RESEARCH ARTICLE

Assessment of energy, exergy, environmental, and economic study of an evacuated tube solar dryer for drying Krishna Tulsi

Thota Swamy Surya Bhaskara Rao[1] · Murugan Sivalingam[1]

Abstract

In the present work, experimental studies of drying Krishna tulsi leaves in an in-house fabricated evacuated tube solar collector (ETSC) connected with an indirect solar dryer are carried out. The acquired findings are compared to those obtained from drying the leaves in open sun drying (OSD). The developed dryer takes 8 h to dry Krishna tulsi leaves; it takes 22 h in the OSD to reach a final moisture content of 12% (db) from an initial moisture content of 47.26% (db). The collector and dryer efficiencies range from 42 to 75%, 0–18%, respectively, with an average solar radiation of 720 ± 20 W/m². The ETSC and drying chamber exergy inflow and outflow vary from 200 to 1400 W, 0 to 60 W, and from 0 to 50 W, 0 to 14 W, respectively. The ETSC and cabinet exergetic efficiencies range from 0.6–4% and 2–85%, respectively. The exergetic loss of the overall drying process is estimated to be 0–40%. The drying system sustainability indices, including improvement potential (IP), sustainability index (SI), and waste exergy ratio (WER), are calculated and presented. The value of the embodied energy of the fabricated dryer is 349.874 kWh. For an expected life span of 20 years, the dryer will reduce CO_2 by 13.2 tonnes and earn carbon credits worth between 10,894 and 43,576 INR. The proposed dryer has a payback period of 0.4 years.

Nomenclatured

Abbreviations

ETSC	Evacuated U-tube solar collector
db	Dry basis
DR	Drying rate
EE	Embodied energy
EPBP	Energy payback period
GWP	Global warming potential
INR	Indian rupees
IP	Improvement potential
MC	Moisture content
MR	Moisture ratio
OSD	Open sun drying
RH	Relative humidity
RTD	Resistance temperature detector

✉ Thota Swamy Surya Bhaskara Rao
bhaskar.mec328@gmail.com

[1] Heat Power Laboratory, Department of Mechanical Engineering, National Institute of Technology, Rourkela 769008, India

SI	Sustainability index
WER	Waste exergy ratio

Symbols

A_c	Area of the collector (m²)
A	Area of the tray (m²)
C	Cost
c_p	Specific heat at constant pressure (kJ/kg K)
D	Diameter (mm)
E_c	Electrical energy consumption of the blower
E_{in}	Input energy
f	Friction factor
Gr	Grashoff number
g	Gravitational energy (m/s²)
h	Enthalpy (kJ/kg)
h_c	Heat transfer coefficient
h_{fg}	Latent heat of vaporization (Kj/kg K)
I	Solar radiation (W/m²)
i_R	Inflation rate
K	Thermal conductivity (W/mK)
k	Drying coefficient
L	Length of pipe (m)
l	Characteristic dimension
L_s	Thickness of the slice

m	Mass of the product
m_a	Mass of air
M_e	Equilibrium moisture content
M_f	Final moisture content
M_o	Initial moisture content (dry basis)
M_r	Moisture removal
M_t	Moisture content at a time t (dry basis)
Nu	Nusselt number
P	Pressure (bar)
Pr	Prandtl number
$P(T_c)$	Partial pressure of air
$P(T_r)$	Partial pressure of air at product surface
Q_{em}	Heat required
Re	Reynolds number
T	Temperature (°C)
t	Drying time (hrs)
T_d	Dryer lifespan
T_s	Temperature of the sun
v	Velocity
W	Work transfer rate
Z	Reference height (m)

Greek

η	Efficiency
ν	Velocity (m/s)
μ	Dynamic viscosity of fluid (kg/m-s)
λ	Relative humidity of drying air

Subscripts

a	Ambient
an	Annual
c	Collector
ci	Collector inlet
co	Collector outlet
dc	Drying chamber
dci	Drying chamber inlet
dco	Drying chamber outlet
dp	Dried product
ds	Drying cost
Ex	Exergy
fd	Fresh drying product
fp	Fresh product
i	Inlet
loss	Exergy loss
o	Outlet
w	Water

Introduction

Since ancient times, Krishna tulsi has been considered a prominent medicinal and aromatic herb belonging to the Lamiaceae family. Krishna tulsi leaves are used for throat infections, skin diseases, respiratory health improvement, and to treat fever. It is a tropical plant native to India and widely cultivated across Southeast Asia. Tulsi is grown for religious and traditional medicinal purposes and for its essential oil. It is popular as a herbal tea, particularly in Ayurvedic medicine. Dried Krishna tulsi leaves are very effective in various health conditions like cold, cough, tight chest, etc. (Bhadra 2020) (Jamshidi and Cohen 2017).

Nowadays, Krishna tulsi leaves are extensively cultivated in countries including France, the United States, Greece, Morocco, Israel, Indonesia, and Hungary. Dried leaves are commonly used in food processing industries. The market for dried leaves is determined based on the quality of the product based on taste, flavor, moisture content, and appearance. From the dried ones, several products like tulsi powder, tea, and capsules are made after processing (Khatun et al. 2014). Regular consumption of taking tulsi powder improves the body's immunity, relieves stress, promotes a healthy metabolism, and reduces blood sugar levels in patients with type-2 diabetes (Jamshidi and Cohen 2017). Handling leaves after harvest determines the end quality and aromatic properties. Color, aroma, and texture are the three key factors in grading product quality on the market. Krishna tulsi leaves are scarce during the off-season. Preservation of these medicinal herbs is required for year-round use. Hence, a proper drying method is required for Krishna tulsi leaves for better storage with less spoilage and higher shelf life (Bhaskara Rao and Murugan 2021) (Babu et al. 2018).

The concept of drying is a process of removing moisture by combining heat and mass transfer. Generally, any food product can be dried by open-sun drying (OSD), which spreads the food product in an open area and is directed toward the sun. Even though it is a simple and economical drying method, it has the following drawbacks; (i) improper drying, (ii) color degradation, (iii) collecting dust and dirt, etc., on the resulting product (Dhanore et al. 2018) (Tomar et al. 2017). Due to hostile weather conditions, open-sun drying always has drawbacks. On the other hand, thermal and electrical dryers consume huge electrical energy and require higher initial investments (Kondareddy et al. 2022). Electrical energy consumption indirectly increases CO_2 emissions, which increase global warming potential (GWP). Due to this, drying food products using cheaper and cleaner energy is a focus of research by various researchers. The utilization of clean and alternative renewable sources has become realistic in the last two decades. In this context, solar energy is abundantly available compared to other renewable energy sources. The application of solar energy is rapidly increasing in different applications, including heating, cooling, power generation, drying, etc., due to its economic, eco-friendly, and availability (Vijayan et al. 2020). A key part on the performance of an efficient solar drying system is the solar thermal collector. The hot air

from the collector is the main factor in how well the dryer reduces moisture from the drying product. In this scenario, an ETSC delivers relatively higher temperatures than a flat plate collector. It achieves higher temperatures even during low sun-shining days than flat plate collectors. ETSC's working temperature range is 40–100 °C, and it is sufficient for drying process. ETSC is flexible if a tube breaks, it can be easily replaced. The maintenance cost is low, and the performance of these collectors is good in cold conditions (Olfian et al. 2020).

Danso-Boateng (2013) performed drying experiments on basil leaves using five different methods, namely, microwave drying, oven drying, hot air drying, sun drying, and ambient air drying to assess the nutritional content. Among all the methods, the microwave drying method took less drying time with the most inhibition of protein and carbohydrate content in the dried leaves. Daghigh and Shafieian (2016) performed energy and exergy analyses on an evacuated heat pipe collector for dual-purpose usage by using a heat exchanger for water heating and drying applications. The system's exergetic performance increased with time and increased to a maximum of about 10.6% at the end of the day. Singh et al. (2022) investigated an ETSC dryer used for drying turmeric, and the thermal efficiency varies from 18.5 to 22.5%. The required time for drying in the greenhouse dryer is reduced by about 55% in comparison with OSD, and the quality of the dried turmeric is good in terms of curcumin, volatile content, and polishing loss. The payback period of energy and costs is reported as 2.95 and 1.10 years, respectively. CO_2 mitigation is given as 209.21 tons.

