Exergy analysis of an indirect type solar dryer integrated with heat pipe technology

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Abstract. Food drying processes require a sizable amount of energy, which contributes significantly to the carbon emissions. Therefore, the integration of sustainable energy in the food processing industries is essential to achieve net zero carbon emissions. This study aims to develop an indirect-type natural convection solar dryer integrated with heat pipes, incorporating exergy performance analysis of its drying chamber. Exergy analysis was conducted to ascertain the type and extent of exergy losses that occur throughout the solar drying process. The estimated maximum instantaneous exergy inflow and outflow were 1.248 W and 0.619 W, respectively, for the drying chamber. The overall exergy efficiency of the drying chamber is 32.49 percent. The average loss of exergy was evaluated to be 0.274 W. The corresponding Waster Energy Ratio, Improvement Potential, and Sustainability Index are 0.68, 0.19 W, and 1.48, respectively.

Keywords: Solar dryer, Heat pipe, Nendran banana, Exergy analysis, Sustainability Indicators

1 Introduction

Solar drying is an economical eco-friendly solution to the high energy cost and Carbon emissions caused by the conventional drying of agricultural products[1]. To evaluate the operational performance of solar drying systems, thermodynamic assessment methods are commonly employed [2]. Exergy is the qualitative way of investigating the systems, whereas energy analysis is the quantitative analysis[3]. Exergy can be defined as the maximum theoretical work obtainable when a system reaches equilibrium with its surrounding

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environment [1,2]. Owing to this characteristic, exergy analysis serves as an effective tool for identifying performance losses, improving system efficiency, and optimizing dryer configurations by simultaneously considering both system parameters and environmental interactions. [2]

Various researchers have reported the exergy performance of the different type solar dryers for different agricultural products[1–7]. Atalay et al. [1] experimented with the direct-type solar dryer containing thermal energy storage (TES) system using pebbles as sensible storage material (packed bed) for 5 mm orange slices. The experiment was carried out both during sunshine time (using solar radiation for drying) and during non-sunshine period (using packed bed TES)[1]. The exergy efficiency in daylight period ranged from 50.18 percent and 66.58 percent, and while using TES, it increased as it ranged between 54.71 percent and 68.37 percent[1]**.** Similarly, Atalay et al. [2] experimented with a large-capacity solar dryer for drying strawberries but with PCM-based latent heat TES system. The exergy efficiencies ranged from 70 and 76 percent and 62.80 and 69.59 percent for daytime and nighttime drying, respectively[2]. Brahma et al. [3] analyzed an indirect solar dryer integrated with different phase change materials placed in the collector section and reported significant variations in exergy efficiency depending on the PCM used. Hatami et al. [4] estimated the exergy efficiency of an indirect-type solar dryer. The results indicated that the maximum exergy efficiency would be 22 percent when the critical moisture ratio was 0.75demonstrated that the exergy efficiency of an indirect solar dryer strongly depends on the critical moisture ratio of the product. Kesavan et al. [6] highlighted that the temperature difference between the inlet and outlet air streams plays a decisive role in determining the exergy efficiency of the drying chamber. A triple-pass solar dryer was used for drying sliced potato, and the mean exergy efficiency was obtained as 53.57 percent[6]. Additional studies have also emphasized that exergy performance varies with product type, dryer configuration, and airflow conditions [8,9]. Despite these advances, research on heat pipe-assisted indirect solar dryers remains limited. Heat pipes offer greater heat transfer performance, minimal thermal resistance, and nearly isothermal operation, which can significantly enhance dryer efficiency. Therefore, the present study investigates the exergy performance and sustainability indicators of a heat pipe-integrated indirect solar dryer used for drying Nendran banana slices under natural convection.

