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Performance Evaluation of an Onsite-Fabricated Solar Dryer for Drying Rhizomes in Rural Bhutan

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Abstract

Post-harvest losses due to the unavailability of appropriate drying technologies poses a significant challenge to the preservation and marketability of agricultural products such as turmeric rhizomes in rural Bhutan [3]. This study evaluates the performance of an onsite-fabricated solar dryer with testing conducted at the Khengrig Numsum Cooperative (KNC) in Zhemgang which is in rural part of Bhutan. The dryer was fabricated on-site using locally available materials to minimize cost and provide an alternative to traditional open sun drying. The dryer was tested over a one-month period by drying turmeric rhizomes. Key parameters such as solar radiation, temperature, relative humidity, drying time and moisture content were monitored throughout the process. The dryer consistently maintained internal chamber temperatures 25- 300C higher than ambient conditions and reduced drying time while comparing to open sun drying. The final product achieved an average moisture content below 10% making it suitable for safe storage and market sale. The result demonstrates that the locally– fabricated solar dryer enhances drying efficiency, reduces contamination risk and improves product quality. This technology offers a viable and replicable solution for small house hold farmers and cooperatives in remote, off-grid regions of Bhutan to reduce post-harvest losses and add value to their agricultural produce.

Keywords— post-harvest; Drying; performance; sustainable; temperature; efficiency

1 Introduction

Agriculture plays a vital role in the livelihood of rural communities in Bhutan with turmeric (curcuma longa) being one of the important high-value crops cultivated in the southern and central regions including Zhemgang [2],[3], [5]. Despite its economic potential, turmeric farming in Bhutan faces significant post-harvest challenges, particularly in the drying phase. Traditional open sun drying methods are commonly practiced but are highly dependent on weather conditions, time-consuming, prone to contamination and often result in inconsistent product quality. Post-harvest losses caused by inefficient drying not only reduce the quality of marketable produce but also negatively impact the quality of key bioactive compounds such as curcumin [7], [8], [4]. These losses are particularly severe in remote areas like Zhemgang, where access to modern grid-powered drying infrastructure is limited. In such contexts, the introduction of decentralized, low-cost and sustainable drying technologies is essential to improve product quality, ensure food safety and enhance income opportunities for small household farmers.

Solar drying presents promising alternative to conventional methods, offering improved efficiency, faster drying rates and reduced spoilage without relying on electricity or fossil fuels. Locally-fabricated solar dryers can be tailored to specific community needs, using materials that are affordable and easily available in the local market. However, the performance of such dryers must be systematically evaluated under actual field conditions to ensure their effectiveness and adaptability. This study aims to evaluate the performance of a locally fabricated solar dryer designed and constructed at the KNC in Zhemgang, Bhutan. The dryer was built using simple design and cost-effective materials with a focus on reducing air leakage and optimizing air circulation without insulation. Turmeric rhizomes were used as the test crop and key parameters such as drying temperature, humidity, solar radia tion, drying time and final moisture contents were monitored throughout the process. The findings of this research are intended to support the broader adoption of solar drying technologies as a viable solution for post-harvest management in Bhutan's rural agricultural sectors.

2 Materials and Methods

2.1 Location and Climatic conditions

KNC is in Tingtibi, under Zhemgang District in the south-central region of Bhutan. It lies at approximately 27.140N latitude and 90.690E longitude at an elevation of 776 meters above sea level. Generally, experiencing subtropical to temperate climate, characterized by warm humid summers and mild cooler winters. Year-round temperature typically ranges between 150C and 300C, occasionally rising to as high as 400C during peak summer months.

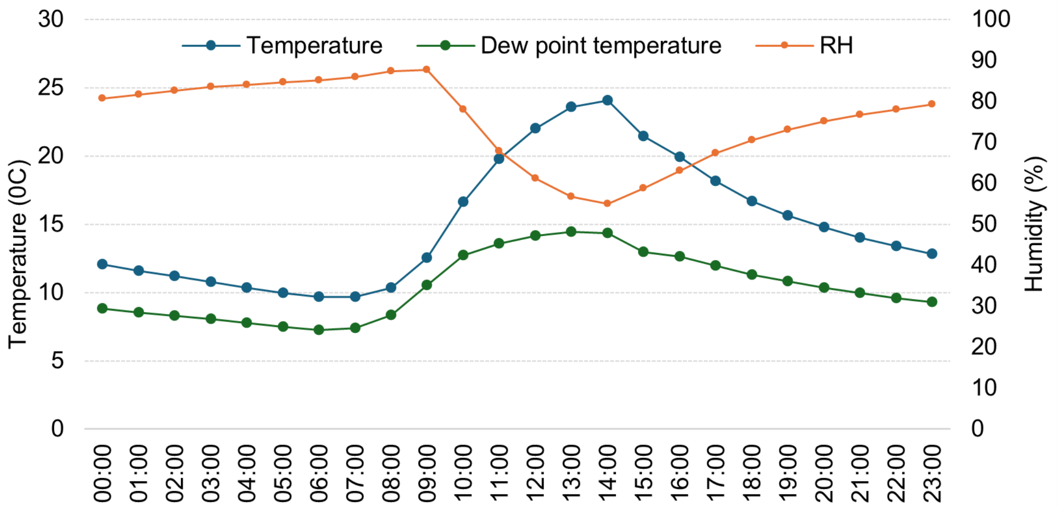

Figure 1: Site ambient condition

The Solar dryer was tested on site from 28 December 2024 to 28 January 2025 during which climatic data was also recorded and the monthly hourly averages as presented in Fig. 1. The test period was selected, since KNC typically receives turmeric from farmers toward the end of the year and begins processing it, drying the rhizomes and producing turmeric powder as the final product. Daily test were carried out between 9:00am and 2:30 pm, the time frame during which the site receives direct sunlight. The monthly half-hourly average solar irradiance as presented in Fig. 2