Malakar et al. (2021) experimented with drying garlic cloves in an ETSC solar dryer with different air flow rates of 1, 2, and 3 m/s. The average exergy efficiency is found to be 56.6%, at a flow rate of 2 m/s, and the highest exergy loss is found at 1 m/s as 4.74 W. The dryer payback period is 1.3 years. In another study, the same authors (Malakar et al. 2022) performed the drying process on the beetroot slices in an ETSC; the final moisture content in the beetroot slices is 9.25%. The highest color change is found in OSD samples, whereas antioxidant activity and phenolic compounds are higher in ETSC samples. Singh and Gaur developed ETSC greenhouse dryer and conducted experiments on drying ginger and tomatoes. The values of the convective heat transfer are ranging between 2.9 and 3.33. Various authors (Sadhishkumar and Balusamy 2014) (Sadeghi et al. 2020) (Das and Akpinar 2020) (Shrivastava et al. 2022) evaluated the value of convective heat transfer for different food products by using different solar dryers and found its significance while designing efficient dryers.

Energy and exergy analyses of an indirect solar dryer with natural and forced convection modes for drying Okra are performed by Mugi and Chandramohan (2021). The dryer's efficiency is higher by about 5% in the forced convection mode. The exergy analysis indicates that drying chamber exergy losses are high in the natural convection mode. The average collector and drying efficiencies are 2.03, 59.32%, 2.44, and 55.45%, in the forced and natural convection modes of drying, respectively. Lakshmi et al. (2019) dried stevia leaves by using a solar dryer in a mixed mode, and the desired moisture content is obtained in 5.5 and 14.5 h in the mixed mode and OSD, respectively. The average dryer exergy efficiency is 59.1%. Antioxidants and flavonoids are higher in the mixed mode, and the payback period is reported as 0.65 years.

The suitable design and optimization of the solar dryer result in maximum moisture reduction of the product with lesser energy utilization. The amount of quality and quantity of energy utilized during the drying process determine the performance of the system. Exergy analysis of a solar drying system indicates the quality of the energy utilized in the drying process, which is also determined by energy analysis. The first law of thermodynamics is used for the energy analysis of drying. It shows how energy is conserved by the various parts of the drying system.

Numerous works related to the drying of food products and medicinal herbs are reported in the literature (Mghazli et al. 2017) (Kabeel et al. 2022) (Rani and Tripathy 2021). Different research studies are carried out on the thin-layer drying of fruits, vegetables, and herbs (Ouaabou et al. 2020) (Vijayan et al. 2016) (Lingayat et al. 2021) (Bahammou et al. 2019b). Different authors studied the thermal performance, energy analysis, and exergy analysis (Tiwari and Tiwari 2017) (Bhardwaj et al. 2019) (Bhaskara Rao and Murugan 2021), environmental analyses (Moosavian et al. 2021) (Srivastava et al. 2021) (Kesavan et al. 2019), and economic analysis (Singh et al. 2006) (Jain and Tewari 2015) (Lakshmi et al. 2019) (Devan et al. 2020) on the solar drying systems. But, a number of energy, exergy, environmental, and economic research studies related to the ETSC-supported dryer are not reported in the literature. And also, the performance evaluation of an ETSC used for drying Krishna tulsi has not yet been done. Based on this research gap, experimental studies are carried out on drying Krishna tulsi using an ETSC supported dryer and then performed the 4E analysis on the newly fabricated dryer.

Novelty and objectives of the research study

The novelty and objectives of the present study aim to evaluate the following: (i) thus far, no studies have been found on drying Krishna tulsi using a solar dryer. Therefore, experiments were carried out on drying Krishna tulsi, and the thermal performance of the ETSC dryer was assessed. (ii) The estimation of the ETSC dryer's energy inflow, outflow, and sustainability indicators was not reported in the literature. As a result, the study is aimed at evaluating the

energy and exergy analysis of the overall drying process in order to determine energy utilization and at determining where thermodynamic improvements can be made by using sustainability indices, and (iii) an environmental and economic analysis of the proposed dryer is performed to assess the environmental impact and cost-related parameters of the novel ETSC dryer.

Materials and methods

Experimental setup

An in-house fabricated U-Tube ETSC combined with an indirect drying chamber was positioned on the Mechanical Engineering Block, NIT Rourkela, India. Figure 1 depicts a schematic view of the experimental test setup. The drying experiments were conducted in January 2022. In each batch, 4 kg of Krishna tulsi leaves were dried. Three batches of Krishna tulsi leaves drying studies were performed. The photo of the fabricated ETSC dryer is displayed in Fig. 2.

The experimental setup comprises (a) an ETSC collector with U-Tube, (b) an indirect drying chamber, and (iii) a centrifugal blower. The ETSC collector is an active mode forced convection type. The air is forced into the collector by an electric blower (0.28 HP, 20 V, 50 Hz, 2800 RPM). An air blower blows atmospheric air into the inlet manifold of the ETSC collector. Air enters every tube of the collector and is heated up by solar radiation that falls on the glass tubes. Hot air leaves the collector's outlet manifold. The inlet and outlet manifolds are sealed with 25 mm thickness of glass wool to reduce heat losses. Thermocouples are placed on both manifolds to measure temperatures at different locations. The collector is directed south with a 19.27° inclination angle.
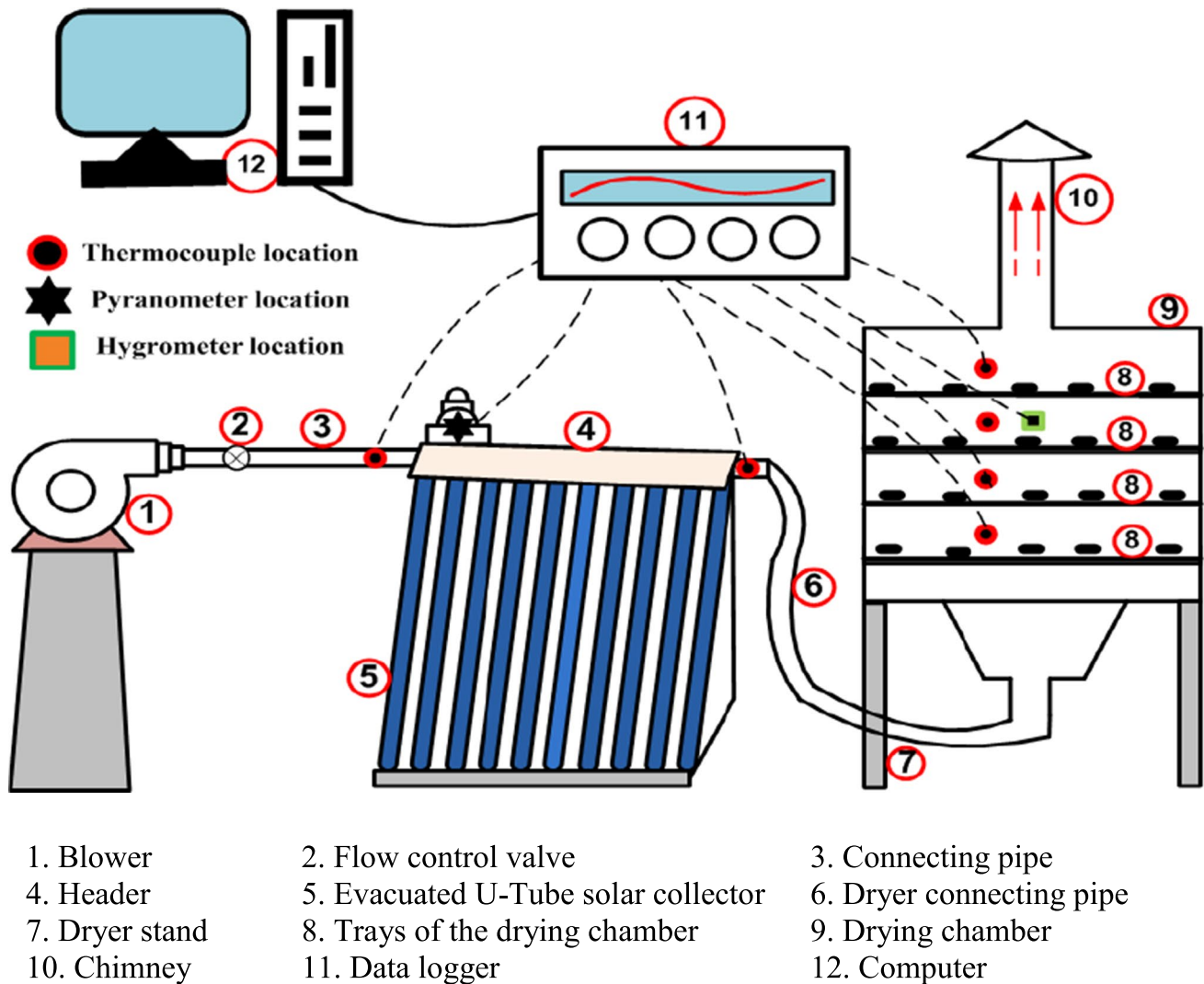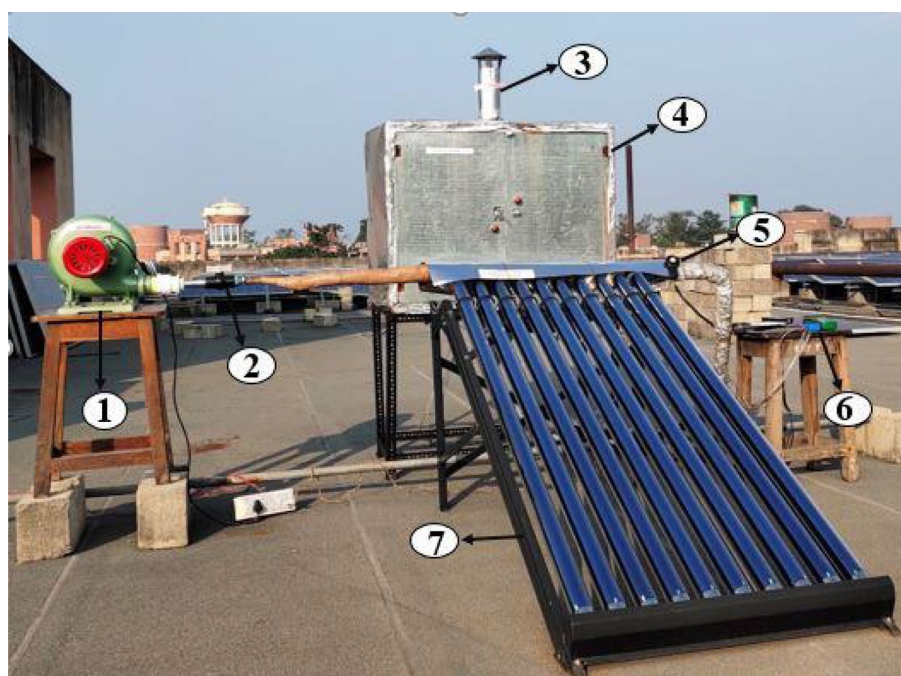