2 Methodology

2.1 Experimental setup

The experimental system consists of a solar air collector, heat pipes, a drying chamber, and a temperature monitoring unit, arranged in a configuration comparable to indirect solar dryers reported in previous studies [7,10]. All of these parts are mounted on a main frame with wheels for ease of portability. The detailed component descriptions are given in **Table 1**. The clearance between the glazing cover in the bottom side and absorber plate is 7 cm. The solar collector's all four sides and the bottom portion were insulated to minimize heat loss. Three circular openings of 24 mm diameter are made on the one side of the solar collector for inserting heat pipes. The upper part of the chamber is made like a trapezoidal dome. Inside the chamber, 3 trays are placed at intervals of 8 cm between them.

Table 1. Detailed specifications of the main parts of the dryer

S.No	Components of HP-ISD	Material used	Dimension/Specification
1.	Solar collector outer frame	MS sheet	100.5 cm × 50.5 cm × 15 cm
2.	Absorber plate	Aluminium	100 cm × 50 cm × 3 mm

3.	Insulation	Glass wool	Thickness - 5 cm
4.	Glazing cover	Borosilicate glass	Double layer, each having 4 mm thickness with a 2 cm gap b/w layers
5.	Drying chamber	Plywood	Thickness – 10 mm, 45 cm × 35 cm × 65 cm
6.	Drying tray	Stainless steel mesh 304	42.5 cm × 32.5 cm, wire thickness – 0.5 mm with 10 mm gap
7.	Heat pipes	Copper tube	Outer diameter – 19 mm, Wall thickness – 0.5 mm, Length – 2 m
8.	Wick structure	Copper screen	100 mesh/inch
9.	Fins (Heat pipe – Condenser section)	Copper sheet	10 cm × 10 cm × 0.5 mm, Interval b/w fins – 13 mm, No.of fins – 20

To enhance heat transfer between the absorber plate and heat pipes, the evaporator sections are slightly flattened to increase the contact surface area. Fins are attached to the condenser section of the heat pipes to improve convective heat transfer within the drying chamber. The complete assembly is mounted on a galvanized iron frame, and the solar collector is inclined at an angle of 10°. A photographic view of the experimental setup is presented in **Fig 1**.

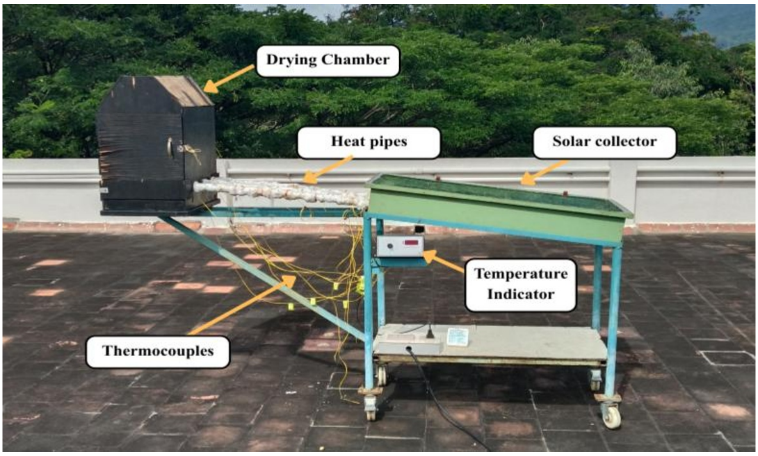


Fig 1. Experimental system of the dryer

Temperature measurements across the system are obtained using twelve K-type thermocouples (T1–T12) connected to a multi-channel temperature indicator. The thermocouples are positioned at critical locations including the absorber plate, heat pipe sections, drying trays, and ambient environment, enabling detailed thermal profiling of the dryer during operation.