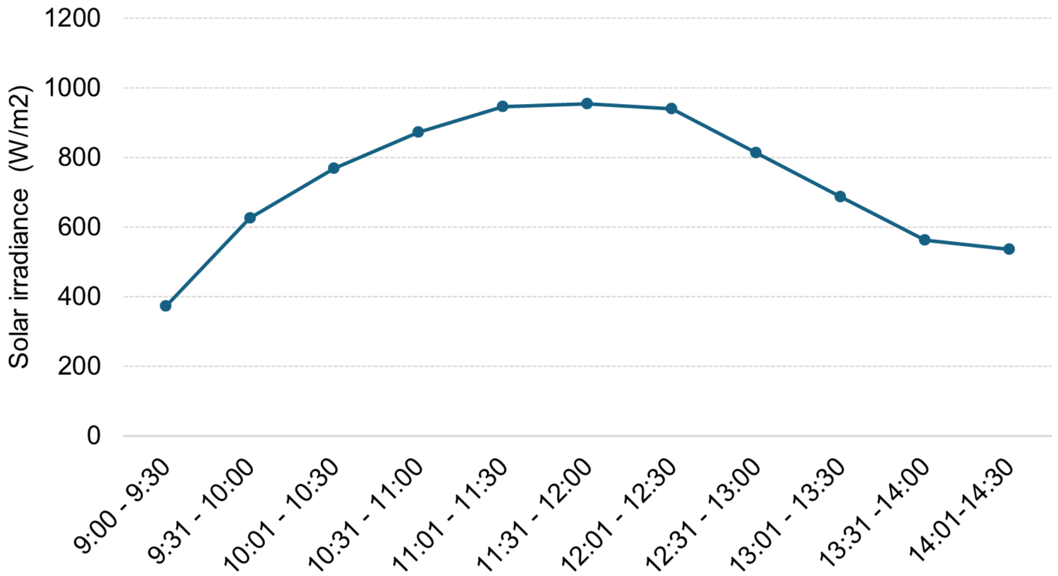

Figure 2: Solar irradiance at site

2.2 Description of solar dryer system

The solar dryer used in this study is an indirect-type cabinet dryer, designed in collaboration with University of Lund, Sweden and fabricated on-site at the KNC in Tingtibi, Zhemgang. The distinctive feature of this dryer is a heat exchanger positioned between the air inlet and outlet. The primary goal of the design was to develop a low-cost, energy–efficient and locally adaptable drying system using materials readily available in the region. The dryer was constructed without any insulation to simplify design and reduce cost, while special attention was given to minimizing air leakage to retain heat. Similar research has also been carried out in Nepal and Bhutan in collaboration with Lund University, Sweden [1]. The central concept of the research remains same and measuring tools used were also of same type, except that the dryer used in this study is a modified version of their dryer. The main components of dryer are as follows and shown in the Fig. 3 with gross dimensions:

- Solar collector unit: The solar collector is a flat-plat type, covered with standard glass to capture solar radiation and heat the air inside. The base absorber is a 2 mm thick mild steel sheet painted black for maximum heat absorption. The collector forms the top part of the drying chamber, with its surface inclined at 35– 400 to the base of dryer to optimize solar gain during the winter season.

- Drying Chamber: The drying chamber is a triangular wooden box with internal trays arranged in two columns, each containing two and three triers of trays respectively to ensure efficient airflow between the trays. The frame is built using locally available timber and plywood, providing both structurally stable and cost effectiveness. The bottom parts of trays are attached with fine wire mesh to support the turmeric rhizomes while drying as well as to ensure uniform air circulation.

- Heat Exchanger:The bottom part of the drying chamber houses a heat exchanger that separates the cold air entering the chamber from the hot air exiting it. Its main purpose is to preheat the incoming air using the heat from the outgoing air, thereby improving thermal efficiency. The detailed part of heat exchanger is as shown in the Fig. 4.

