{Ex_{ls}}{Ex_{in}} \quad (22)$$

Sustainability indicators for exergy

Energy sustainability indicators include metrics like the Environmental Impact Factor (EIF), Improvement Potential (IP), Sustainability Index (SI), and Waste Exergy Ratio (WER). For evaluating the sustainability and energy-related aspects of a system or process, several metrics—WER, IP, SI, and EIF—are crucial¹⁹.

$$SI = \frac{1}{1 - \eta_{ex}} \quad (23)$$

$$WER = \frac{Ex_{ls}}{Ex_{in}} \quad (24)$$

$$EIF = WER \frac{1}{\eta_{ex}} \quad (25)$$

$$IP = (1 - \eta_{ex}) Ex_{ls} \quad (26)$$

Regarding the drying cabinet in AMISD with and without PCM, both versions of the dryer are available²⁰. energy sustainability parameters were computed. A comparative exergetic analysis of the drying process was conducted in order to compare and appraise the outcomes of the two configurations.

A calculation of costs

To determine the payback period for drying Turkey Berries, an economic study was done on both the AMISD with and without Phase Change Material²¹. Interest rates and inflation were taken into account in the assessment to take economic considerations into account²². The study considered a range of expenses, including those related to raw materials, labour charges for installation, maintenance, and operations; additionally, costs associated with fresh and dry food products were also considered.

The cost of the dryer for 1 year (C_a) is estimated using,

$$C_a = \left[C_T + \sum_{k=1}^{L_d} (C_{m,k} + C_{op}) \beta^k \right] \left[\frac{\beta - 1}{\beta (\beta^{L_d} - 1)} \right] \quad (27)$$

The total cost of the dryer's raw materials (C_{rm}) plus the labor fee for installation (C_{li}) is its capital cost (C_T).

$$C_T = C_{rm} + C_{li} \quad (28)$$

A year maintenance costs (Cm, k), operating costs (Cop) is equal to 2% of CT. L_d is the ISD lifetime expressed in years.

A constant known as β can be written as

$$\beta = \frac{100 + i_d}{100 + i_f} \quad (29)$$

The discount and inflation rate were taken as 7.7% and 4.5%, respectively²³.

The dried food product annual drying cost per unit (C_{dry}) is estimated from C_a and the dried food products quantity in a year (Q_{dry})

$$C_{dry} = \frac{C_a}{Q_{dry}} \quad (30)$$

$$Q_{dry} = Q_{hr} H_{yr} \quad (31)$$

The quantity of dried food products produced in an hour and the number of hours of sun exposure in a year are represented by the numbers Q_{hr} and H_{yr} , respectively.

The annual savings (S_a) is determined by²⁸,

$$S_a = Q_{dry} P_{dry} - Q_{fr} P_{fr} - Q_{dry} C_{dry} \quad (32)$$

P_{dry} and P_{fr} stand for the price of dried and fresh goods, respectively, in the context presented. Q_{fr} is the amount of fresh food products consumed in a given year.

P_{dry} and P_{fr} , the prices of dried and fresh commodities, respectively, are indicated in this context. Q_{fr} represents the amount of fresh food products consumed annually.

$$N = \frac{\ln \left(1 - \frac{C_r}{S_a} (i_d - i_f) \right)}{\ln \left(\frac{1 + i_f}{1 + i_d} \right)} \quad (33)$$

Environmental analysis

Embodied energy and operational energy (E_{emb}) are the two forms of energy used in any constructive system²⁴. The energy needed for raw material extraction, transportation, and final product assembly is known as embodied energy, and it goes towards building a solar dryer. On the other hand, the energy required for the system to run on a daily basis is known as operational energy. The dryer doesn't require traditional energy sources to operate because it runs on solar energy²⁵.

All sources, including electricity produced from traditional fossil fuels that contribute to environmental impact through CO₂ emissions, are considered when determining the embodied energy (E_{emb}) of each material. This thorough analysis includes computing carbon credits gained throughout calculating the energy payback period (EPBP), evaluating CO₂ emissions, the lifespan of the solar dryer and measuring the embodied energy of the complete arrangement.

The amount of time needed to recoup the Embodied Energy (E_{emb}) used to pay for the building materials of a solar dryer is known as the Energy Payback Period (EPBP). This time frame is computed as the amount of time it will take for the operating energy savings of the solar dryer to offset the embodied energy used in the extraction and use of its building materials.

$$EPBP = \frac{E_{emb} \text{ (kWh)}}{E_{AO} \text{ (kWh/year)}} \quad (34)$$

The dryer's annual energy output (EAO) is calculated using

$$E_{AO} = E_{DO} \times D_{yr} \quad (35)$$

where D_{yr} , which stands for "active sunshine days," is believed to mean 220 days annually. The solar dryer's daily energy production (kWh) is calculated using

$$E_{DO} = \frac{m_w \times h_{fg}}{3.6 \times 10^6} \quad (36)$$

Emission of carbon dioxide (CO₂)

It is observed that a coal-fired power station emits 0.98 kg CO₂ for every kWh produced. Next, using, the annual CO₂ emission is computed.

$$\text{Annual CO}_2 \text{ emission} = \frac{E_{emb} \times 0.98}{L_d} \text{ kg/yr} \quad (37)$$

The internal losses (L_i) and transmission losses (L_t) due to domestic appliances, also occur in the real process.

$$\text{Yearly CO}_2\text{emission} = \frac{E_{emb}}{L_d} \times \frac{1}{1 - L_t} \times \frac{1}{1 - L_t} \times 0.98 \text{ kg/yr} \quad (38)$$

Carbon dioxide (CO₂) mitigation

The ISD (kg) mitigation of CO₂ is determined using,

$$\text{CO}_2\text{mitigation} = (E_{AO} \times L_d - E_{emb}) \times 20.042 \quad (39)$$

where L_d is the ISD's lifetime in 5 to 30 years.

Carbon credit earned

By determining the amount of carbon mitigation achieved and then applying the conversion factor of one carbon credit per ton mitigation of carbon, the total amount of carbon credits obtained year may be ascertained²⁶. To find the total amount of carbon credits earned annually, use the following formula:

$$\text{Carbon credit earned} = \text{CO}_2\text{mitigation} \times \text{price per tonne}.$$

Results and discussion

The AMISD was used for an experimental test that lasted three days²⁷, from October 20 to 23, without Phase Change Material (PCM), and from October 24 to 26, using PCM. The drying time was represented by the X-axis, and it varied from 8:00 AM to 6:00 PM. Between 270 and 1020 W/m² were the ranges of solar irradiance (I_{sr}) for the corresponding times. Interestingly, throughout the course of six consecutive days in identical weather, the trials showed that the average I_{sr} stayed constant for both dryers. In order to analysis the initial moisture content (MC) of turkey berries, samples were heated to 105 °C for 24 h in a hot air oven. Using a weighing balance, weights for the starting and final masses were noted. Turkey berry initial MC average was identified to be 4.12 kg/kg of dry basis (db).

ISD's energy analysis

The Fig. 3 demonstrates the feasible heat supplied to a solar panel was created by monitoring the sun's intensity between the hours of 8 AM and 6 PM²⁹. The intensity increased from 200.8 W to 1180 W between 12 and 1 pm in the absence of phase change material (PCM). On the other hand, 1200 W was reached in the same period by PCM-enhanced experiments. The solar intensity decreased as the sun set, reaching 192 W by 6:00 PM in the evening. The graphical display highlights the beneficial effect of PCM, which results in increased solar radiation absorption and extends the useful life of solar energy over the course of the experiment.

The Fig. 4. represents the comparison of efficiency of Collector in cases with and without Phase Change Material (PCM)³⁰. The collection efficiency peaks at 89.6% about 1 PM, having started at 11% initially at 8.00 AM. The efficiency progressively decreases with the sun's westward movement, reaching 35% by 6 PM in the absence of PCM. On the other hand, the collector efficiency is noticeably higher when PCM is used. It obtains 86.2% at 1 PM, which is better than the non-PCM case. By 6 P.M., the efficiency is still relatively high at 4.017%. This demonstrates how adding PCM can improve and maintain the efficiency of solar collectors throughout the day.

Both studies began at 8:00 AM To analyze the efficiency of solar dryers are both with and without phase-change material (PCM). Efficiency started at 0% and increased to 11% by 11:00 AM in the absence of PCM, but it reached 15.2% in the same time frame with the presence of PCM. Efficiency increased until stabilizing between 11:00 AM and 12:00 PM. Efficiency reached 14.8% with PCM by noon. PCM integration increased efficiency overall by 2.63% is shown in Fig. 5. This illustrates how the solar dryer's PCM usage leads to a steady increase in drying efficiency and highlights the material's potential for improving solar drying procedures.

The study shows that shifting from a collector efficiency of 14.8–15.23% in addition to increasing SAC exergy efficiency from 6.84 to 7.1% is due to PCM functioning as a latent heat storage medium. The PCM function as an energy storage element to sustain an even temperature difference between collector surfaces and operation fluid while reducing heat leakage. Solar energy utilization becomes more efficient through thermal buffering which eliminates swift energy load variations and boosts conversion efficiency. The system requires less energy to dry each kilogram of moisture because the thermal energy remains stable throughout the drying operation.

The Energy Utilization Ratio (EUR) in solar dryer¹ with and without Phase Change Material during the drying phase is compared and which was shown in Fig. 6. When PCM was included with the system the Energy Utilization Ratio (EUR) reached 29.31% whereas it operated at 28% without PCM. The ratio displays thermodynamic importance even though the change in numbers is marginal. The presented value exceeds those found in other PCM-based solar drying systems. A study achieved an Energy Utilization Ratio of 26.5% within a fin-enhanced PCM-integrated indirect dryer and research measured an ratio of 27.4% through their use of paraffin-based thermal storage³⁵. Galileo-era PCM module design along with solar power-enabled airflow methods allowed researchers to achieve elevated EUR values because it improved both temperature constancy and air movement throughout the drying process.