1. Blower	2. Flow control valve	3. Connecting pipe
4. Header	5. Evacuated U-Tube solar collector	6. Dryer connecting pipe
7. Dryer stand	8. Trays of the drying chamber	9. Drying chamber
10. Chimney	11. Data logger	12. Computer

Fig. 1 Schematic view of the experimental test setup

Fig. 2 Photograph of the experimental setup

1. Blower   2. Flow control valve   3. Chimney   4. Drying chamber
5. Pyranometer   6. Measuring devices   7. U-Tube evacuated solar collector

An indirect drying chamber is made up of galvanized iron sheets, and glass wool is used to insulate it on all sides. Four trays are placed in the drying chamber with equal spacing of 150 mm between them. The dimensions of each tray are 500 × 1000 mm. The product to be dried is placed on drying chamber trays. Four RTD-type thermocouples are installed near each tray in the drying chamber to measure the temperature, and all thermocouples are connected to a temperature data logger. The heated air will be transferred to the bottom of the drying cabinet from the ETSC. Hot air passes upward through each tray in the chamber. Then, the moist air leaves through a chimney at the top of the drying chamber. Forced convection solar drying has a higher drying rate than natural convection dryers. The flow rate of the drying air in the chamber is maintained at 0.03 kg/s, and this is controlled by regulating the ball valve placed between the blower and collector inlet manifold. The ETSC and drying cabinet specifications are listed in Table 1.

Sample preparation and experimentation

Krishna tulsi leaves are available from March to June in spring. Fresh Krishna tulsi leaves were bought from the local market and rinsed with water. After cleaning the leaves, they are spread over a place to remove water particles accumulated on the surface of the leaves. The leaves are kept in a room for one day before drying experiment. The initial moisture

Table 1 ETSC and drying cabinet specifications

Evacuated tube solar collector (ETSC)	
Length	1.8 m
Inner diameter of glass tube	44 mm
Outer diameter of glass tube	58 mm
Collector area	1.44 m^2
Material of the glass	Borosilicate
Coating material on glass	Aluminum nitride
Tilt angle	19.27^0
Material of the U-tube	Copper
U-tube diameter	8 mm
U-tube thickness	1 mm
Manifold diameter	20 mm
Working fluid	Air
Drying chamber	
Area	3.25 m^2
Volume	0.375 m^3
Number of drying trays	4
Tray area	0.36 m^2
Distance among trays	0.15 m
Height of the chimney	0.3 m
Rate of mass flow	0.02955 kg/sec
Air density	1.225 kg/m^3
Glass wool thickness	25 mm
Glass wool density	64 kg/m^3

Fig. 3 Tulsi leaves drying in the (**a**) drying chamber and (**b**) open sun

content of Krishna tulsi leaves is calculated by the hot air oven drying method (Kesavan et al. 2019). Fresh Krishna tulsi leaves are spread over the drying trays, and a portion of leaves is also dispersed in the open sun for drying, as shown in Fig. 3. The moisture loss in the leaves is calculated using a digital weighing scale for every hour. The trays are interchanged frequently during the drying process for uniform drying. Experiments are carried out until there is no change in the drying product weight in the ETSC and OSD. After drying, leaves are packed into propylene bags to prevent moisture absorption. The ambient and drying chamber relative humidity is recorded using a digital hygrometer. The thermocouples placed at the collector and different locations in the drying chamber are connected to a temperature data logger for continuous temperature measurement. A pyranometer is

placed near the collector to measure solar radiation. The experiments are conducted at Rourkela (22.26° N, 84.85° E), India.

Uncertainty of the experimentation

Uncertainty analysis of the entire experimental procedure is necessary to estimate errors in different measured quantities. These errors may be due to human errors in noting the data, data approximation, less accuracy in measuring devices, etc. In this experimental study, uncertainty is calculated for the temperatures and relative humidity of air, sample weight, solar radiation, and velocities of air (Dhalsamant et al. 2018). Table 2 gives details of the different instruments used in the current experiment.

The uncertainty of the dependent (W_R) and independent (w_1, w_2, …w_n) variables is computed from the equation below (Goud et al. 2019) (Kesavan et al. 2019).

$$W_R = \left[\left(\frac{\delta R}{\delta X_1} W_1 \right)^2 + \left(\frac{\delta R}{\delta X_2} W_2 \right)^2 + \left(\frac{\delta R}{\delta X_n} W_n \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

where W_R is the uncertainty of the estimated value and w_1, w_2, …w_n are the errors in the independent variables. Table 3 shows the uncertainty calculation of all measuring devices.