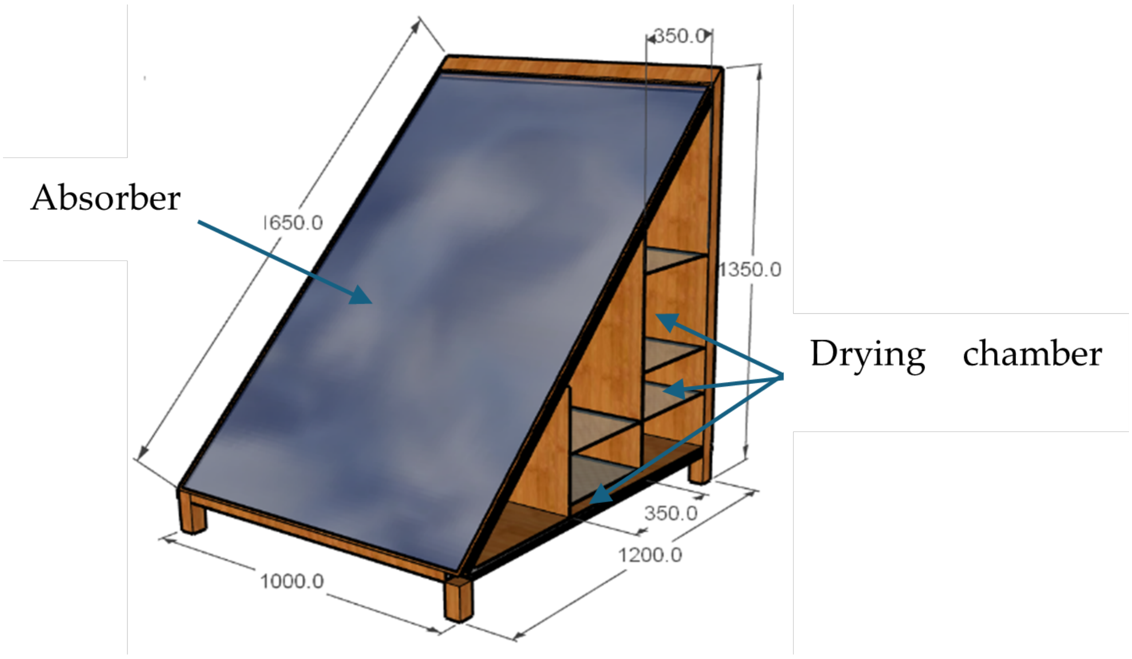

Figure 3: Dryer details with gross dimensions

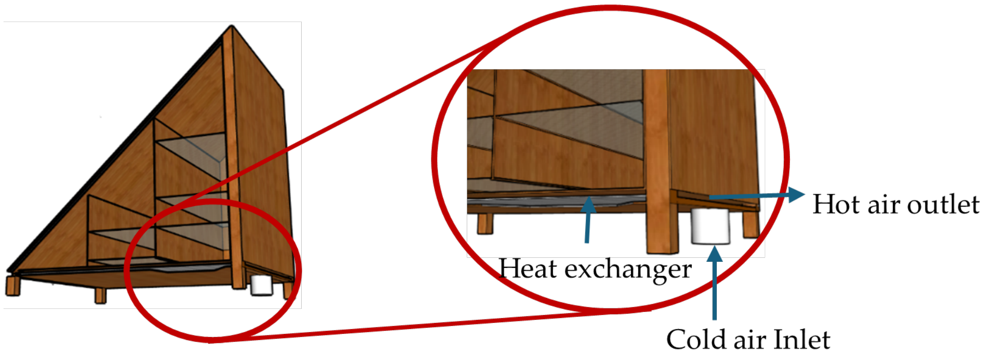

Figure 4: Exploded view of heat exchanger

- Air circulation system: The dryer operates on a forced circulation system with both the air inlet and exhaust located at the bottom of the chamber. Ambient air is drawn in through the inlet using a small-capacity AC or DC exhaust fan and directed into the solar collector unit, where it is heated. The heated air then rises to the top of the collector and is forced into the drying chamber flowing downward. An additional AC or DC fan is installed at the partition between the two compartments to enhance air circulation inside the chamber. The partition itself is perforated to allow airflow from the right to the left compartment. From the left compartment, the air moves toward the heat exchanger, where it preheats the incoming ambient air before it enters the collector. The detail air passage of the system as shown in the Fig 5.

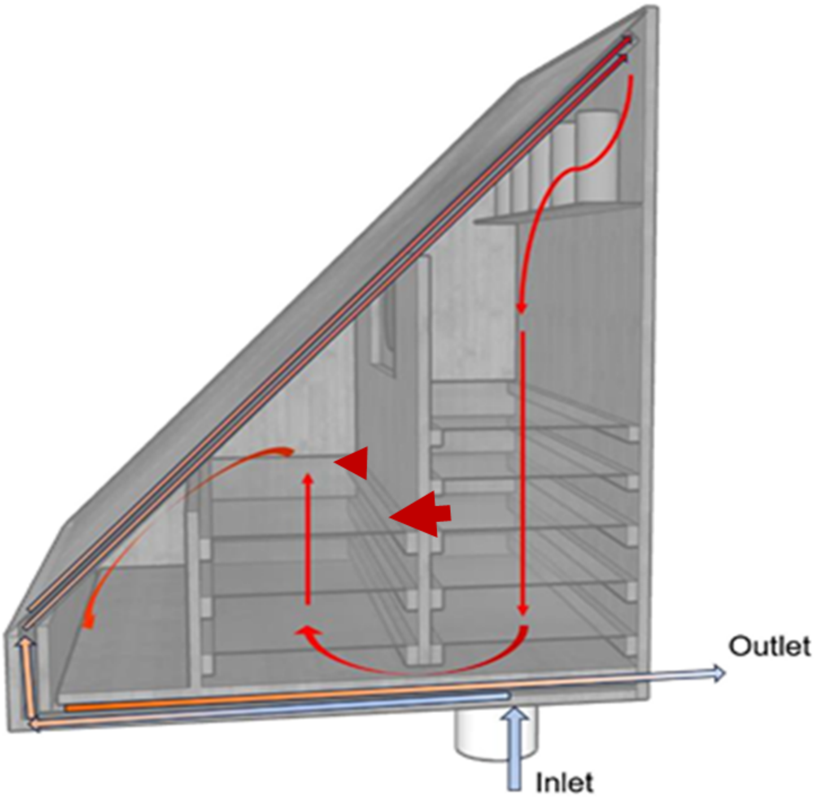

Figure 5: Anticipated air flow pattern (photo credit-Lara Constanze Müller, Lund University)

2.3 Dryer Materials and overall cost estimate

All materials were obtained from nearby local hardware stores to ensure reproducibility. The materials and its cost estimate as tabulated in Table 1.