2.2 Experimental procedure

The field test was carried out on a sunshine day of the month of July at the location 10°56'02.5"N 76°44'43.8"E. Nendran banana slices of 2 mm thickness weighing a total of 1 kg is uniformly placed in three trays, with the top, middle, and bottom trays having 330 g, 330 g, and 340 g, respectively. Temperature at T1 to T12, weight of the samples, Relative humidity inside and outside the drying chamber were recorded at one-hour intervals. Drying experiments were performed between 09:30 AM and 04:30 PM until the samples attained constant moisture content. Solar irradiance was measured using a calibrated solar power meter, while relative humidity was monitored using a digital humidity sensor. All instruments used in the experiment were selected to ensure adequate accuracy and repeatability of measurements.

2.3 Exergy Analysis of Drying Chamber

To perform the exergy analysis, steady-state operating conditions were assumed for each measurement interval. The thermodynamic formulations used in the analysis were adopted from established literature **[3,6]**.

2.3.1 Exergy Input

The exergy input to the drying chamber was determined following the thermodynamic approach reported in earlier studies **[3,6].**

$$Ex_{in\_d} = \dot{m}C_{pa}[(T_{di} - T_a) - T_a ln(T_{di}/T_a)] \tag{1}$$

Here, $\dot{m}$ is the mass flow rate of the air medium inside the chamber; C_{pa} is the specific heat capacity of the air (1.005 kJ/kg K). Since, this is a natural convection type drying, the air flow occurs only due to the stack effect (temperature and density difference between outside and inside air). So, the mass flow rate was determined based on the stack effect (chimney effect) formula for buoyancy-driven flow.

$$\dot{m} = \rho C_d\, A \sqrt{2gH \frac{\Delta T}{T_{avg}}} \tag{2}$$

C_d is the discharge coefficient through the chimney opening (here, C_d was taken as 0.65 which is normal for natural convection), A is the area of chimney opening (A= 0.0004m^2) , H is the height of the chimney (H= 0.65m) from the bottom of the drying chamber, ΔT is the maximum temperature gradient between the inside and outside (hot and cold side) of the drying chamber that causes the airflow, T_{avg} is the mean of temperature of inside and outside of the drying chamber, and ρ is the density of the air medium (here taken as 1.0731 kg/m^3).

2.3.2 Exergy Output

The exergy output to the drying chamber was determined following the thermodynamic approach reported in earlier studies **[3,6].**

$$Ex_{out\_d} = \dot{m}C_{pa}[(T_{do} - T_a) - T_a ln(T_{do}/T_a)] \tag{3}$$

T_{di} and T_{do} denote the inflow and outflow temperatures of the drying chamber. Here, for calculation, the heat pipe condenser's mean temperature (average of T7, T8 and T9 thermocouple values) was taken as the inlet temperature and the temperature at the last tray (T10) was taken as outlet temperature.

2.3.3 Exergy Efficiency

Exergy efficiency represents the ratio of useful exergy utilized for moisture removal to the exergy supplied by the drying air. It provides insight into the thermodynamic effectiveness of the drying chamber and was computed following the methodology described in previous investigations [7,9].

$$\eta_{Ex\_d} = \frac{Ex_{out\_d}}{Ex_{in\_d}} = 1 - \frac{Ex_{loss}}{Ex_{in\_d}} \qquad (4)$$

2.4 Sustainability Indicators

Sustainability indicators derived from exergy analysis were employed to assess the environmental and thermodynamic performance of the drying chamber. These indicators provide quantitative insight into the extent of useful energy utilization and the potential for further system improvement. In this study, the Sustainability Index (SI), Improvement Potential (IP), and Waste Energy Ratio (WER) were selected as key performance metrics, as recommended in previous exergy-based assessments of solar drying systems [9]**,**