Performance evaluation

Moisture removal

The amount of moisture level present in Krishna tulsi leaves is measured by using Eq. (2) (Gilago et al. 2023)

$$MC(db) = \frac{M_i - M_f}{M_f} \quad (2)$$

Moisture ratio (MR)

The moisture ratio of Krishna tulsi leaves is estimated by Eq. (3) (Saxena and Gaur 2020)

Table 2 Experiment uncertainty details

Instrument	Finding	Manufacturer	Range	Accuracy
Pyranometer	Solar radiation	Metravi Pyranometer-207	0–1999 W/m^2	± 10 W/m^2
Weight balance	Weight	Health Sense-KS 33	0–500 g	± 0.01 g
Anemometer	Wind velocity	Metravi AVM-04 Anemometer	0–45 m/s	± 0.1 m/s
Hygrometer	Relative humidity	Metravi HT-305A	0–100% RH	± 3% RH
RTD sensor	Temperature	ACE Instruments PT 100 Sensor	0–400° C	± 1 °C

Table 3 Uncertainty values of the measuring devices used in this study

Measurement	Solar radiation (W/m²)	Temperature (°C)	Relative humidity (%)	Weight (kg)	Air velocity (m/s)	Total experimental uncertainty
Uncertainty	1.4141	0.3041	0.1414	0.2004	0.1414	± 1.4737%

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{3}$$

$$MR = \frac{M_t}{M_o} \tag{4}$$

where M_t and M_0 are the moisture content at time t, and Eq. (4) can be used because of the continuous change in moisture content of the drying product.

Drying rate (DR)

The food product drying rate is determined by Eq. (5) (Tiwari and Tiwari 2017)

$$DR = \frac{\Delta M}{\Delta t} \tag{5}$$

where ΔM and Δt are mass loss in the product and time interval, respectively.

Energy analysis

The energy analysis of a drying system can be expressed by mass and energy conservation equations (Hancioglu et al. 2010) (Dincer 2011).

The equation for mass conservation of air is commonly expressed as

$$\sum m_{ai} = \sum m_{ao} \tag{6}$$

The equation for mass conservation is expressed as

$$Q - W = \sum m_o \left(h_o + \frac{v_o^2}{2} + Z_o g \right) - \sum m_i \left(h_i + \frac{v_i^2}{2} + Z_i g \right) \tag{7}$$

where Q and W are the rate of heat and work transfers respectively, m_i and m_o are mass flow rate of air at inlet and outlet, h_i and h_o are the enthalpies of air at inlet and outlet, v_i and v_o are the velocities of the air at the inlet and outlet, Z_i and Z_o are the height of the collector and drying chamber at inlet and outlet from the reference, and g is the gravitational energy.

Energy analysis of the collector

The useful energy gained by the solar collector is given in Eq. (8)

$$Q_c = m_a C_p \left(T_{co} - T_{ci} \right) \tag{8}$$

The efficiency of ETSC collector can be determined by the Eq. (9).

$$\eta_c = \frac{m_a C_p \left(T_{co} - T_{ci} \right)}{IA_c} \tag{9}$$

Energy analysis of the drying chamber

The amount of heat utilized in the drying chamber (using a psychrometric chart) by Eq. (10)

$$Q_{dc} = m_{a,dc} C_p \left(h_{dci,T} - h_{dco,T} \right) \tag{10}$$

where h_{dci} and h_{dco} are the enthalpies of the drying air at drying chamber inlet and outlet.

The efficiency of the drying cabinet is expressed by Eq. (11)

$$\eta_{dc} = \frac{Q_{dc}}{IA} = \frac{m_{a,dc} C_p \left(h_{dci,T} - h_{dco,T} \right)}{IA} \tag{11}$$

Exergy analysis

Exergy analysis of the drying system is carried out, where thermodynamic improvements can be made for efficiency by using thermodynamics second law. The values of exergy inflow, outflow, loss, and efficiency are calculated for the drying process. Exergetic efficiency is the proportion of the amount of exergy utilized to reduce the moisture of a product to the exergy given to the product during the drying process (Bahammou et al. 2019a) (Rani and Tripathy 2021).

The following assumptions are taken while performing the exergy analysis.

(i)   The flow is considered steady
(ii) Potential and kinetic energy effects are neglected

(iii) The velocity difference between the inlet and outlet is minimal

Exergy analysis of the collector

The exergy of the solar radiation falls on the ETSC by Eq. (12) (Ge et al. 2014)

$$Ex_{rad,c} = A_c I \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right] \quad (12)$$

The exergy inflow to the collector is expressed by Eq. (13)

$$Ex_{in,c} = m_a c_{pa} \left[(T_{ci} - T_a) - T_a \, In \left(\frac{T_{ci}}{T_A} \right) \right] \quad (13)$$

The exergy outflow of the collector is written by Eq. (14)

$$Ex_{out,c} = m_a c_{pa} \left[(T_{co} - T_a) - T_a \, In \left(\frac{T_{co}}{T_a} \right) \right] \quad (14)$$

The exergy efficiency of the collector is expressed by Eq. (15)

$$\eta_{Ex,c} = \frac{Ex_{out,c}}{Ex_{in,c}} \quad (15)$$

Exergy analysis of the drying chamber

The expression for the inflow of exergy to the drying chamber can be written by Eq. (16); (Sansaniwal et al. 2018) (Rabha and Muthukumar 2017)

$$Ex_{in,dc} = m_a c_{pa} \left[(T_{dci} - T_a) - T_a \, In \left(\frac{T_{dci}}{Ta} \right) \right] \quad (16)$$

The outflow of exergy from a drying chamber can be written by Eq. (17)

$$Ex_{out,dc} = m_a c_{pa} \left[(T_{dco} - T_a) - T_a \, In \left(\frac{T_{dco}}{T_a} \right) \right] \quad (17)$$

The drying chamber exergy loss can be written as Eq. (18)

$$Ex_{loss} = Ex_{in} - Ex_{out} \quad (18)$$

The drying chamber's exergy efficiency is expressed in Eq. (19) (Bhardwaj et al. 2019)

$$\eta_{Ex,dc} = \frac{Ex_{out,dc}}{Ex_{in,dc}} \quad (19)$$

Sustainability analysis

The indicators of sustainability are influenced by the changes in the system's exergy loss. IP, SI, and WER of the drying system can be expressed in Eqs. (20–22) (Ndukwu et al. 2017)

$$IP = (1 - \eta_{Ex}) Ex_{loss} \quad (20)$$

$$SI = \frac{1}{1 - \eta_{Ex,d}} \quad (21)$$

$$WER = \frac{Ex_{loss,dc}}{Ex_{i,dc}} \quad (22)$$

Environmental analysis

Before dryer fabrication, all the materials used for construction should be analyzed to know their environmental effects.

Energy payback period

The energy payback period of the ETSC drying system can be calculated by Eq. (23) (EL khadraoui et al. 2019)

$$Energy\ pay\ back\ period (EPBP) = \frac{EE(kWh)}{E_{O,T}(kWh/year)} \quad (23)$$

where EE and $E_{0,T}$ are the embodied energy and total energy output per year by the entire drying system.

CO_2 emissions

CO_2 emissions omitted by the dryer can be calculated by using Eq. (24) (Eltawil et al. 2018)

$$CO_2\ emision\ per\ year = \frac{EE \times 0.98}{LT_d} \quad (24)$$

where LT_d is the overall dryer lifespan

CO_2 mitigation

The value of CO_2 mitigation from the ETSC dryer is calculated by Eq. (25) (Singh and Gaur 2021)

$$CO_2\ mitigation\ by\ the\ dryer = (E_{O,T} \times LT_d - EE) \times 2.042 \quad (25)$$

The carbon credit obtained with the ETSC dryer is calculated by Eq. (26) (Srivastava et al. 2021)

$$carbon\ credit\ earned = NetCO_2 \times Cost\ of\ mitigation \quad (26)$$

Economic evaluation

An economic evaluation of a drying system is an effective tool for designing a dryer for considering the cost parameters. In the present analysis, the life cycle saving method and payback period are considered for evaluating costs. In the life cycle saving method, initially, the value of the savings per day is evaluated, and then per year is calculated to dry the product (Singh et al. 2006) (Sethi and Dhiman 2020).

The cost of drying a fresh product (C_{fd}) can be calculated by Eq. (27)

$$C_{fd} = C_{fp} \times \frac{m_{fp}}{m_{dp}} \quad (27)$$

where C_{fp}, m_{fp}, and m_{dp} are the cost of the fresh product (undried product), the mass of the fresh, and dried samples.