SAC's exergy analysis

The Solar Air Collector's (SAC) energy input, output, and loss were all measured³¹. At noon, SAC's energy input peaked in relation to solar radiation and sun temperature. Variations were seen in the results, which ranged from 410.4 to 1268 W (with PCM) to 410.4–1384 W (without PCM). This realization emphasizes how the sun's radiation dynamically affects SAC's energy efficiency is shown in Fig. 7.

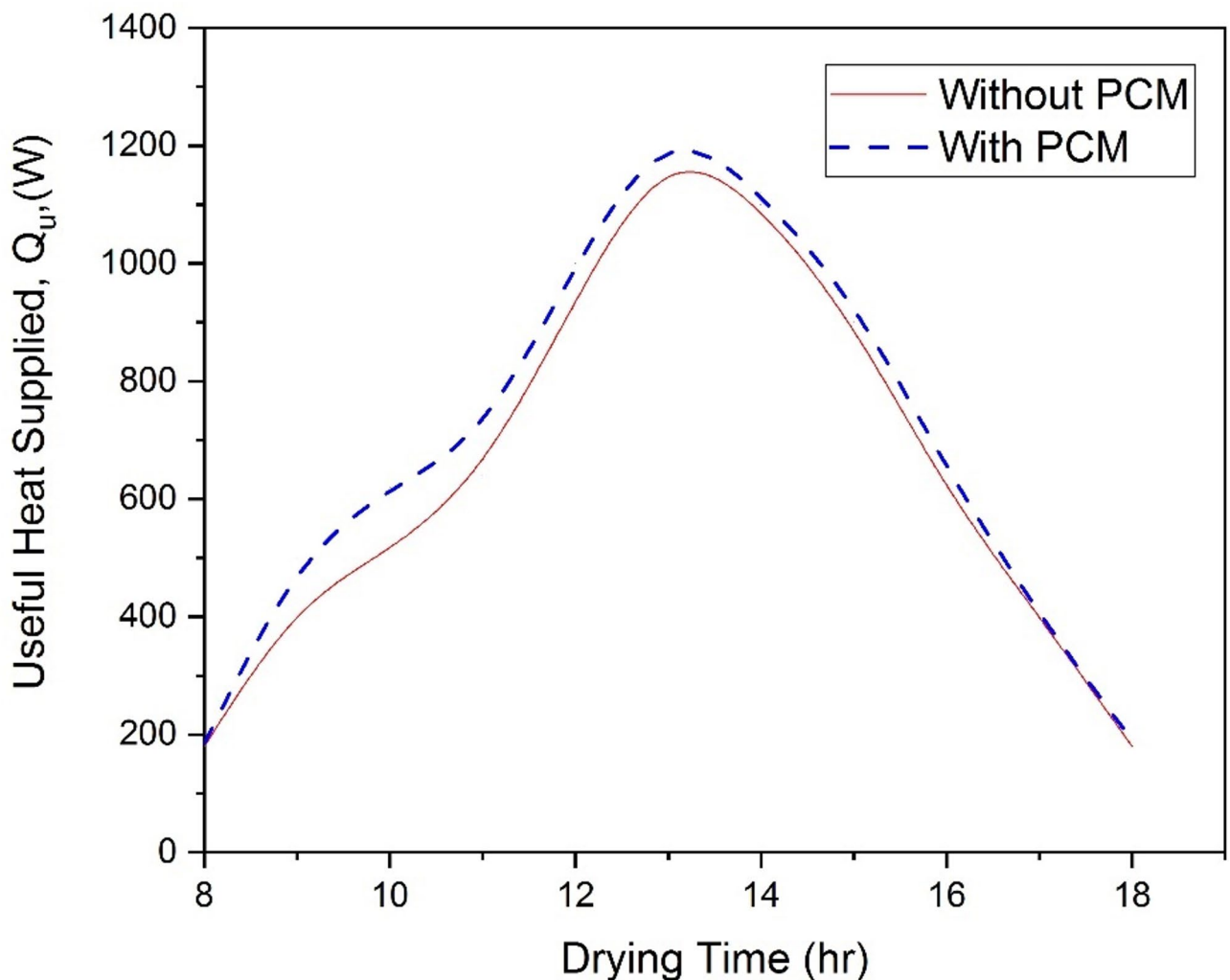


Fig. 3. Solar Intensity vs. Time occurred under clear skies between 8:00 AM and 6:00 PM during drying trials. The irradiance value started at 420 W/m² during 8:00 AM before reaching its maximum of 1180 W/m² at noon while diminishing afterward.

The SAC's energy output ranged from 1.04 to 61.3 W, 1.02 to 59.2 W, respectively, with and without PCM. Figure 8 illustrates the energy loss with PCM (from 400 to 1394 W) compared to without PCM (from 400 to 1382 W) due to the collector's extremely high temperature. The collector's energy efficiency ($\eta_{ex, coll}$) in relation to drying time in both ISDs. Since the energy input of both dryers is nearly equal, $\eta_{ex, coll}$ is directly influenced by the SAC's energy output, which is depends on the temperature of the output. The exergy efficiency of solar panel with PCM is obtained as 6.84% and with PCM is 7.1%.

Figure 9 discusses the collector's exergy efficiency (η_{SAC}) in relation to drying time in both ISDs. Given that the energy input of both dryers is equal, the exergy output of SAC directly affects, η_{SAC} subject to the SAC outlet's temperature. With TES, SAC's energy efficiency is 7.1% as opposed to 6.84% without it, a 0.95% gain. In the ISD the average collector exergy efficiency (η_{SAC}) is found to be 2.28%⁴.

Drying chamber exergy analysis

The Fig. 10 shows the exergy loss of DC motor and drying time, The drying cabinet's exergy input (Ex_{in}) and the drying chamber's outlet and inlet temperatures, equal the SAC's exergy output. Td_{co} and the mass flow rate of air are factors that affect the Ex_{out} , $Ex_{out, dc}$ and $Ex_{s, dc}$ have greater values in the PCM experiment setup than in the setting without PCM because the drying chamber's temperature affects both setups' mass flow rates of air. It's observe that Exergy output is observed to be 55.16% with PCM and 55.16 without PCM. The Fig. 11 shows the exergy out of DC motor increases by 0.95%, 81.6% without PCM and exergy efficiency increases to maximum of 81.2% with PCM³². The Fig. 12 shows the comparison of dying time vs. exergy efficiency of DC motor, the efficiency of DC motor is increased from 80 to 81.4%.

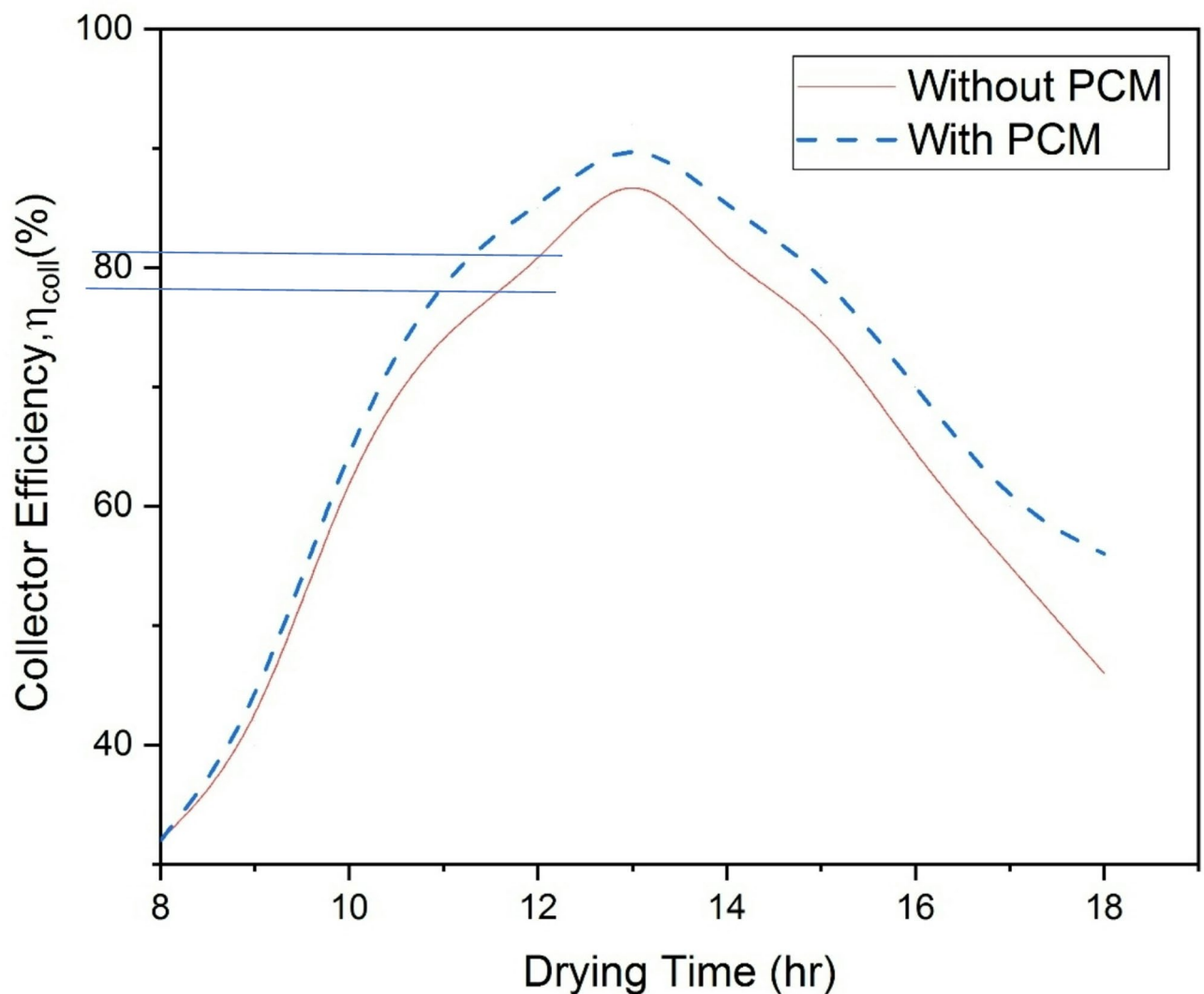


Fig. 4. Performance will be measured under the two different configurations: Setup 1 without PCM integration and Setup 2 with PCM integration. The PCM-based system reached its highest performance level of 15.23% efficiency at 11:00 AM when solar irradiance reached 1150–1180 W/m².