Table 1: Material estimation and costing

Sl. No.	Materials specification	Quantity	Unit	Rate (Nu.)	Amount (Nu.)
1	Plywood, L (8') W (4') T (20mm thick)	4.00	pieces	1500.00	6000.00
2	Nails, 1 and half inch	1.00	kg	100.00	100.00
3	Fevicol	1.00	kg	260.00	260.00
5	PGI sheet, 9' x 3', 1.5 mm thick	1.00	piece	1530.00	1530.00
6	Window glass L (1.7m) W (1.2) T (5mm)	21.50	Sq.ft	60.00	1290.00
7	Enamel paints, black	1.00	kgs	195.00	195.00
8	Paint brush	1.00	No.	100.00	100.00
9	AC Exhaust fan, smallest diameter (150 mm or less)	2.00	No.	2000.00	4000.00
10	Silica sealant	2.00	Tubes	700.00	1400.00
				Material cost	14875.00
				Labor cost (3 persons, 2 days)	7800.00
				Overall cost (Material + Labor)	22675.00
				Cost in USD (1 USD = 85 Nu.)	266.76

To maintain cost effectiveness and simplicity, no insulation and complex controls were used. Instead, more focus was placed on ensuring good air circulation and minimizing heat losses through leakages.

2.4 Experimental procedure and instruments used

2.4.1 Sample preparation:

Fresh turmeric sliced in 2- 3 mm thick provided by the KNC as test material for feeding into the dryer. The thickness is maintained for consistency in drying, as shown in Fig. 6.

Figure 6: Freshly sliced sample

2.4.2 Drying process:

Freshly sliced rhizomes were dried from 9:00 am to 2:30 pm for the time during which the site receives direct solar radiation. The test was conducted for a month long. Each batch consisted of approximately 5– 7 kg of sliced turmeric, loaded onto a tray. Drying was continued on consecutive days until the desired moisture content was achieved. The moisture level was verified through physical inspection by an experienced staff of KNC who produces turmeric powder for export, as shown in Fig. 7.

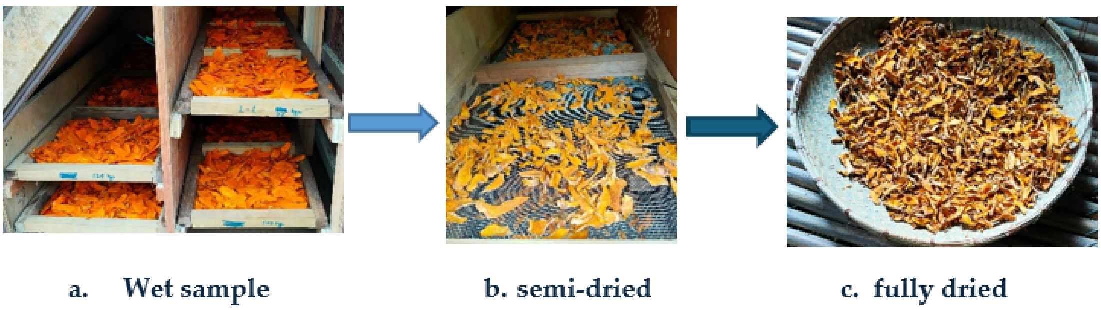

Figure 7: Fresh to dried product

2.4.3 Data collection:

All required parameters, including ambient conditions, solar radiation, temperature and humidity of the drying chamber, were monitored and recorded throughout the testing process. Temperature measurements were taken at fifteen different points in the dryer using thermocouples labeled T1 to T15. Five thermocouples were placed inside the drying chamber, one on each of the five shelves. Three thermo couples were installed at the absorber inlet, the absorber outlet and the exhaust, respectively, and an additional thermocouple was placed at the dryer inlet. Global solar radiation was measured by maintaining the same inclination as the solar collector. The detailed locations of the thermocouples, sensors and instruments used are shown in Fig. 8 and in the Table 2 respectively. Relative humidity was measured by placing a humidity sensor inside the chamber. All thermocouples, the pyranometer and the humidity sensor were connected to Campbell Scientific data logger for continuous recording. To record the ambient conditions at the site, a USB-type data logger was used to measure the temperature, humidity, and dew point temperature.