The price for drying 1 kg of fresh Krishna tulsi leaves (C_{ds}) is the sum of the price of the fresh leaves to the cost of dried leaves (C_{fd}) and the overall cost of the solar drying process (C_s), shown by Eq. (28).

$$C_{ds} = C_{fd} + C_d \quad (28)$$

The overall drying cost (C_s) is calculated from the cost of annualized drying (C_{an}). The annual drying cost is calculated by Eq. (29).

$$C_{an} = C_{ac} + C_m - V_a + C_{rf} + C_{re} \quad (29)$$

where C_{ac} is the annualized capital cost, C_m is the maintenance cost (assumed as 10% of the overall cost), C_{rf} is the running fuel cost, C_{re} is the electricity cost, and V_a is the salvage cost (assumed as 5% of the total cost).

The annualized capital cost (C_{ac}) of a solar dryer can be estimated from the capital cost (C_{cc}) and the capital recovery factor (C_{rf}), as shown by Eqs. (30 and 31) (Singh et al. 2021).

$$C_{ac} = C_{cc} + C_{rf} \quad (30)$$

$$C_{rf} = \frac{k \times (1+k)^n}{(1+k)^n - 1} \quad (31)$$

The unit cost of electrical energy to run the blower is calculated by Eq. (32)

$$C_{re} = t_{hr} \times P_{bl} \times C_{ele} \quad (32)$$

where t_{hr} is the blower running time in hours, P_{bl} is the power consumption value, and C_{ele} is the electricity cost in units.

The total mass of Krishna tulsi leaves in the ETSC dryer per year (m_y) is expressed as Eq. (33)

$$m_y = m_d \times \frac{t_{sun}}{t_d} \quad (33)$$

where m_d is the mass of Krishna tulsi leaves dried per batch, t_{sun} is the availability of the total sunny days for solar drying (assuming 200 clear sunny days in a year), and t_d is the total time taken for drying one batch.

The amount of savings for drying a single kg (S_{kg}) of Krishna tulsi leaves is the price difference between the current market price (C_{mp}) of the dried product and the amount of the cost to dry in the solar dryer (C_{sd}), which is given as Eq. (34).

$$S_{kg} = C_{mp} - C_{sd} \quad (34)$$

The amount of savings per day (S_d) in ETSC drying is calculated by the ratio between the amount of savings per batch (S_b) to the typical time for drying it (t_t), expressed as Eq. (35).

$$S_d = \frac{S_b}{t_t} = \frac{S_{kg} \times m_d}{t_t} \quad (35)$$

The amount of annual savings (R_k) to dry the product in the nth year is calculated by Eq. (36)

$$R_k = R_d \times t_{sun} \times (1 + i_R)^{n-1} \quad (36)$$

where "i_R" is the inflation rate.

The ETSC dryer payback period is expressed as Eq. (37)

$$N = \frac{In\left[1 - \frac{C_{cc}}{R_1}(k - i_R)\right]}{In\left[\frac{1+i_R}{1+k}\right]} \quad (37)$$

where R_1 is the savings during the operations in the first year.

Pressure loss in the air heater

It is important to find the ETSC pressure drop during the experiment. The air was sent to the ETSC inlet by forced convection. The pressure drop increases with the friction factor of the pipe. Smooth surface of the inner tube was used in this study as roughened tube increases pressure loss and it create obstacle to the flow. Pressure drop can be calculated by using the Darcy-Weisbach formula and expressed in Eq. (38)

$$\Delta P = \frac{\rho f L v^2}{2D} \tag{38}$$

The Reynolds number of the fluid flow in the air heater is calculated by using Eq. (39)

$$Re = \frac{\rho v D}{\mu} \tag{39}$$

For the laminar flow (Re < 2000), the friction factor can be expressed by Eq. (40)

$$f = \frac{64}{Re} = \frac{64\mu}{\rho v D} \tag{40}$$

By substituting the value of "f" in the Eq. (38), the pressure loss of the ETSC can be determined.

Determination of the convective heat transfer coefficient

The term convective heat transfer is an important parameter in the effectiveness of a drying system and helps in the design of an efficient dryer. The value depends on the product, size, drying time, and moisture content of the product to be dried (Kumar et al. 2023). Convective heat transfer coefficient (h_c) of a drying system is represented by the following Eq. (41) (Lingayat et al. 2020) (Elbrashy et al. 2022).

$$h_c = \frac{K Nu}{l} \tag{41}$$

Let Q_{em} be the heat used to evaporate the moisture, represented with Eq. (42) (Manchanda et al. 2019) (Barnwal and Tiwari 2008)

$$Q_{em} = 0.016 h_c \left[P(T_c) - \lambda P(T_r) \right] \tag{42}$$

where $P(T_c)$ is the partial pressure of air at drying product; λ is the relative humidity of the air; $P(T_r)$ is the partial pressure of air near the drying product.

By placing the value of h_c in the Eq. (42)

$$Q_{em} = 0.016 \frac{K Nu}{l} \left[P(T_c) - \gamma P(T_r) \right] \tag{43}$$

The amount of the moisture evaporation from the drying product can be calculated as

$$M_{evaporation} = \frac{Q_{em}}{h_{fg}} A_t T \tag{44}$$

where A is the tray area in m^2, t is time, and h_{fg} is the latent heat value in kJ/kg K.

By substituting Q_{em} in Eq. (44)

$$M_{evaporation} = \frac{0.016 \, K \, Nu \left[P(T_c) - \gamma P(T_r) \right]}{1 h_{fg}} A_t t \tag{45}$$

Let us assume

$$z = \frac{0.016 K \left[P(T_c) - \lambda P(T_r) \right]}{1 h_{fg}} A_t t \tag{46}$$

Then

$$M_{evaporation} = z Nu \tag{47}$$

Here

$$Nu = \frac{M_{evaporation}}{z} = C [Re \times Pr]^n \; (forced \; convection) \tag{48}$$

$$Nu = \frac{M_{evaporation}}{z} = C [Gr \times Pr]^n \; (natural \; convection) \tag{49}$$

Applying a logarithm to both sides

$$In \, Nu = n \times In \, (Gr \times Pr) + In \, [C] \tag{50}$$

$$In \, Nu = n \times In \, (Re \times Pr) + In \, [C] \tag{51}$$

The above equations are in linear equation $y = mx + c$ form.

The constants C and n in the linear equation are evaluated by linear regression analysis

$$n = \frac{n \times \sum (XY) - \sum (X) \times \sum (Y)}{N \sum (X^2) - \left(\sum X \right)^2} \tag{52}$$

$$C = \frac{\sum (X^2) \times \sum (Y) - \sum (XY) \times \sum (X)}{N \times \sum (X^2) - \left(\sum X \right)^2} \tag{53}$$

Results and discussions

Experimental conditions

Krishna tulsi leaves are dried in ETSC and OSD. The final MC of $12 \pm 2\%$ (db) of Krishna tulsi leaves is attained in 8 h in the ETSC dryer and 22 h in OSD. During the experimentation, the ambient temperature and solar radiation values with drying time are displayed in Fig. 4. Solar radiation is higher at 2 PM due to higher solar intensities and lesser at the initial stages of drying each day. The radiation is nearly the same on all three days of the experimentation, and the average solar intensity is 720 ± 20 W/m^2. The ambient temperature on
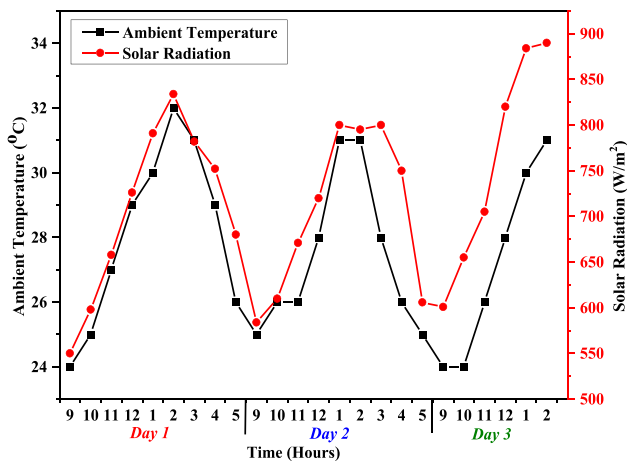
Fig. 4 Ambient temperature, solar radiation with drying time

the temperatures of the heated air coming out of ETSC vary between 65 and 68 °C, with the highest value of 82 °C when solar radiation is high. The inlet and outlet temperatures of the drying cabinet vary between 50–55 and 40–38 °C, respectively. The useful heat gain in the collector also depends on solar radiation and ranges between 100 and 560 W. The experiment ambient relative humidity ranges between 75 and 45% and is inversely affected by solar radiation. The relative humidity values in the drying chamber range from 40 to 26%; this may be due to moisture removal taking place continuously in the drying chamber.