Indices of energy sustainability

A drying cabinet's sustainability index (SI), waste energy ratio (WER), improvement potential (IP) and environmental impact factor (EIF), are assessed. For both settings, the SI and WER with drying times are mentioned in the Fig. 13. While WER dropped with drying time over the course of a day, SI increased. With PCM setup, the SI values were greater, and in the absence of PCM, the WER values were higher. The SI value starts from 0.92–9.21% without PCM and 0.921–9.3% with PCM, The WER initially begins from 18% to 3.41% without PCM, whereas in the PCM case the WER efficiency starts from 18 to 3.1%³³.

The comparison of Improvement Potential (IP) in Indirect Solar Dryers (ISD) with and without Thermal Energy Storage is shown in the Fig. 14. While ISD without TES stabilizes at 5.12 W, ISD with TES first exhibits a declining trend in IP from 22.45 W to a stable state at 6.23 W. For all scenarios, the Environmental Impact Factor (EIF) graph shows a steady rise. In the absence of Phase Change Material (PCM), EIF increases to 13.12% and stays stable until 2:00 PM, at which point it starts to decline. When PCM is used, EIF consistently decreases from 12:00 PM to 1:00 PM, then slightly increases until 2:00 PM and then continues to decline until 6:00 PM.

Figure 15 displays the error map that illustrates the variations in the moisture ratio between the expected and observed values during the length of the drying time during model validation. Between 9:00 and 18:00, there are essentially no errors. Error values, however, vary from 0.0439 to 0.0710 in the early stages of drying and in the hours after sunset. The moisture ratio is calculated by dividing the difference between the equilibrium and final moisture contents by the difference between the initial and equilibrium moisture contents.

Drying kinetics of Turkey berries

The experimental period registered ambient temperatures starting at 29 °C until reaching 37 °C at 1:00 PM together with a relative humidity decrease from 65 to 42% throughout this time. The natural environmental

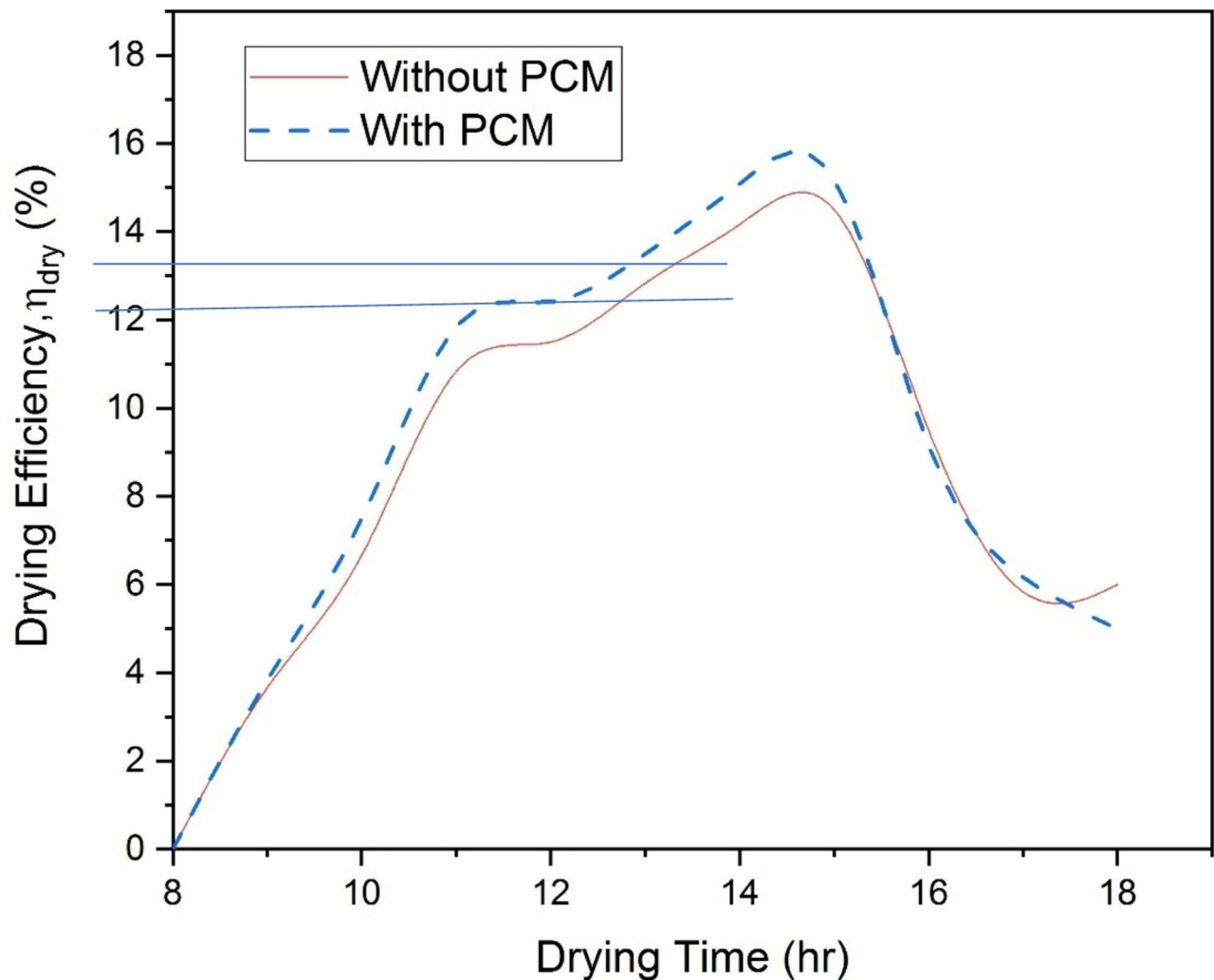


Fig. 5. Drying time vs. drying efficiency. The most efficient drying time occurred during 11:00 AM to 1:00 PM in Setup 2 (PCM). The drying procedure occurred under environmental conditions with an average temperature of 32.5 °C alongside relative humidity that remained between 45 and 55%.

variations strongly affected how fast the berries dried. The drying speed increased when temperatures were high and humidity levels decreased because the berries lost weight quickly during this specific period. The drying process became slower when humidity values were elevated after sunset and during early morning hours because air vapor pressure difference between the dried berries and surrounding air decreased. The obtained observations validate the predicted moisture ratios while highlighting how environmental conditions affect solar drying operations.

Cost analysis

The cost assessment of the ISD is essential to evaluate its feasibility. This study focuses on analyzing the economic aspects of environmental for experimental setup with TES, employing payback period methodologies and life cycle saving. The investigation aims to determine the viability of the ISD based on its economic performance in this specific environmental context. The cost of fresh Turkey Berries is ₹50 per kg, and dried turkey berries is ₹250 per kg. A 10% interest rate, a 20-year ISD lifespan, and a 5% inflation rate are used to examine Setup 1, which has a cheaper capital cost and no thermal energy storage unit. This makes Setup 1 a more financially competitive choice than Setup 2. The economic analysis, with capital cost estimating errors within an acceptable 5% range, is presented in Table 3 for three configurations of Industrial Solar Dryers (ISD) utilized for drying turkey berries. Annual savings and cumulative present values are despite setup 1 having a longer drying duration and fewer testing days. Interestingly, setup 2's capital costs can be recouped in less than a year, as the payback period calculation shows. These findings, which are shorter than the ISD's predicted lifespan and show how effective and economically viable the ISD setups for drying turkey berries are when compared to other drying trials. ISD setup 2 is clearly a better investment for drying turkey berry slices than setup 1, as demonstrated by the economic analysis carried out in this study. In terms of economic feasibility for the particular application of