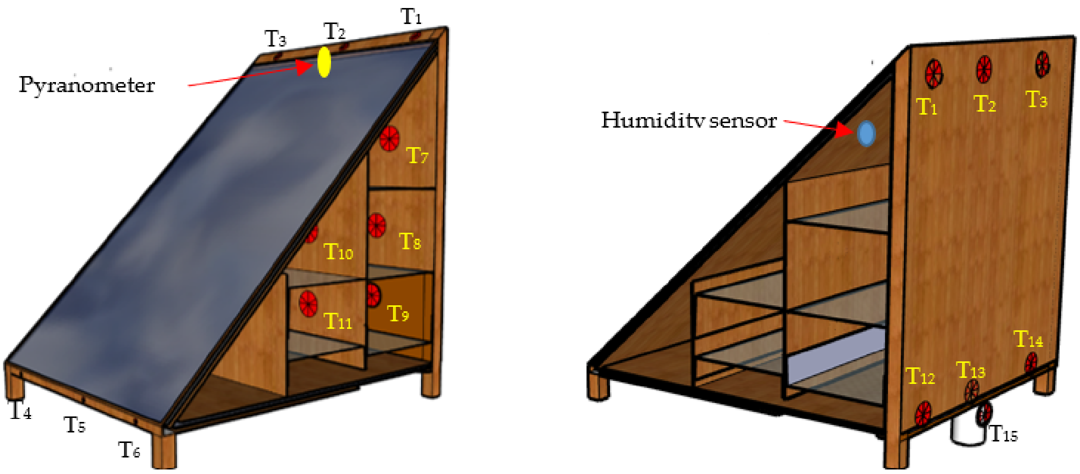

Figure 8: Sensors location on the dryer

Table 2: Instrument used for measuring parameters

Parameter	Instruments	Accuracy
Temperature	T-type thermocouple	±1°C
Air velocity	Anemometer (Hotwire)	±0.1 m/sec
Digital logger	Campbell Scientific (CR 1000)	–
Extension logger	Campbell Scientific (AM 16/32)	–
Solar radiation	CR11	±5
Humidity sensor		
Weighting balance		

2.5 Mathematical Representation

All the mathematical models used to describe the drying kinetic are represented under this section are same as those applied in the previous research conducted in Nepal and Bhutan, since the central idea remains the same except the design of the dryer [7].

2.5.1 Heat exchanger:

The energy equation (equation 1) give the amount of energy the cold air receives from the heat exchanger:

$$Q_{\text{Th,cold}} = \dot{m}_a \, c_p \left(T_{\text{cold,out}} - T_{\text{cold,in}}\right) \tag{1}$$

Where mass flow rate, specific heat capacity, cold-side outlet temperature, and cold-side inlet temperature are represented by $\dot{m}_a$, c_p, $T_{\text{cold,out}}$, and $T_{\text{cold,in}}$, respectively.

Similarly, the energy equation of the hot side is given by (equation 2).

$$Q_{\text{Th,hot}} = \dot{m}_a \, c_p \left(T_{\text{hot,in}} - T_{\text{hot,out}}\right) \tag{2}$$

Where hot-side inlet and hot-side outlet air temperatures are denoted by $T_{\text{hot,in}}$ and $T_{\text{hot,out}}$, respectively.

The maximum possible heat transfer in a flat plate heat exchanger is given by Equation (3).

$$\dot{Q}_{\text{max}} = \dot{m}_a \, c_p \left(T_{\text{hot,in}} - T_{\text{hot,out}}\right) \tag{3}$$

Here, the cross-sectional area of the collector and the solar intensity are denoted by A_c and I_t, respectively.

The effectiveness of the heat exchanger is defined as the ratio of actual heat transfer to the maximum possible heat transfer in the heat exchanger. The interesting aspect of Equation (2) and Equation (3) is that the effectiveness on the hot and cold sides must be equal under ideal conditions, which do not occur in the presence of leakage. In such a scenario, the leakage occurring in the system can be estimated. At the same time, the specific heat capacity of air on both sides is assumed to be the same.

$$\varepsilon_{\text{cold}} = \frac{\dot{m}_a c_p \left(T_{\text{cold,out}} - T_{\text{cold,in}}\right)}{\dot{m}_a c_p \left(T_{\text{hot,in}} - T_{\text{cold,in}}\right)} \tag{4}$$

2.5.2 Solar collector

The heated air leaving the collector carries useful thermal energy given by equation below:

$$\dot{Q}_{\text{useful}} = \dot{m}_a \, c_p \left(T_{\text{abs,out}} - T_{\text{abs,in}}\right) \tag{5}$$

Where the mass flow rate of air, specific heat of air, absorber inlet air temperature, and absorber outlet air temperature are denoted by $\dot{m}_a$, c_p, $T_{\text{abs,in}}$, and $T_{\text{abs,out}}$, respectively.

The thermal efficiency of the absorber is the ratio of thermal energy collected by the air leaving the absorber to the incident solar energy on the tilted surface over a particular period. The thermal efficiency of the solar collector at any time t is given by the equation below:

$$\eta_{c,t} = \frac{\dot{Q}_{\text{useful}}}{A_c I_t} \tag{6}$$

Here, the cross-sectional area of the collector and the solar intensity are denoted by A_c and I_t, respectively.