The change in the moisture ratio and the rate of drying of leaves with respective drying times in the ETSC and OSD are portrayed in Fig. 6.

Initially, the drying process of Krishna tulsi leaves occurs rapidly in both modes of drying, and then the process is carried out in the falling rate period. The maximum reduction in moisture ratio is observed in the first six hours of the drying period. Afterwards, the moisture ratio slowly decreases. With the progression of time, the desired moisture is obtained after 8 h of drying in the ETSC drying mode and 22 h of drying in OSD mode. The drying rate could significantly affect the quality and aesthetics of the drying product. The drying rate of Krishna tulsi leaves is calculated by Eq. (5) with experimental data. It can be seen from the figure that the drying rate is higher in the ETSC compared to the OSD. This occurs due to the higher uniform temperatures coming out of the ETSC, whereas no uniform temperatures are noted in the OSD.
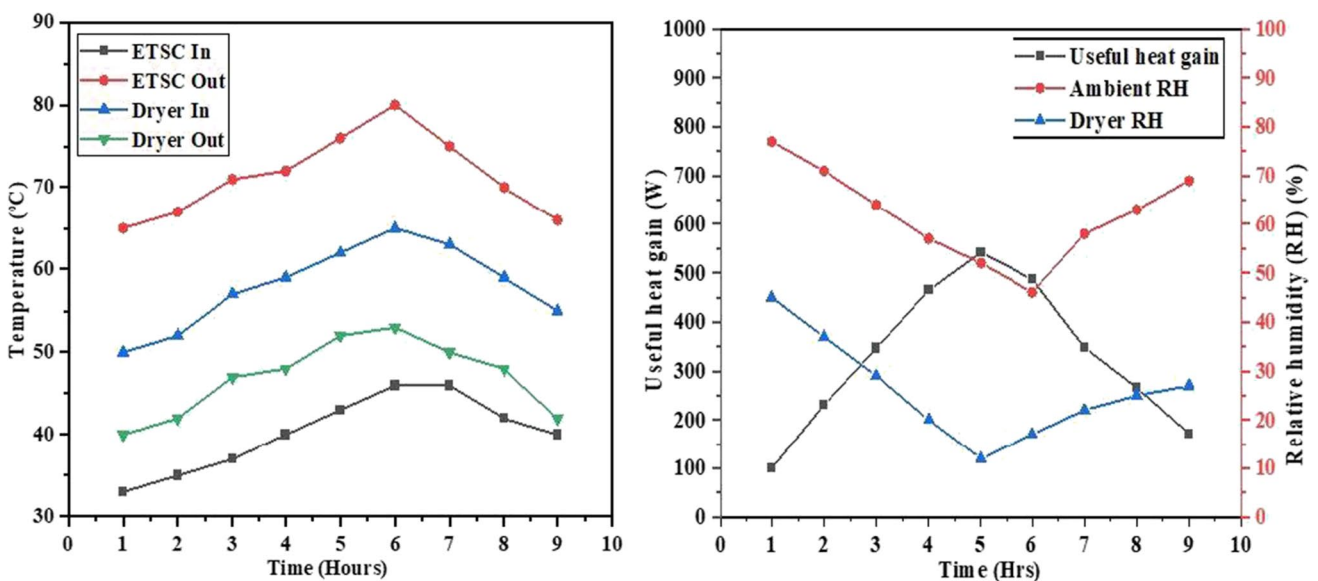
all three days ranges between 24 and 34 °C. The highest ambient temperature is found between 1 and 2 PM every day. The variation in ambient temperature might be due to changes in global solar radiation throughout the day. It can be observed from the figure that, with the increased solar intensity and ambient temperatures during the experimentation, the drying time of Krishna tulsi is reduced significantly.

Temperatures at different locations, relative humidity of the air at ambient and in the dryer, and useful heat gain during the experiment are depicted in Fig. 5. The inlet temperatures of ambient air entering the collector range from 33 to 40 °C during the experiment. After that,

Fig. 5 (**a**) Temperatures at different locations and (**b**) relative humidities of air and useful heat gain during the experiment
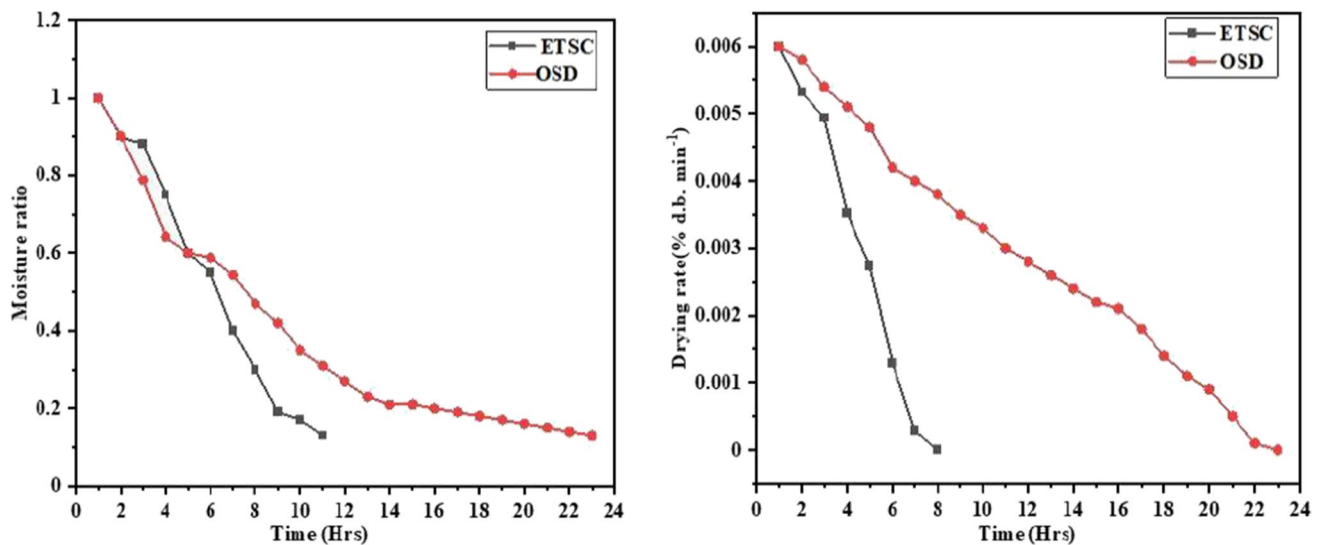
Fig. 6 Variation of (**a**) moisture ratio and (**b**) drying rate with the drying time

Energy analysis of the drying system

ETSC collector thermal efficiency is between 42 and 75% with quick heat generation. This is due to the absorption of heat by the copper tubes from the aluminum fin and the glass tube. At higher temperatures, the efficiency of the collector is found high. The dryer's efficiency is found as 0–46%. The efficiencies of the ETSC and drying chamber with the change in time are shown in Fig. 7. The starting value of 1 on the *X*-axis indicates 9 AM.
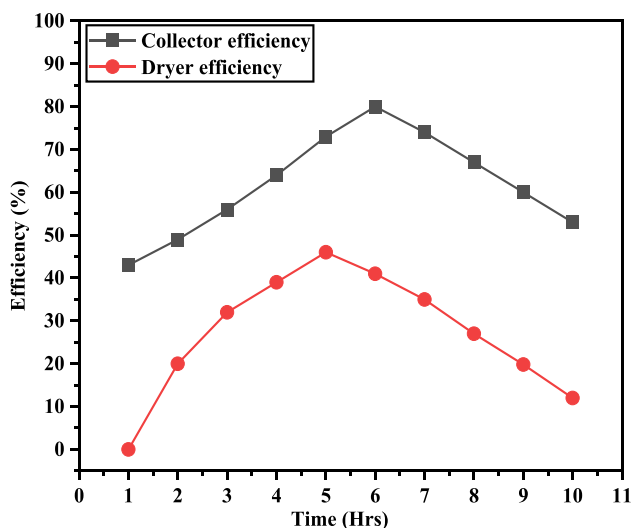
Fig. 7 Change of efficiencies in the collector and the dryer with the time

Exergy analysis of the drying system

ETSC and drying chamber exergy inflow, exergy outflow, and exergetic efficiency values are shown in Fig. 8. ETSC exergy inflow and outflow rates range between 200–1400 and 0–60 W, respectively. The drying chamber's inflow and outflow values are 0–50 and 0–14 W, respectively.