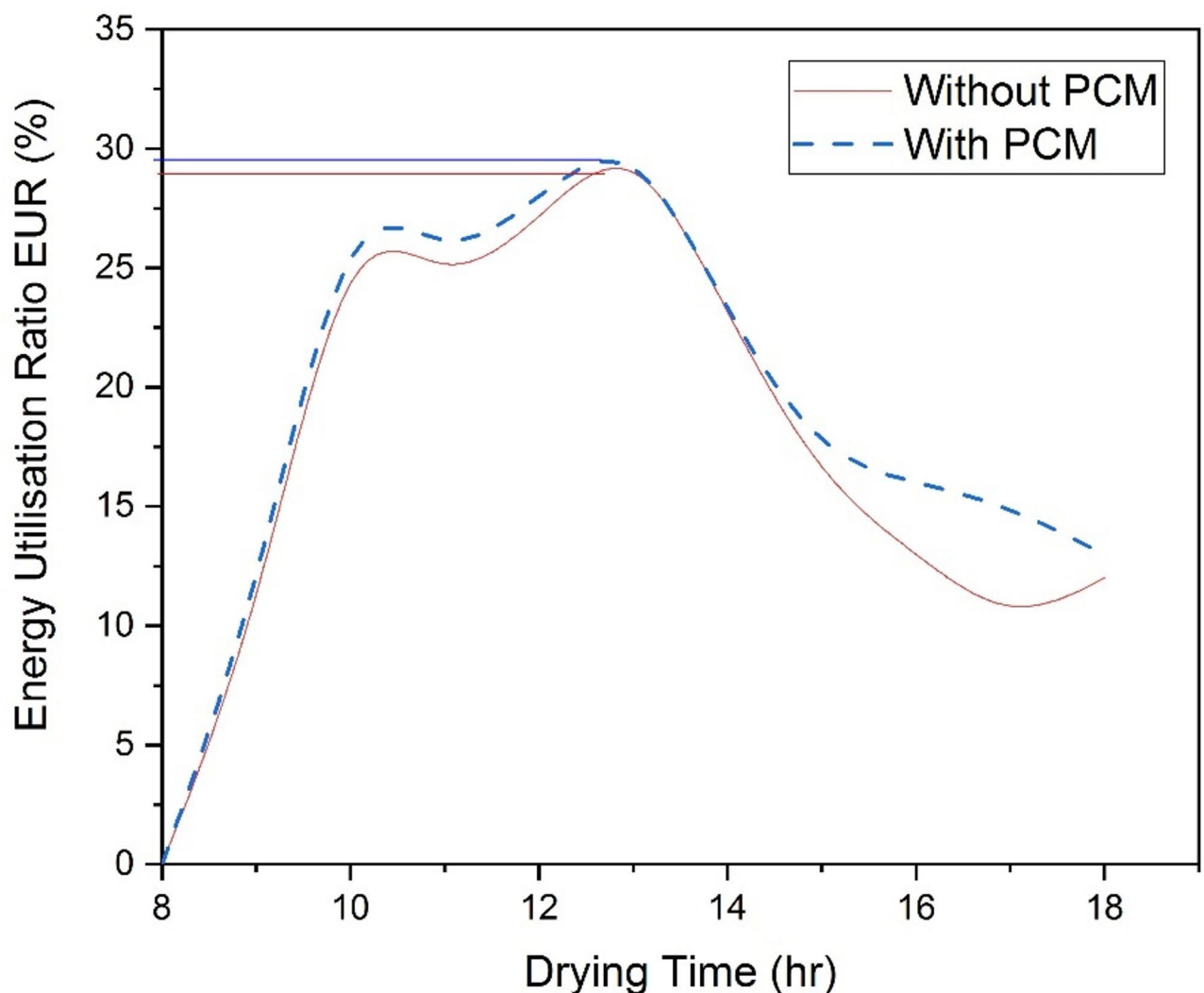


Fig. 6. The Energy Utilization Ratio (EUR) relationships during Setup 1 and Setup 2 with the operating time. During a period when solar irradiance reached higher than 1100 W/m^2 the PCM-enhanced dryer reached its peak Energy Utilization Ratio at 29.31% at exactly 12:00 PM.

drying turkey berries, setup 2 is a more acceptable option due to its more favourable financial future, as indicated by the results³⁴.

1 kg of moisture is evaporated in 10.5 h by the ISD, which is fully operating from 7:00 a.m. to 06:00 p.m. In addition, depending on the weather, this operational duration may vary; The ISD evaporation ability is 1.6 kg per day on average. The ISD's EPT has been observed to be 1.419 yrs. This is a far shorter period of time than the 35-year life span of an ISD that is being provided. For the life lengths of 5, 10, 15, 20, 25, 30 and 35 years, the annual CO_2 mitigations, emissions have been computed using Eqs. (37–39). The findings are shown in Fig. 16¹⁰. The predicted thirty-five-year operational time used in CO_2 emission reduction analysis reflects reported solar dryer and thermal system service periods with scheduled maintenance included. Real-world aging of solar collectors along with PV modules and PCM materials leads to performance diminishing that affects system operational efficiency during long-term operation. Research data demonstrates that collector systems decline by 0.5–1% annually but PCM thermal material thermal storage capacity diminishes by 10–15% after 10–15 years of repeated thermal cycling. The estimates took into account a conservative degradation rate of 0.75% per year by making adjusted calculations. The redesigned version maintains vast long-term emission cuts yet provides reductions that fall between 18 and 22% below linear estimates. System maintenance throughout its operational lifetime together with regular PCM replacement becomes essential because it ensures long-term environmental benefits.

The material proportions in the AMISD with and without TES framework change when it comes to energy observation is shown in Fig. 17. A frame weighing 35.14 kg is the most substantial component, followed by a glass cover (0.9 kg), absorber plate (1.8 kg), insulation (4.2 kg), trays (2 kg), insulation (12.4 kg), diverging duct (6.2 kg), DC fan (0.15 kg), PV module (4.2 kg), and PCM (1 kg).

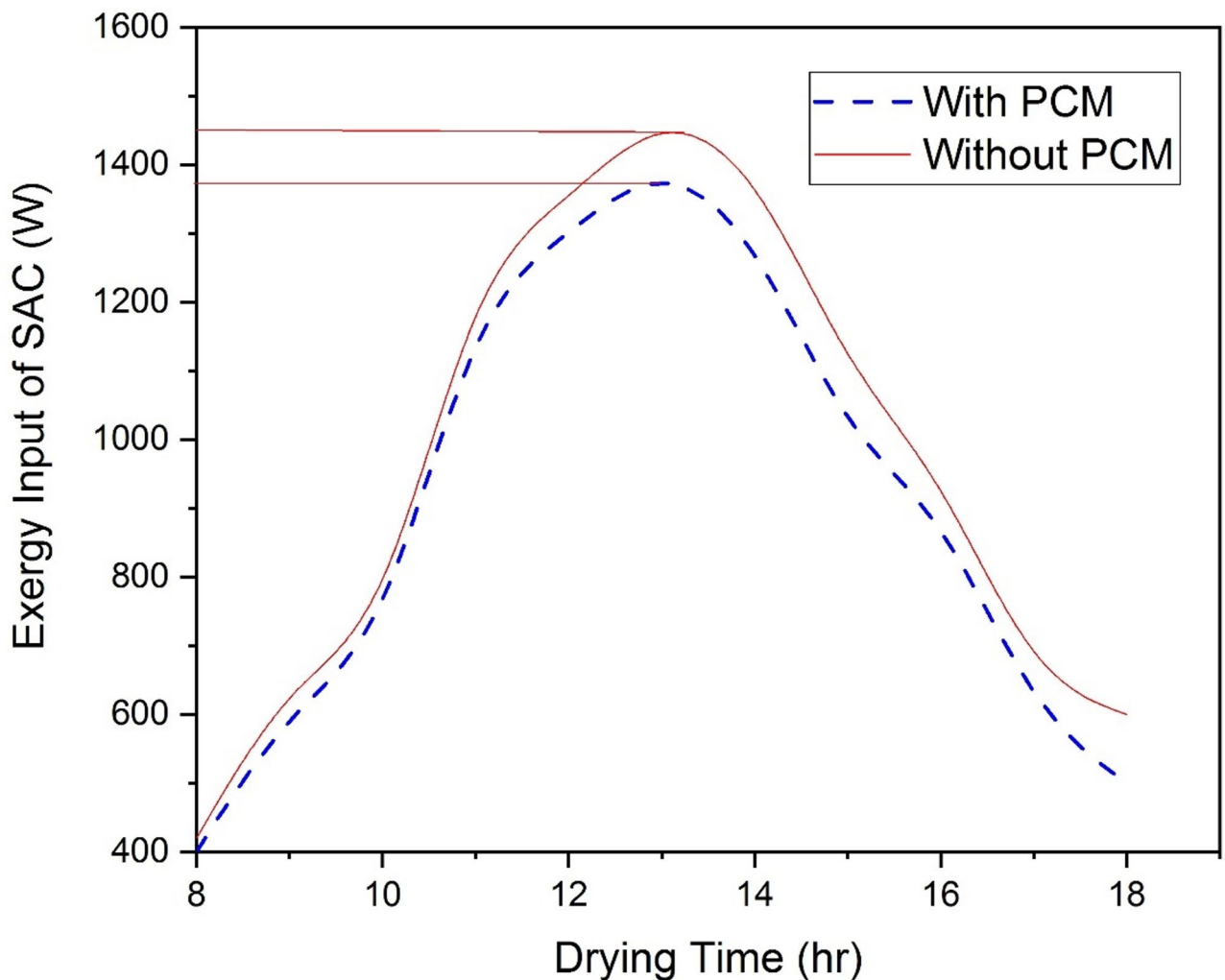


Fig. 7. Drying time vs. exergy input of SAC Under the conditions of 1:00 PM and 1160 W/m^2 irradiance Setup 2 (with PCM) achieved its highest exergy efficiency value of 55.16%. The operating temperatures within the ambient environment fell between $30\text{--}37^\circ\text{C}$.

Conclusions

Solar thermal energy harvesting along with thermal storage duration becomes stable through the implementation of Phase Change Materials (PCM) in solar thermal systems. The Active Mode Indirect Solar Dryer (AMISD) underwent six days of performance tests while sustaining continuous irradiance during which PCM implementation received analysis and PCM was absent in another set of tests. The Turkey Berries began with 4.12 kg/kg (dry basis) moisture content. When PCM was incorporated into the solar collector it achieved its maximum efficiency of 86.2% at 1:00 PM which sustained until afternoon. The efficiency rate of the solar dryer reached 15.2% when PCM was integrated while the baseline efficiency stood at 14.8% in its original state without PCM. The installation of PCM improved water extraction capabilities because it resulted in a 1.31% rise in Energy Utilization Ratio (EUR) from 28.0 to 29.31%. The implementation of PCM allowed 1268 W peak solar input operations and energy-saving heat retention capabilities. Exergy efficiency of the collector reached 0.95% increase to complement the 7.1% rise in energy output. The entry of PCM in the system enabled the DC motor to reach 81.4% efficiency. The implementation of PCM technology in solar dryers produced multiple advances across throughout the sustainability performance indicators including SI, WER, IP and EIF. During economic recovery the PCM-included payback system (Setup 2) needed 0.92 years and its payment period stayed between 0.74 and 1.29 years despite differing electricity prices and capital expenditure amounts. Of the predicted 35-year system operation the EPT reached 1.42 years.