$$SI = \frac{1}{1-\eta_{Ex\_d}} \qquad (5)$$

$$IP = \left(1 - \eta_{Ex\_d}\right)Ex_{loss} \qquad (6)$$

$$WER = \frac{Ex_{loss}}{Ex_{in\_d}} \qquad (7)$$

3 Results and Discussion

3.1 Exergy Analysis of Drying Chamber

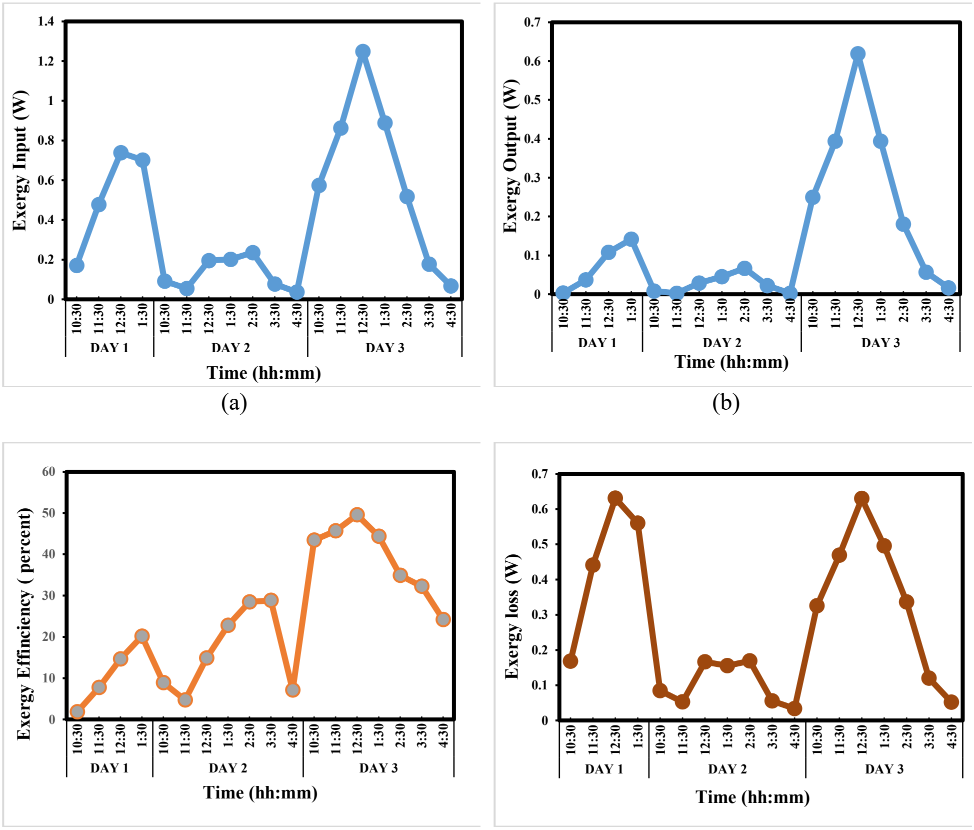
The drying test was carried out on continuous three days; the moisture content of banana slices was reduced from 60 percent (wb) to 10.7 percent (wb) after 15 hours of drying across these three days. The solar irradiation varies from 562 W/m^2 to 1088 W/m^2 during the experiment. On all days, the experiment started at 10:30 AM on the morning and on the first day the experiment got stopped on 01:30 PM due to dark cloudy weather, but continued up to 04:30 PM on day 2 and day 3. For the calculation purpose, the mean ambient temperature value of 35°C was used as standard temperature for all calculations. The temperature inside the drying chamber varies between 44°C and 76°C during the experiment. The average mass flow rate was estimated to be 0.00024 kg/s, which is far low compared to the other natural convection indirect solar dryers as reported by V.R.Mugi et al.[10] It was reported to be 0.044 kg/s [10]. So, the corresponding values such as exergy input, output, and efficiency are also far low while comparing with this study as tabulated in **Table 2.** Here, the mass flow rate was determined using the stack or chimney effect formula as mentioned in **Eqn. 2**. Though the mass flow rate is low for this study, it was a feasible value when considering the drying time which was 15 hours, the size of the drying chamber, and the size of the chimney opening.