2.5.3 Moisture content and drying rate

The initial and final moisture content of turmeric rhizome is determined by using the standard oven drying method:

$$\text{Moisture content (\%)} = \frac{w_i - w_f}{w_i} \times 100 \tag{7}$$

Where: w_i = initial weight of the sample and w_f = final weight of the sample

The drying rate is the amount of moisture evaporated from the product over a fixed time interval per unit area. The sample weight measured at intervals of 5.5 h is used to evaluate the drying kinetics under constant airflow conditions. The drying rate for a time interval Δt is calculated using the equation below:

$$D_r = \frac{m_t - m_{t+\Delta t}}{\Delta t} \tag{8}$$

Where the sample masses at time t and $t + \Delta t$ are represented by m_t and $m_{t+\Delta t}$, respectively, over the measurement interval Δt. This study considers the initial area of the fresh product to remain constant throughout the test.

3 Results and Discussions

3.1 Solar Intensity and Temperature data

As mentioned in Section *Description of Solar Dryer System*, the dryer is uninsulated and operates with a constant airflow rate of approximately 2 m^3/min, supplied by a small exhaust fan attached to the inlet pipe. An average of thirty-two days of recorded data shows the variation in solar irradiance, drying chamber temperature, and ambient temperature for a daily drying period of 5.5 hours, as shown in Fig. 9.

At the site, it is observed that the solar irradiance follows a parabolic pattern, increasing until noon and decreasing in the afternoon. The drying chamber temperature shows a similar trend. However, the ambient temperature varies between 14°C and 24°C. The variation in dryer performance is mainly influenced by the intensity of solar irradiance under constant airflow conditions.

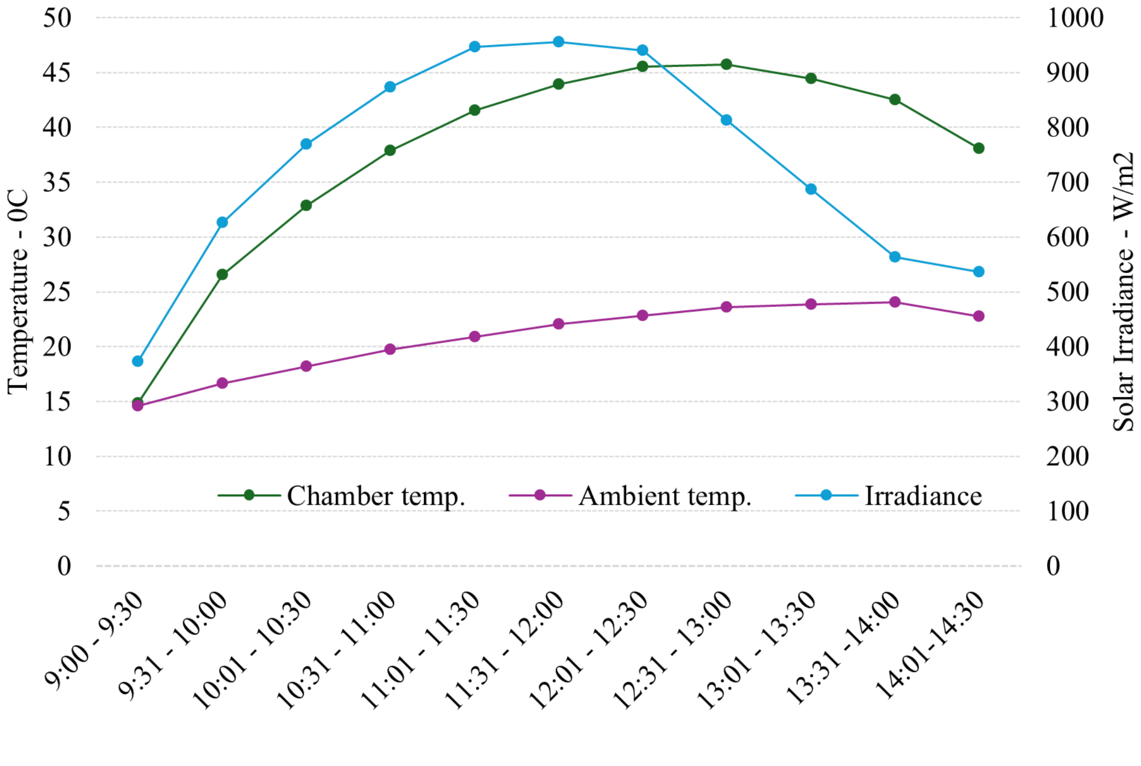

Figure 9: Half hourly average temperature of drying chamber and ambient, and solar irradiance

3.2 Solar air collector thermal efficiency

The performance of the solar air collector is analyzed based on the measured temperature different at the inlet and outlet of the collector. The inlet and outlet temperatures mainly vary with the intensity of solar irradiance, since the air flow rate in the system is kept constant. The variations in temperature and solar irradiance are shown in Fig.10. The maximum efficiency achieved by the solar collector is 74% at the peak hour of solar irradiance. Efficiency is calculated based on Eqn. 6.

At both the inlet and outlet of the solar air collector, three temperature sensors are installed to measure the temperatures accurately. Fig. 11 shows the temperature recorded by three different sensors designated as T1 to T6 at inlet and outlet of solar air collector. The efficiency of solar air collector will increase with the increase in temperature difference between inlet and outlet.