Solar collector efficiency will decrease by 5 to 15% when PCM technology is integrated into solar drying systems because of issues with PCM material degradation along with surface wear and dust accumulation. Development of PCM storage systems demands further research regarding extended performance assessment alongside PCM decay prediction assessments across different climatic environments and component maintenance practices. The system needs to undergo testing at low solar irradiances below 400 W/m^2 during winter months and monsoons to prove yearly performance and gain worldwide adoption for eco-friendly agricultural practices.

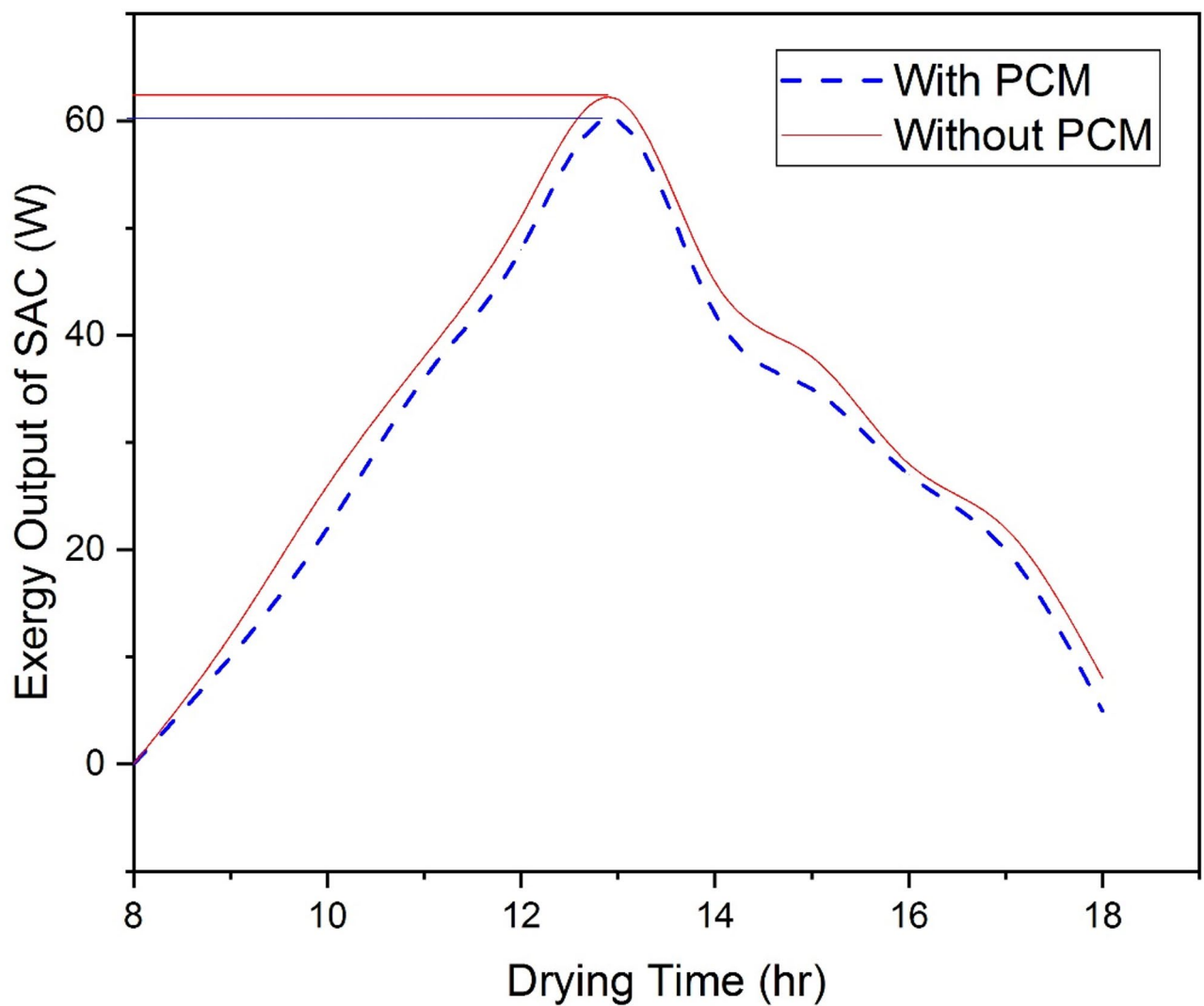


Fig. 8. Drying time vs. exergy output of SAC. When PCM was added to the system the resulting exergy efficiency rose from 80.0–81.4%. Tests took place under daylight conditions reaching more than 1100 W/m².

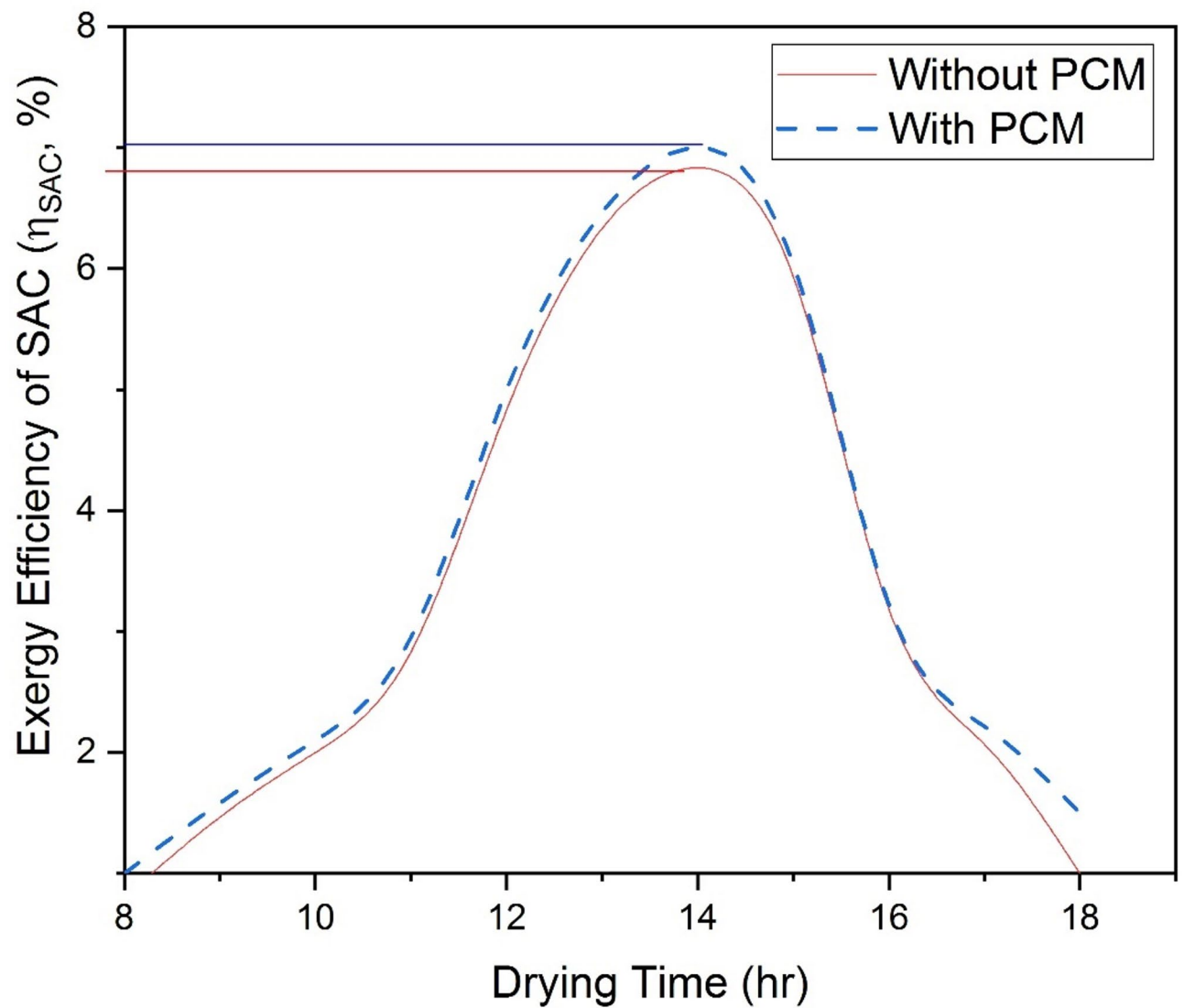


Fig. 9. Drying time vs. exergy efficiency of SAC for Setup 1 (without PCM) and Setup 2 (with PCM). The solar input reached its highest point at 1180 W/m² during noon while it started at 420 W/m² at 8:00 AM. The incorporation of PCM systems into Setup 2 improved peak energy loss management while keeping the system more stable.