The ETSC exergetic efficiency initially increases to 28%, and then decreases over time. The values of exergy loss vary between 300 and 1100 W. The exergy losses increase with drying time and range between 2 and 85% in the drying chamber. The exergetic efficiency of the drying system varies from 23 to 45%, and this is shown in Fig. 9. This parameter depends on the moisture content of the product to be dried. It is likely that some amount of energy is absorbed by dryer walls due to absorbancy and improper insulation in the dryer walls. The exergetic efficiency is found lower at the beginning and medium stages of drying due to the higher energy requirement for the drying process to remove high moisture levels. The higher efficiency is found in the last hours of the drying process due to the less energy requirement of the drying product.

Exergy sustainability analysis of the drying system

Exergy sustainability parameters are useful parameters to improve dryer design more efficiently. A lower value of exergy losses indicates the dryer's effectiveness. Exergy indices, namely, sustainability index, waste exergy ratio, and improvement potential, are calculated. The
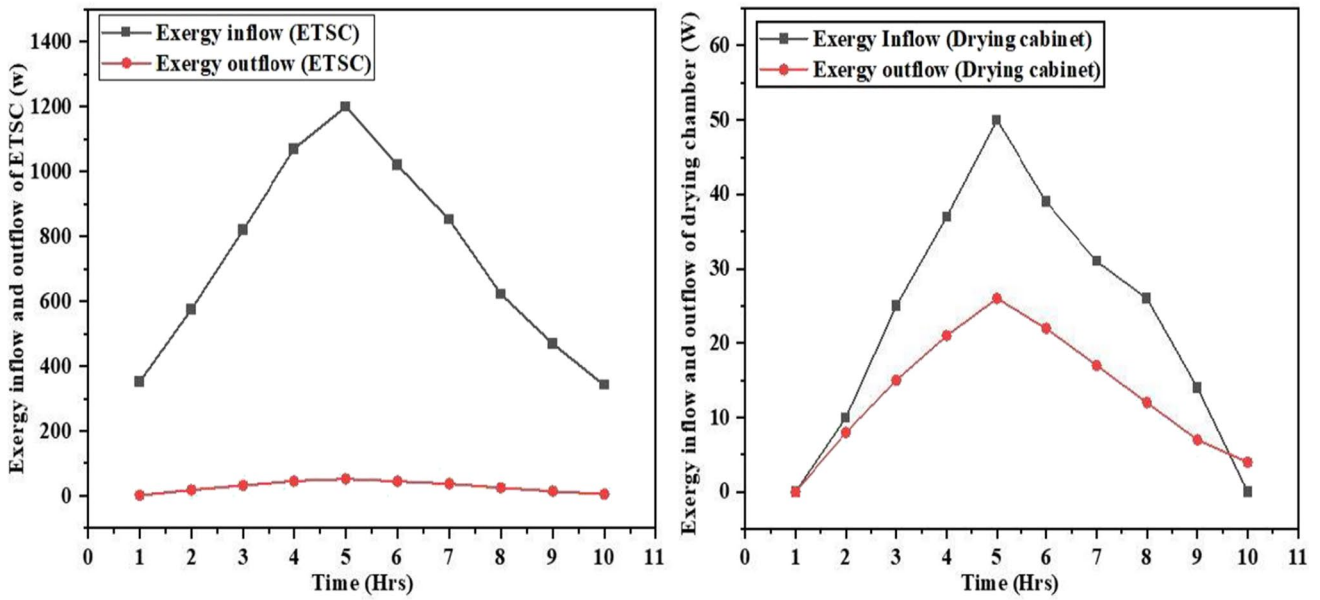
Fig. 8 Variation in inflow and outflow of exergy: (**a**) ETSC and (**b**) drying cabinet with the time

waste exergy ratio is an essential parameter in exergy analysis and indicates the loss of exergy per unit of input exergy. The sustainability index, the waste exergy ratio, and improvement potential range from 0–18, 10–1, and 0–10, respectively. Figure 10 shows how the sustainability indices changes with drying time. The sustainability index increases as the drying time lengthens, whereas the waste exergy ratio declines as the drying time increases. The dryer's improvement potential is found through the change in solar radiation. It increases as solar radiation values increase and the other way around.

Environmental analysis of the drying system

The embodied energy of the ETSC dryer is calculated by taking the values of the energy density of different materials used to fabricate the dryer. The embodied energy required by the different materials to construct the solar dryer is given in Table 4. The dryer EPBT is estimated by the embodied energy value. Considering the dryer's life span of 20 years, the energy payback time (EPBT) of the ETSC dryer is calculated as 1.2 years. Environmental analysis estimated that the energy payback period for the
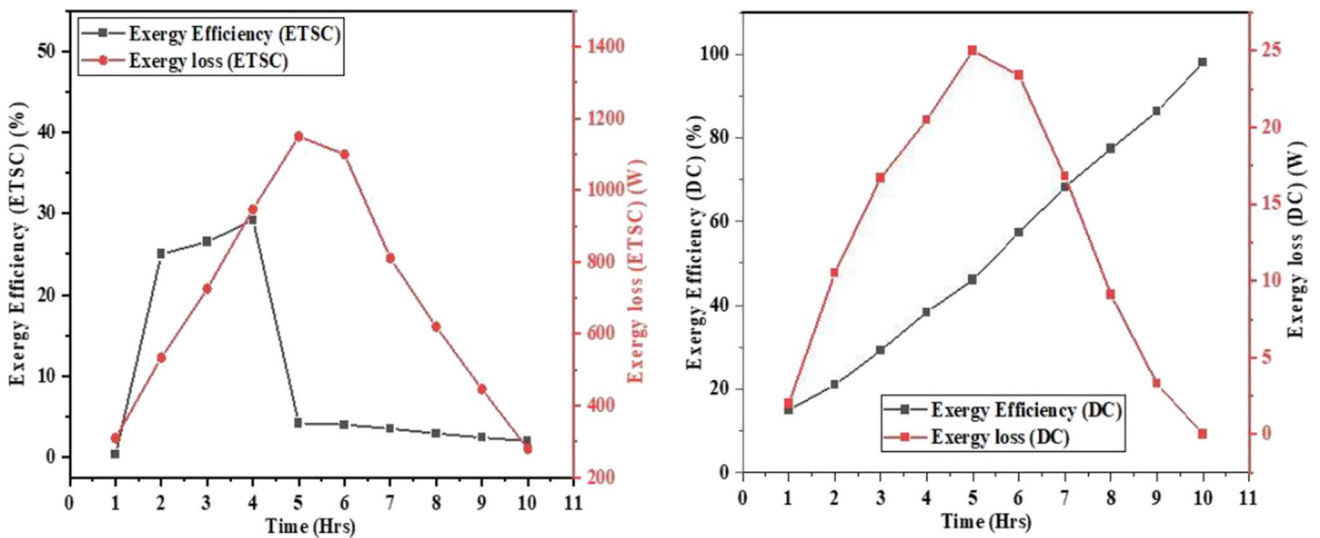