3.1.1 Exergy Input

The exergy input was determined using the **Eqn. 1.** As seen in **Fig 2(a)**., the maximum exergy input to the drying chamber was 1.248 W at 12:30 PM on day 3 of drying. While the minimum exergy input was 0.0364 W at 04:30 PM on day 2. Average exergy input to the drying chamber was 0.407 W.

3.1.2 Exergy Output

The exergy output was determined using **Eqn. 3**. In **Fig 2(b)**., the maximum exergy output from the drying chamber was 0.619 W at 12:30 PM on day 3 of drying. While the minimum exergy output was 0.003 W at 11:30 AM on day 2. Average exergy output from the drying chamber was 0.132 W. During peak solar hours (12:30 PM to 02:30 PM), the highest exergy values were observed, as the temperature gradient and available solar radiation are so high. Again, in the evening time the lower exergy values were observed.



(a)

(b)

(c)

(d)

Fig 2. (a) Exergy input vs time, (b) Exergy output vs time, (c) Exergy efficiency vs time (d)Exergy loss vs time

3.1.3 Exergy Efficiency

Fig 2(c). shows the instantaneous exergy efficiency of the drying chamber over time during the drying period and it was determined using **Eqn. 4**. The maximum exergy efficiency was recorded as 49.57 percent at 12:30 PM on day 2, which is comparable to trends reported for natural convection solar dryers. The average exergy efficiency on day 1, day 2, and day 3 are 13.86 percent, 19.89 percent, and 44.06 percent, respectively. The overall exergy efficiency of the drying chamber was 32.49 percent. It was determined by dividing the sum of all exergy output values by sum of all exergy output values. While comparing the performance of the drying chamber day-wise, it was a steady increase in exergy output, which is the effect of reaching steady state inside the drying chamber with a constant decrease in water content from the product.

3.1.4 Exergy loss

The exergy loss was estimated using **Eqn. 4**. In **Fig 2(d).,** the maximum exergy loss was 0.63 W, and the minimum exergy loss was 0.033 W while calculating discretely relative to time. The average exergy loss was evaluated to be 0.274 W.

3.2 Sustainability Indicators

The sustainability indicators such as Sustainability Index (SI), Improvement potential (IP), and Waster Energy Ratio were calculated using the **Eqn. 5, Eqn. 6, and Eqn. 7,** respectively. The corresponding values of sustainability indicators with respect to minimum, maximum and average exergy parameters are given in **Table 2**.

Table 2. Exergy Analysis parameters and Sustainability Indicators for the drying chamber

Parameters	**Current Study**			**V.R. Mugi et al. [10]**
	Max. Value	**Min. Value**	**Mean value**	**Mean Value**
Exergy input (W)	1.248	0.0364	0.407	24.19
Exergy output (W)	0.619	0.003	0.132	13.75
Exergy Efficiency (percent)	49.57	1.88	32.49	55.45
Exergy loss (W)	0.63	0.033	0.274	10.45
Sustainability Index	1.98	1.02	1.48	3.69
Improvement Potential (W)	0.54	0.03	0.19	5.21
Waste Energy Ratio	0.98	0.50	0.68	0.445

4 Conclusion

This study presented an exergy-based performance evaluation of a heat pipe-integrated indirect solar dryer operating under natural convection for drying Nendran banana slices. The results demonstrated that the drying chamber achieved a maximum instantaneous exergy efficiency of 49.57% during peak sunshine hours, with an overall average efficiency of 32.49%.

The average exergy input and output were determined as 0.407 W and 0.132 W, respectively, while the mean exergy loss was calculated as 0.274 W. Sustainability indicators such as the Sustainability Index, Improvement Potential, and Waste Energy Ratio further highlighted the scope for enhancing system performance by increasing airflow rate and reducing thermodynamic losses.

Overall, the findings confirm that integrating heat pipes into indirect solar dryers can improve thermal performance uniformity; however, further optimization of airflow conditions is required to enhance exergy efficiency and reduce drying time.

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