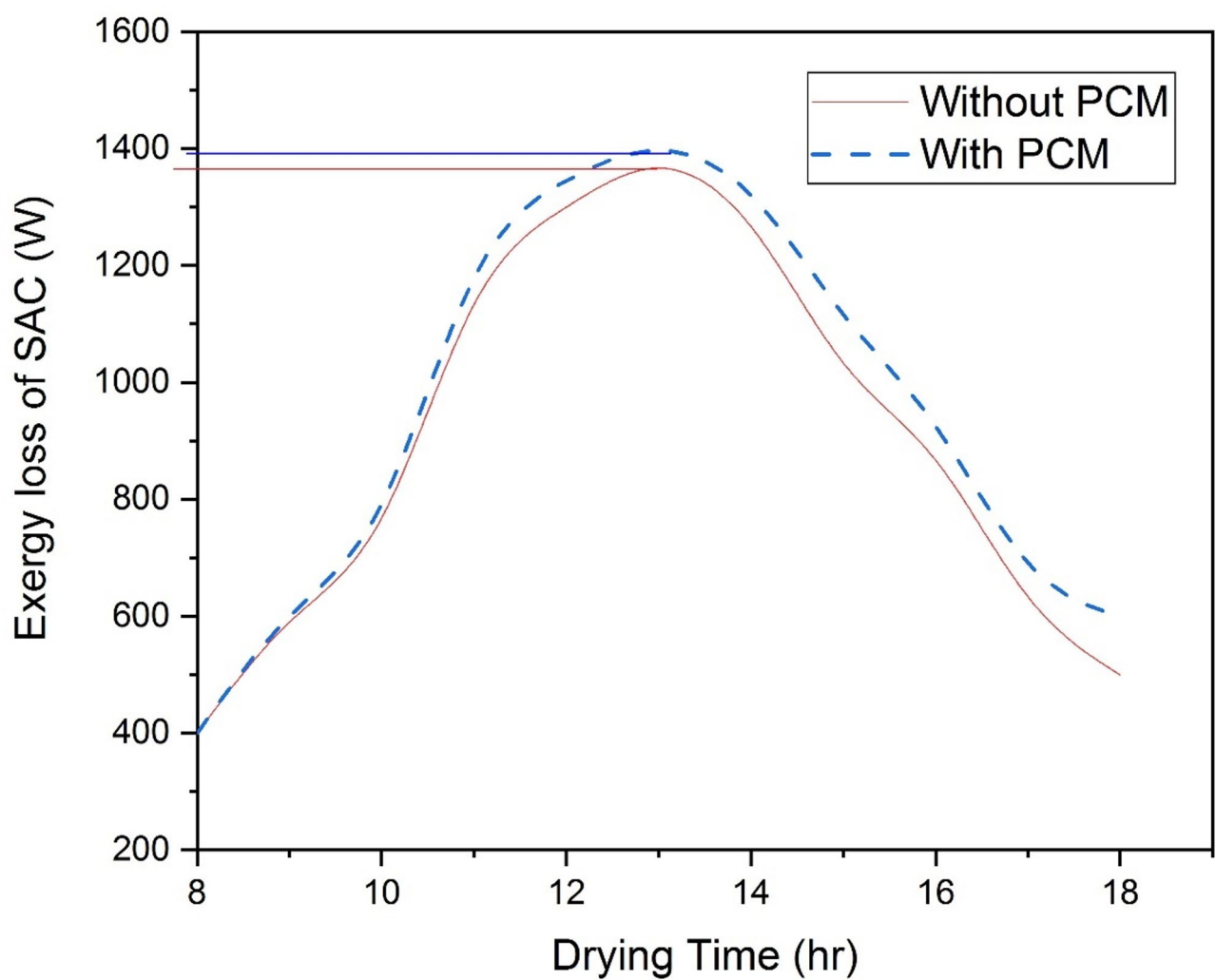


Fig. 10. Drying time vs. exergy loss of SAC.

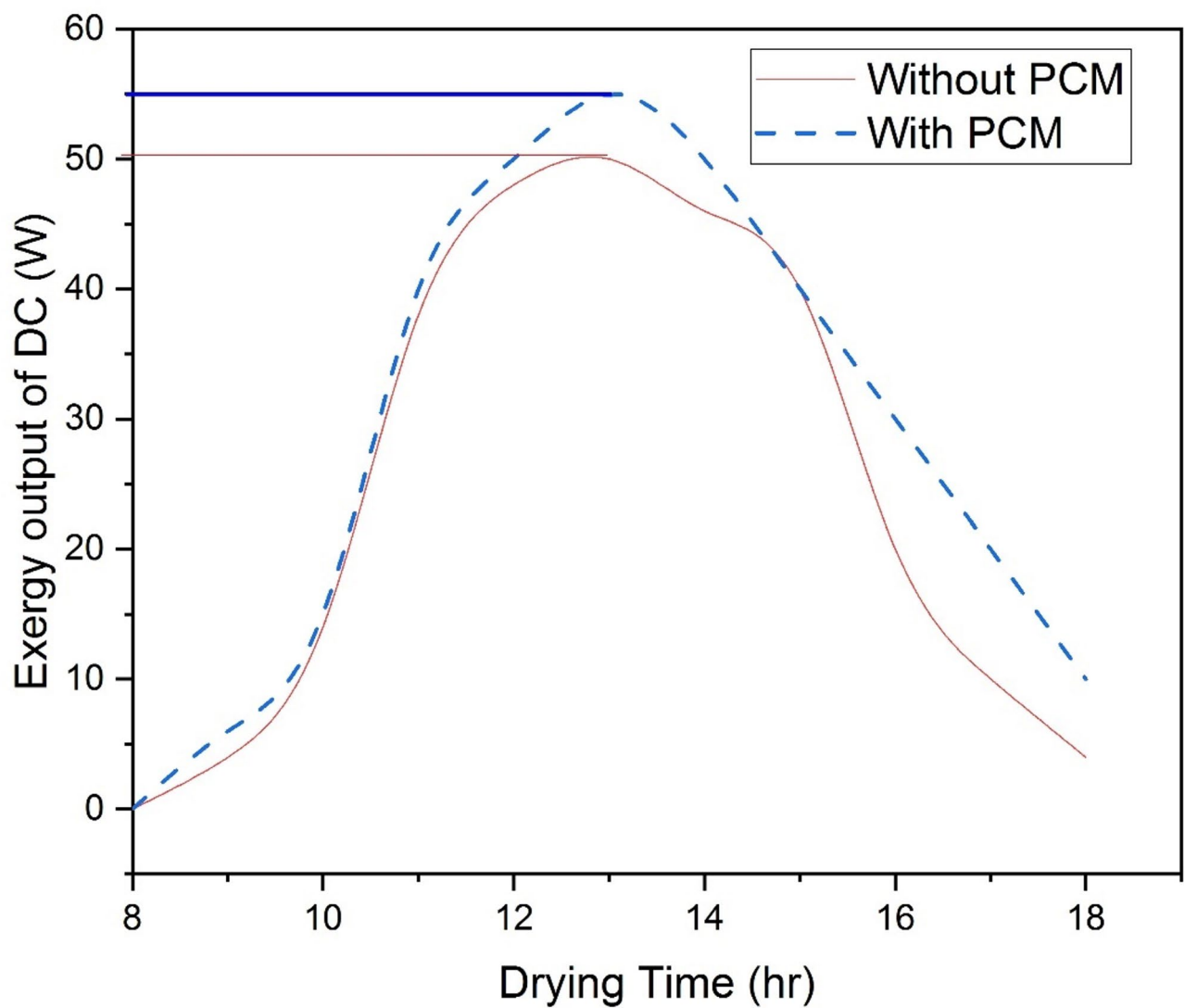


Fig. 11. Drying time vs. exergy output of DC.

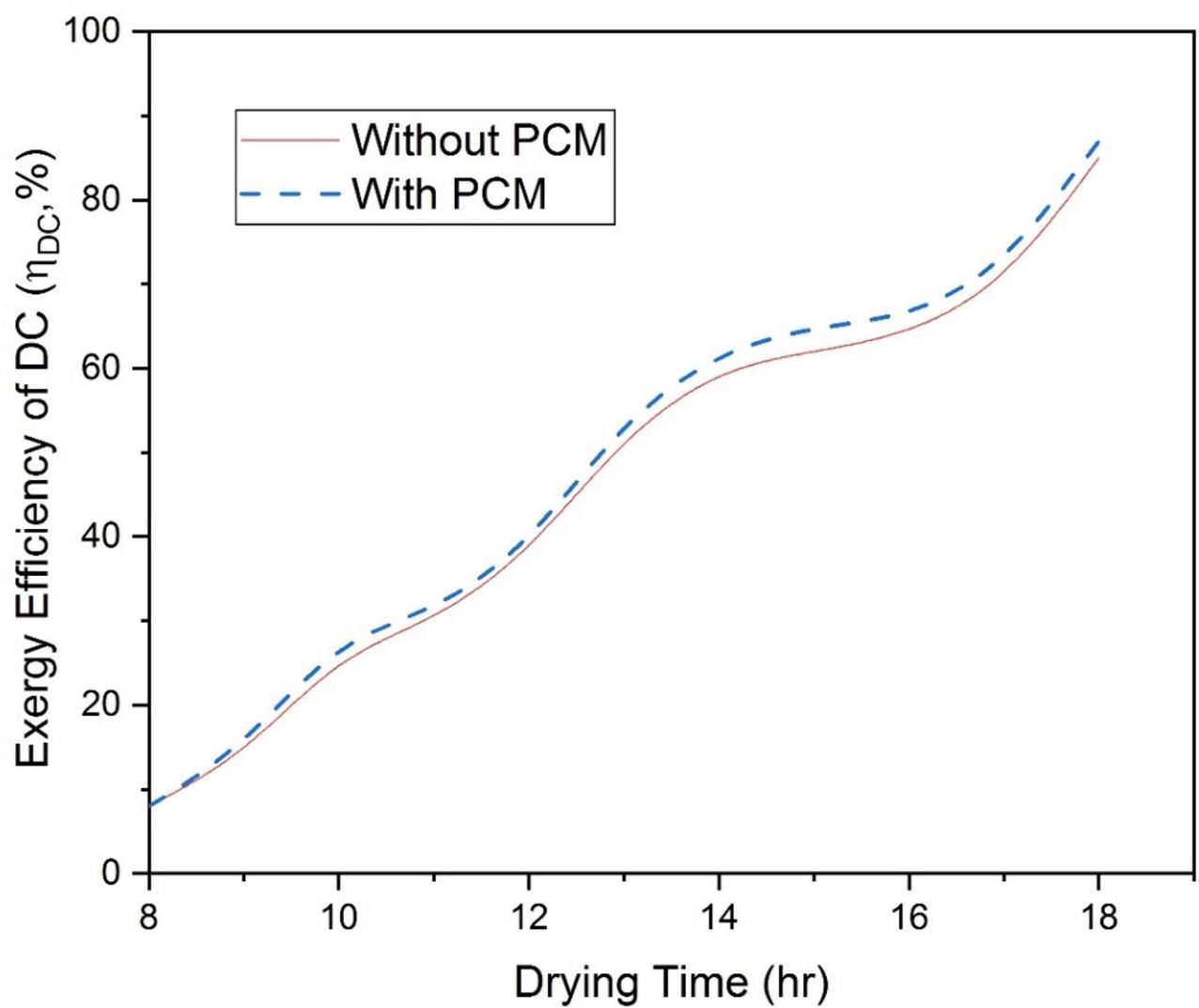


Fig. 12. Drying time vs. exergy efficiency of DC.