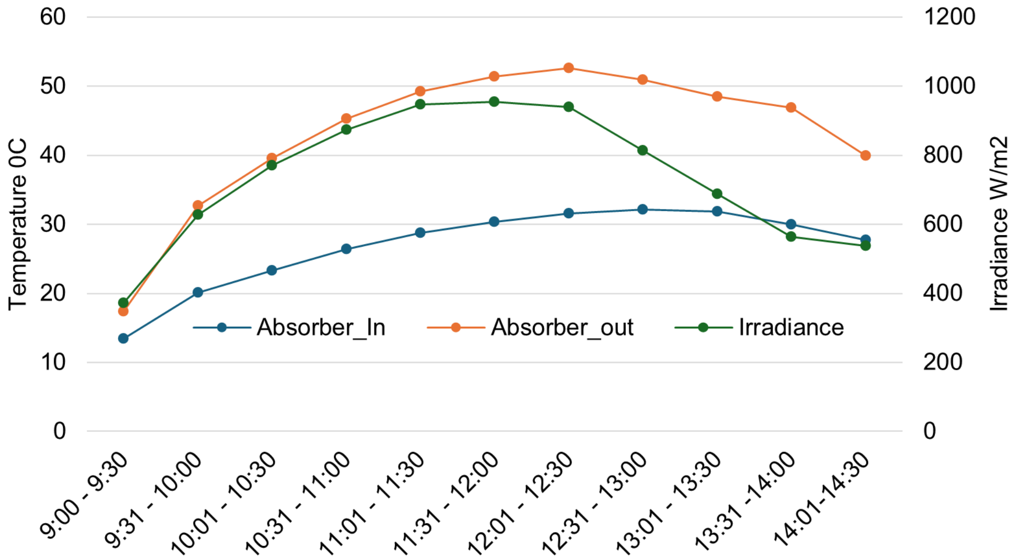

Figure 10: Average temperature of 3 sensors at absorber inlet and outlet, and solar irradiance

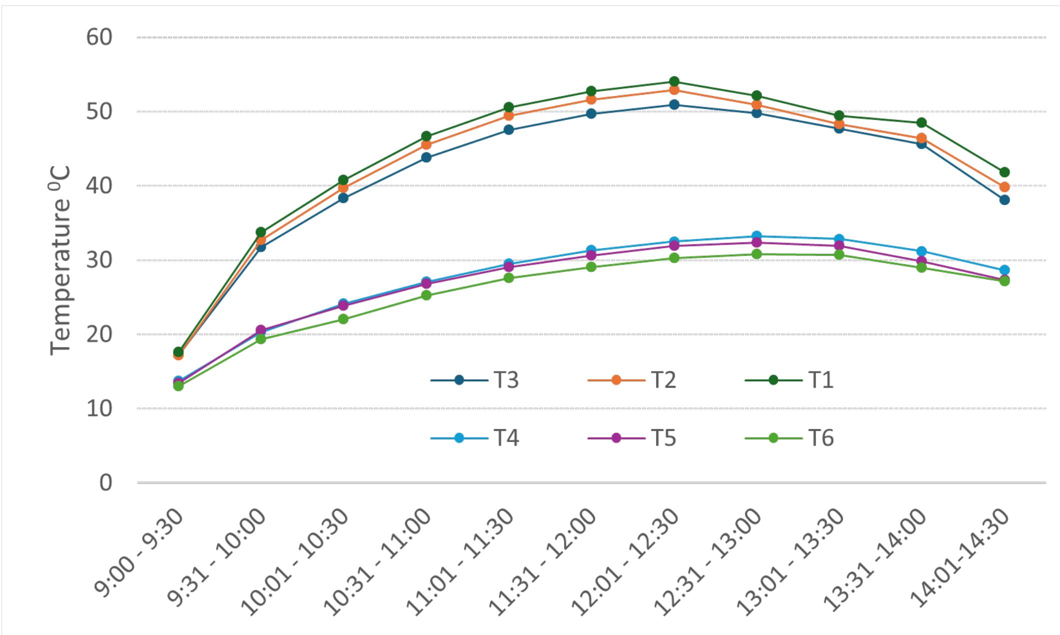

Figure 11: Average temperature recorded by 3 sensors at inlet and outlet of absorber

3.3 Drying Chamber

The main purpose of the solar drying process is to remove moisture from food by circulating heated air within the drying chamber. The temperature difference between the inlet and outlet of the dryer as well as the relative humidity over the time as shown in the Fig. 12. It can be observed from Fig. 12 that a greater temperature difference between the inlet and outlet corresponds to a lower relative humidity inside the chamber. The air inflow and internal circulation are maintained by an exhaust fan and an internal fan respectively.