Fig. 9 Variation in exergy efficiency and exergy loss: (**a**) ETSC and (**b**) drying cabinet with the drying hours
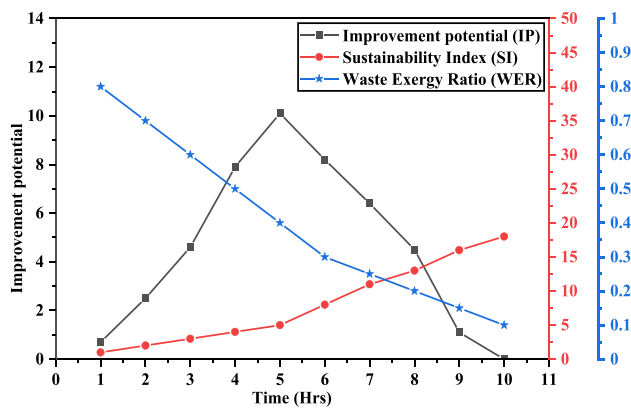
Fig. 10 Change in the sustainability indices of the dryer with the drying time

Table 5 Cost of the various devices/materials used in the dryer fabrication

Device/material	Cost (INR)
Glass tubes	12,000
Blower	6000
Stand for ETSC and drying cabinet	2000
Copper tubes	13,500
Insulation material	1500
GI Sheet	1450
Fabrication cost	3550
Total	40,000

ETSC solar dryer is 2.21 years. For the developed dryer's anticipated 20-year lifespan, the CO_2 mitigation and earned carbon credit values are found as 13.2 tonnes and INR 10,894 to 43,576, respectively. With this evaluation, the ETSC-supported solar dryer would be an alternative option for the preservation and retention of various agricultural goods with ecological protection. Generally, with solar dryers, CO_2 emissions decrease with the mitigation increase, and the system credit increases with the dryer life span.

Economic analysis of the ETSC dryer

The economic aspect of a solar dryer plays a significant role in the commercialization of the product. It reveals many economic factors for further use. The manufacturing cost of the entire drying system and the cost of drying the product should be lesser than the same dried product already available on the market. In some cases regardless of the product price, the quality of the dried product is much more significant when taken for medicinal use. An indirect solar dryer with ETSC is fabricated with a capital cost of 40,000 INR. Table 5 gives the price of the different materials/products used to make the dryer.

The price of the material purchased was the market price in Rourkela, Odisha, India. The inflation rate is assumed to be 7%, and the price of fresh and dried Krishna tulsi leaves is 30 and 250 INR, respectively. The annual drying cost of the product in the ETSC dryer is 2500 INR. The payback period is calculated as 0.4 years. The reported value to an ETSC-supported dryer is comparatively lower than thermal/electric dryers and found higher quality in the dried product than the products dried in OSD.

Pressure drop in the ETSC

Pressure drop and flow rate are interconnected. A constant mass flow rate of air was maintained throughout the experimental procedure. Reynolds number was calculated and the flow is laminar. From the experimental calculation, the pressure loss between the ETSC inlet and outlet is found to be 0.21 bar.

Table 4 Embodied energy of the various materials employed in the proposed dryer

Material	Usage	Quantity (kg)	Energy density (kWh/kg)	Total embodied energy (kWh)
Mild steel	Supporting structures	12	8.89	106.68
GI sheet	Drying cabinet	5	2.45	12.25
Glass tubes	Collector	6	7.28	43.68
Insulation	Glass wool	4	4.04	16.16
Wire mesh trays	To place the products for drying	0.4	19.44	7.776
Painting	Coating on supporting structures	0.6	25.11	15.066
Fittings	Bolts, nuts, nails, screws	0.5	8.89	4.445
Copper pipe	Header and U-pipe	7.2	19.61	141.192
Aluminum fin	To transfer the heat from the glass tube to the copper pipe	0.25	10.5	2.625
Total embodied energy = 349.874				

Table 6 Heat transfer coefficient values from the regression analysis

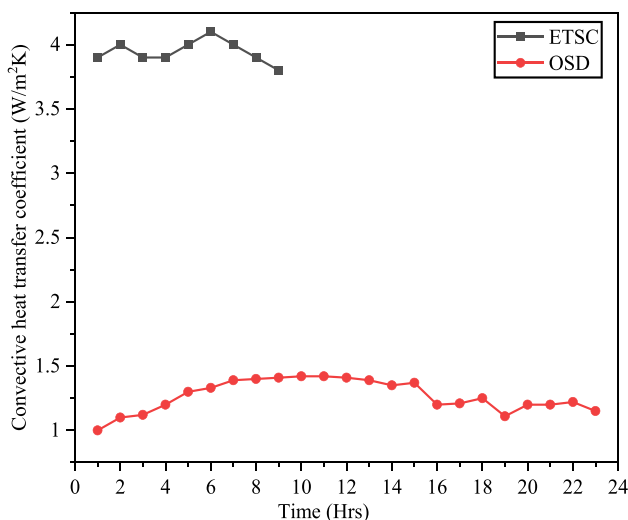| Drying method	C	n
ETSC	1.29	0.126
OSD	0.81	0.062

Convective heat transfer coefficient

Regression analysis was used to evaluate the constants in the convective heat transfer equations. By substituting the values of C and n, the value of h_c can be evaluated. Table 6 lists the constants in the ETSC and OSD drying modes. Higher values of the convective heat transfer coefficient increase drying rates of the product. The average value of heat transfer coefficient in ETSC and OSD modes is 4.1 and 1.3 W/m^{2}K respectively. The results are also in good agreement with those published by other researchers (Kumar et al. 2023) and (Sansaniwal et al., 2023). The change in convective heat transfer coefficient with drying time is shown in Fig. 11.

Conclusion

An experimental investigation was carried out with the use of ETSC connected indirect solar dryer to dry Krishna tulsi leaves. Further energy, exergy, environmental, and economic analyses of the drying system were also performed. The research yielded the following conclusions;

A temperature of 40 °C is found higher in the collector outlet than the atmospheric temperature. The temperatures entering the drying chamber range between 60 and 70 °C, indicating that the device is capable the required drying temperatures

The developed ETSC dryer takes 8 h to dry Krishna tulsi leaves, whereas it takes 22 h in the OSD. According to the results, the ETSC dryer has a significantly shorter drying time than the OSD.

The exergy inflow and outflow of the ETSC and the drying chamber change from 200–1400 W, 0–60 W, and 0–50 W to 0–14 W, respectively. The ETSC and drying chamber exergetic efficiency vary from 0.6–4% and 2–85%, respectively. The overall drying process has an exergetic loss of between 0 and 40%.

The collector and dryer efficiencies vary from 42–75% and 0–18%, respectively, with solar radiation varying from 720 ± 20 W/m^2. Dryer sustainability indices are calculated. The values of the sustainability index, waste exergy ratio, and improvement potential are 0–18, 10–1, and 0–10, respectively.

The value of the embodied energy of the fabricated ETSCS dryer is 349.874 kWh.

For the dryer's anticipated 20-year lifespan, the CO_2 mitigation and earned carbon credit values are 13.2 tonnes and INR 10,894 to 43,576, respectively. This parameter shows the adoption of solar dryers for environmental sustainability toward a greener world.

The payback period for the proposed dryer is estimated to be 0.4 years.

The developed dryer can be suitable for drying products that are sensitive to direct solar radiation. The results of the current research can broadly be useful in the applications of drying Krishna tulsi leaves in the pharma industry for use in the medical field.

Fig. 11 Change in the convective heat transfer coefficient with the drying time

Declarations

Ethical approval Hereby, I declare that the following statements: (1) This material is the authors' own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors' own research and analysis in a truthful and complete manner. (4) The paper properly credits the meaningful contributions of co-authors and co-researchers. (5) The results are appropriately placed in the context of prior and existing research. (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference. (7) All authors

have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

Consent to participate The authors read and understand the guidelines for participation and agreed to participate.

Consent for publication The authors have agreed to have the paper published by Springer.

Competing interests The authors declare no competing interests.

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