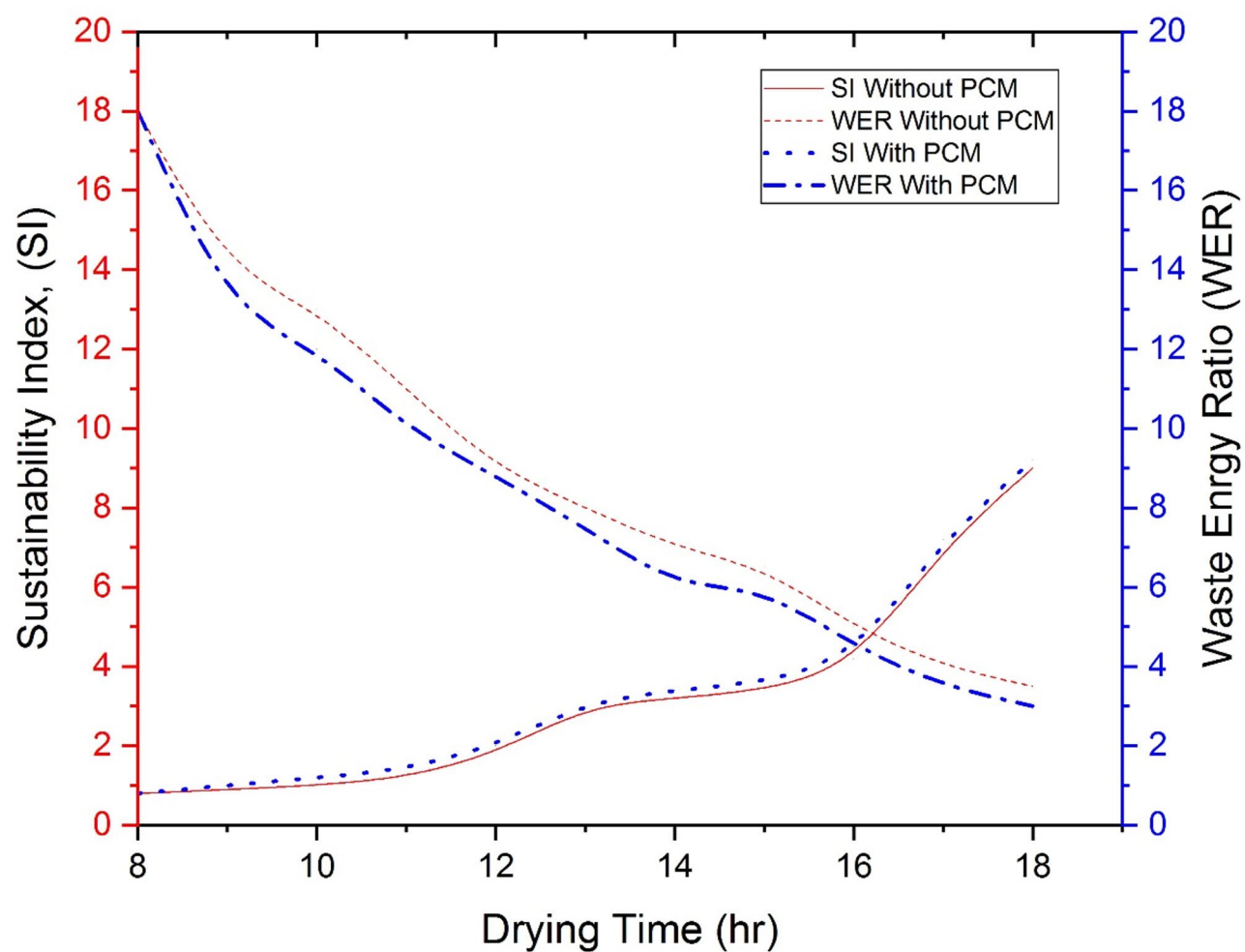


Fig. 13. Drying time vs. sustainability index.

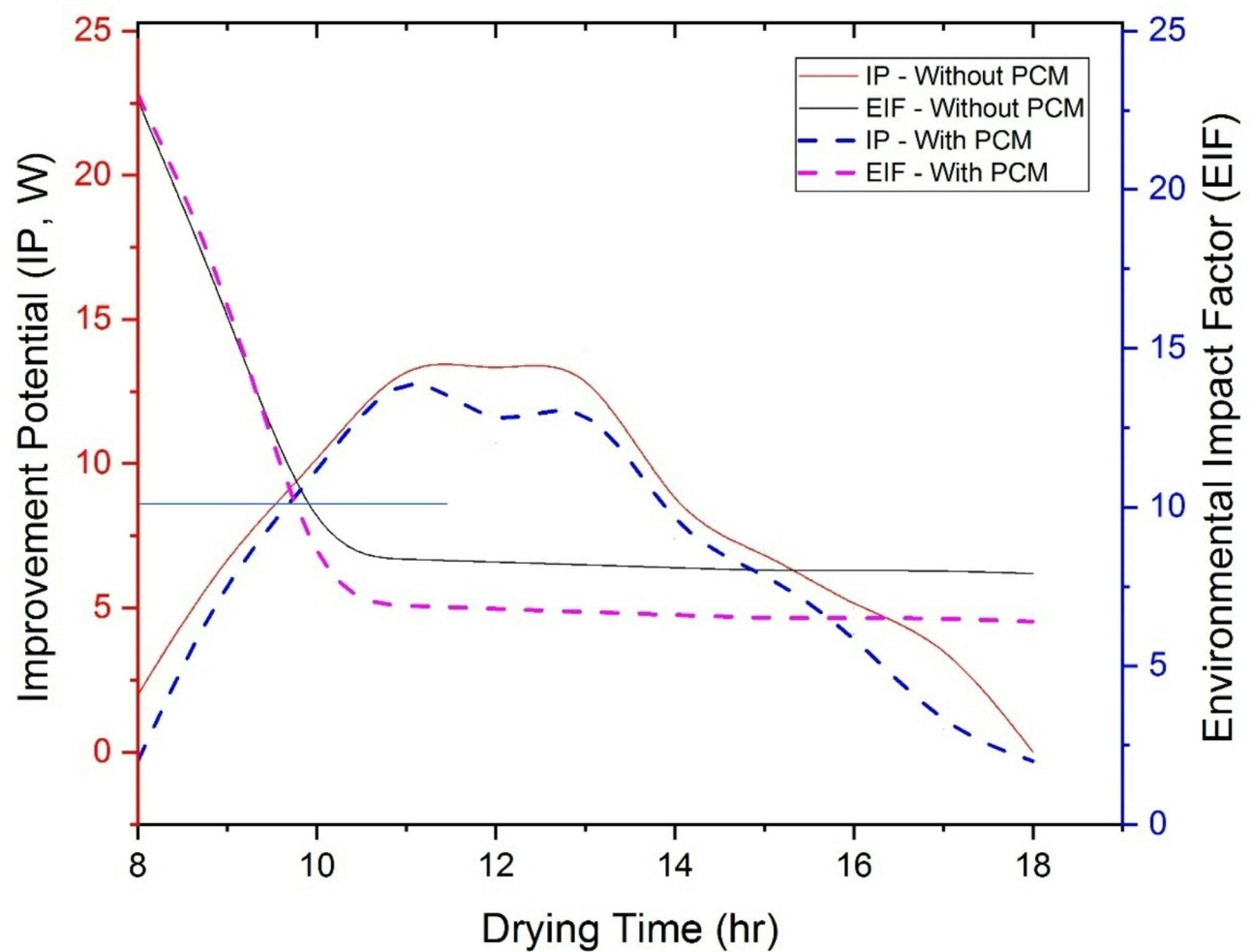


Fig. 14. Drying time vs. improvement potential and environmental impact factor.

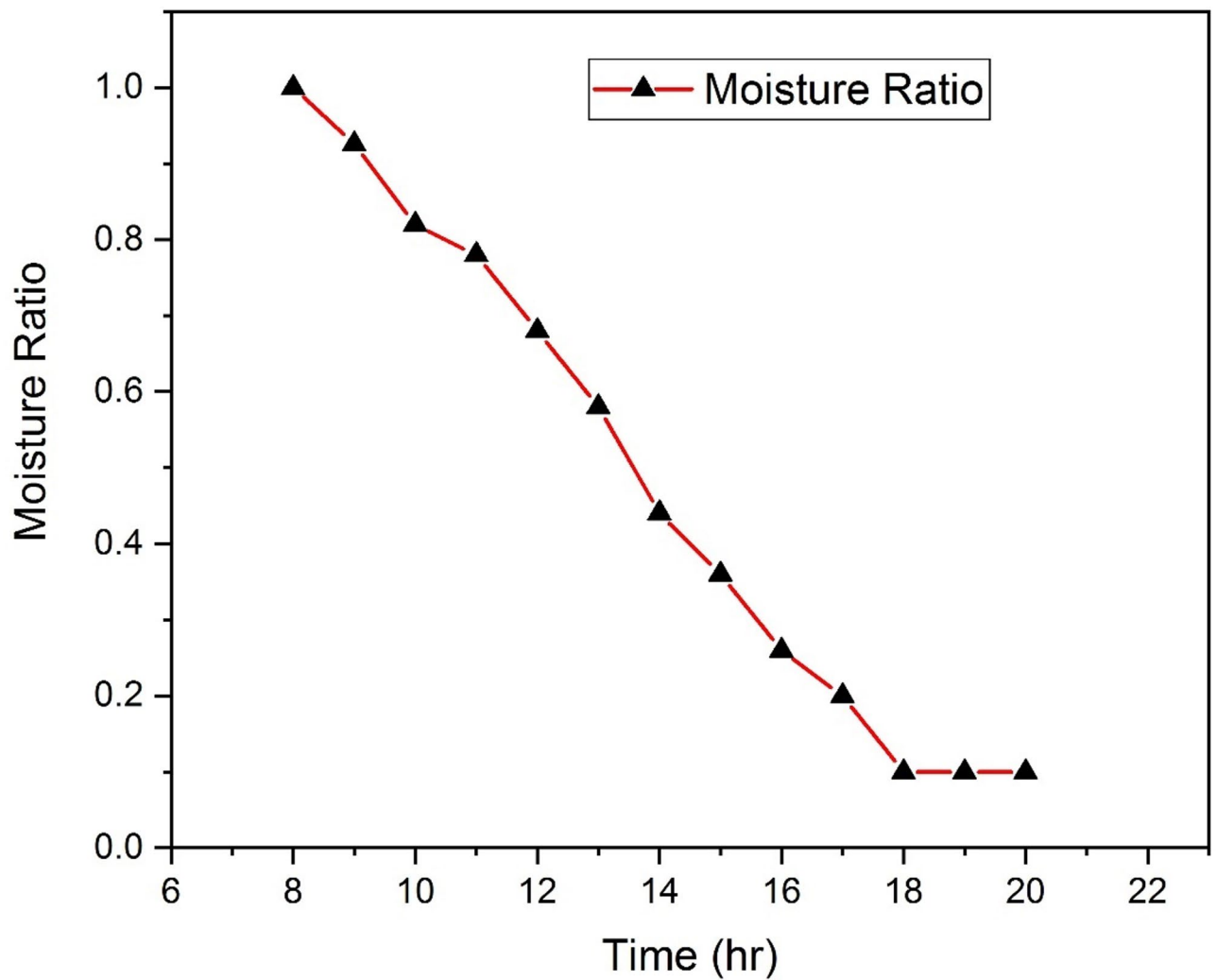


Fig. 15. Drying time vs. moisture ratio.

S. No	Parameters	Without PCMES unit, ISD ISA	With PCMES unit, ISD ISA
1	Capital cost setup (₹)	10,200	11,020
2	Annual cost of the ISD (₹)	1280	1350
3	Number of test-taking days in a year	172	172
4	Salvage value (₹)	1050	1120
5	The ISD's annual salvage value (₹)	17.346	18.01
6	Saving for Turkey berries per kg (₹/kg)	10.02	20.04
7	The ISD's price per kilogram of turkey berries. (₹/kg)	240.415	230.15
8	Payback period (years)	1.6	0.92
9	Savings per day(₹/day)	60	120

Table 3. The economic analysis of ISD.

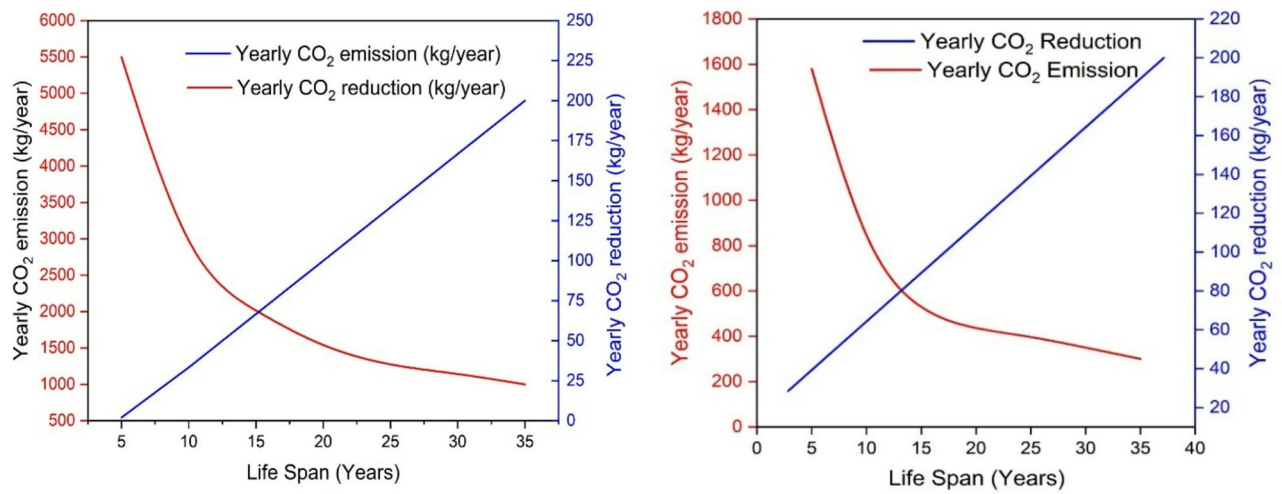


Fig. 16. Life span Vs yearly CO₂ emission.

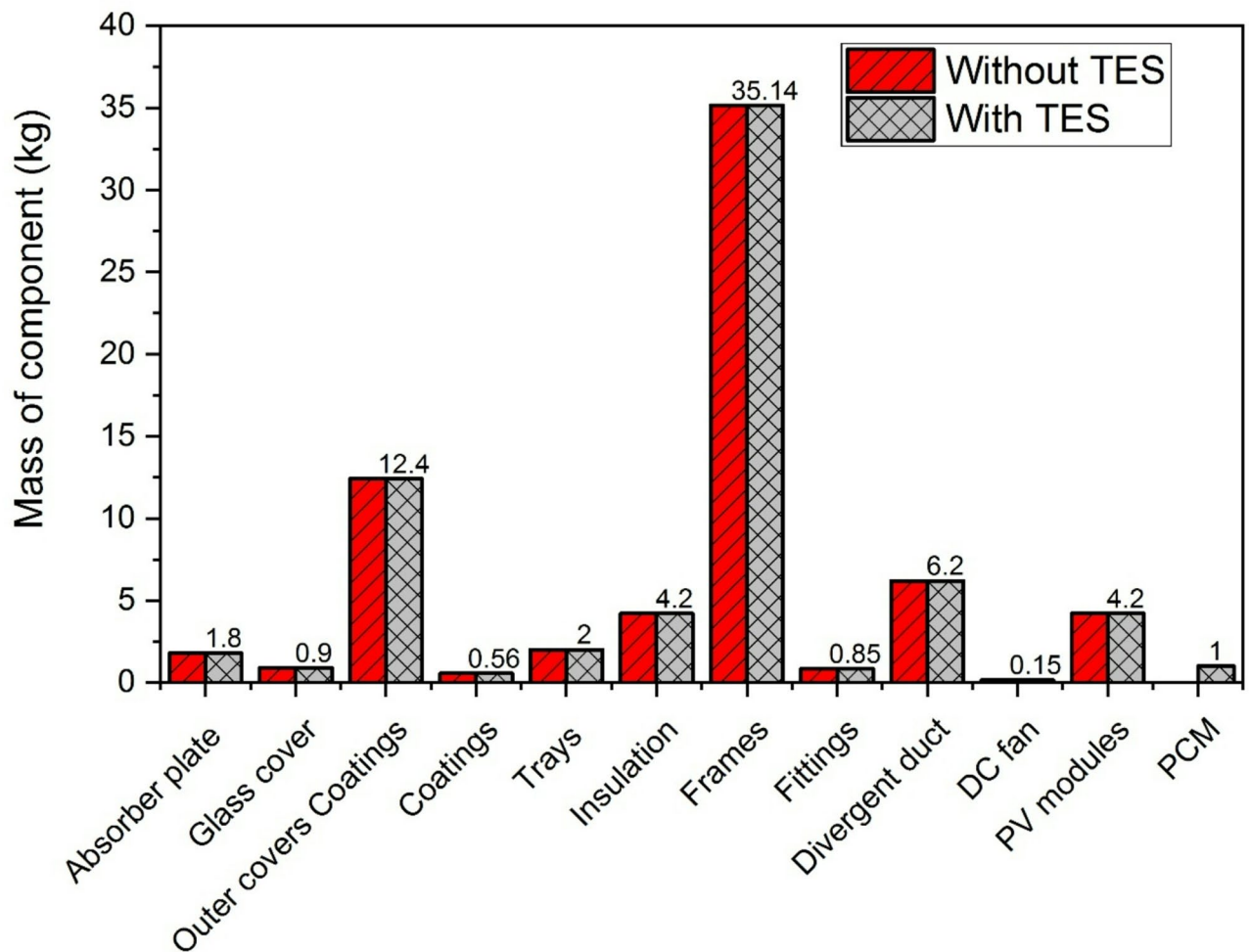


Fig. 17. Materials vs. mass of component.

Data availability

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

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Author contributions

Senthil Kumar K : Validation, Visualization, Writing – review & editing. Vasanthi R : Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. Mahdi Sh. Jaafar : Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. Arunkumar Munimathan : Formal analysis, Methodology, Software, Validation. Manoj Kumar Shanmugam: Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. Mamdooh Alwetaishi : Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. Asif Afzal : Visualization, Validation, Software, Methodology, Investigation, Formal analysis. Parvathy Rajendran : Formal analysis, Conceptualization, Writing – review & editing. It Ee Lee : Formal analysis, Validation, Conceptualization, Writing – review & editing.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to P.R. or I.E.L.

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