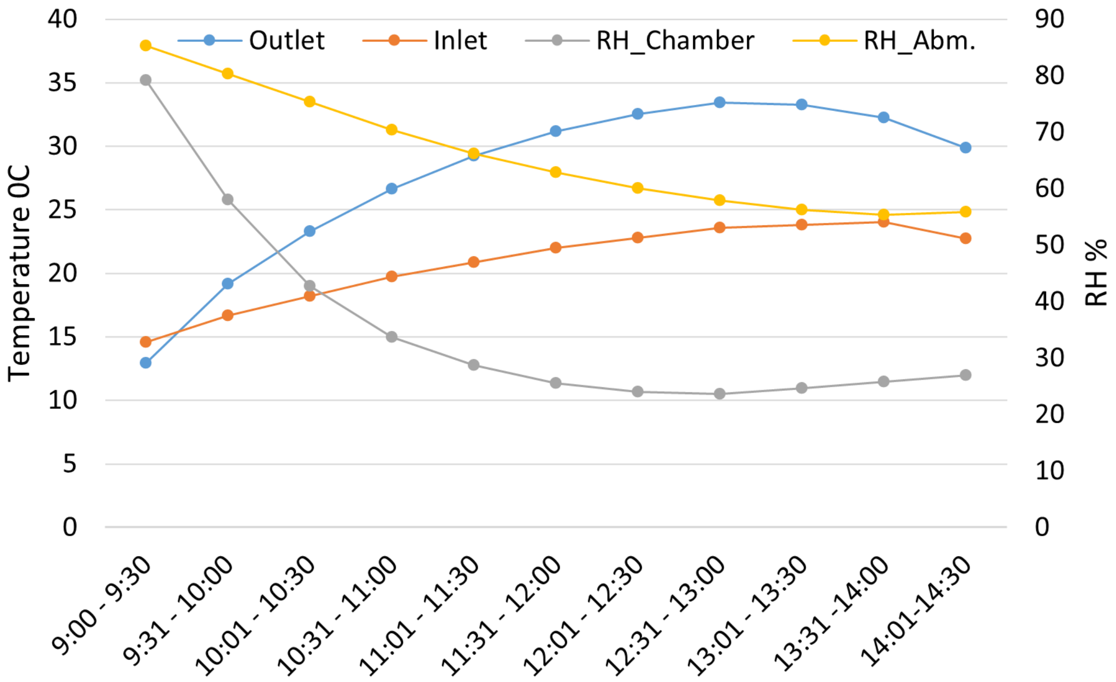

Figure 12: Humidity of drying chamber and ambient air and temperature of dryer inlet and outlet

3.4 Moisture content and drying rate

The moisture content of the samples are calculated using Eqn. 7 which is wet bases. Moisture removal from fresh turmeric was recorded over thirty two days and then averaged to determine the moisture removal during the daily five and a half hour drying period. The initial moisture content of fresh turmeric was considered to be 93% [6] and the drying in the solar dryer reduced the moisture by 66%. The results indicate that the dryer is able to maintain lower relative humidity and higher temperatures inside the drying chamber which enhances moisture loss as shown in Fig. 13.

3.5 Heat exchanger

The heat exchanger incorporated in the dryer preheats the air before it enters the absorber by utilizing the waste heat exiting the dryer. No further analysis is conducted here, since detailed literature is available from previous studies carried out in Bhutan and Nepal [**?**]. This study also uses the same concept of incorporating a heat exchanger in a modified dryer.

The temperature difference between the air inlet and outlet of the heat exchanger, as shown in Fig. 14, clearly demonstrates the performance of the heat exchanger. The maximum achievable temperature difference is 11.53°C during peak hours.

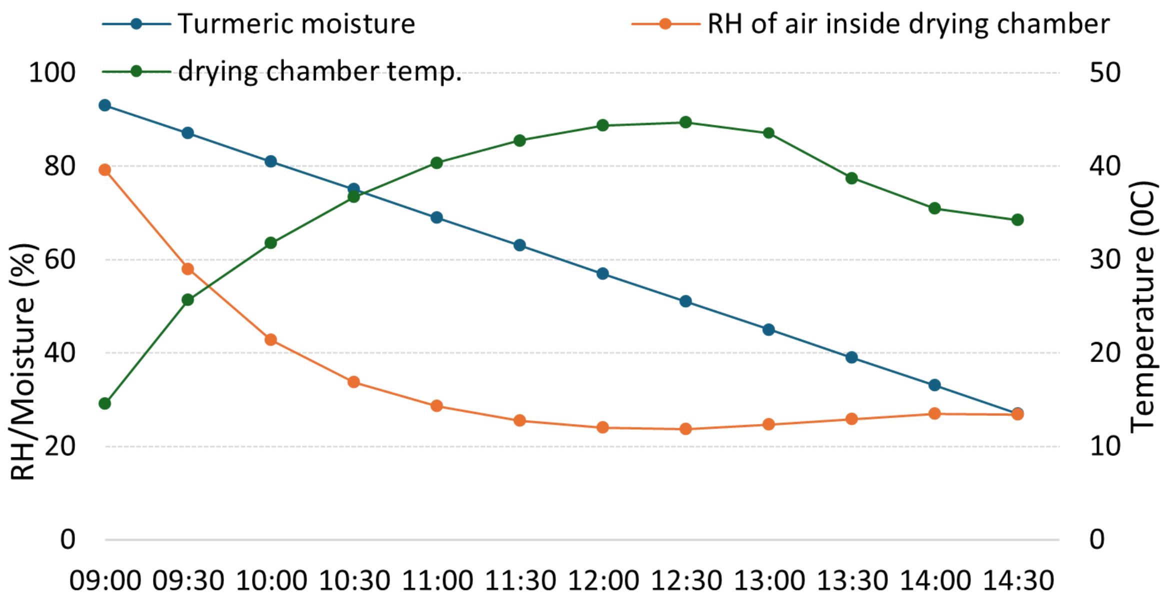

Figure 13: Sample moisture removal rate, drying chamber temperature and RH

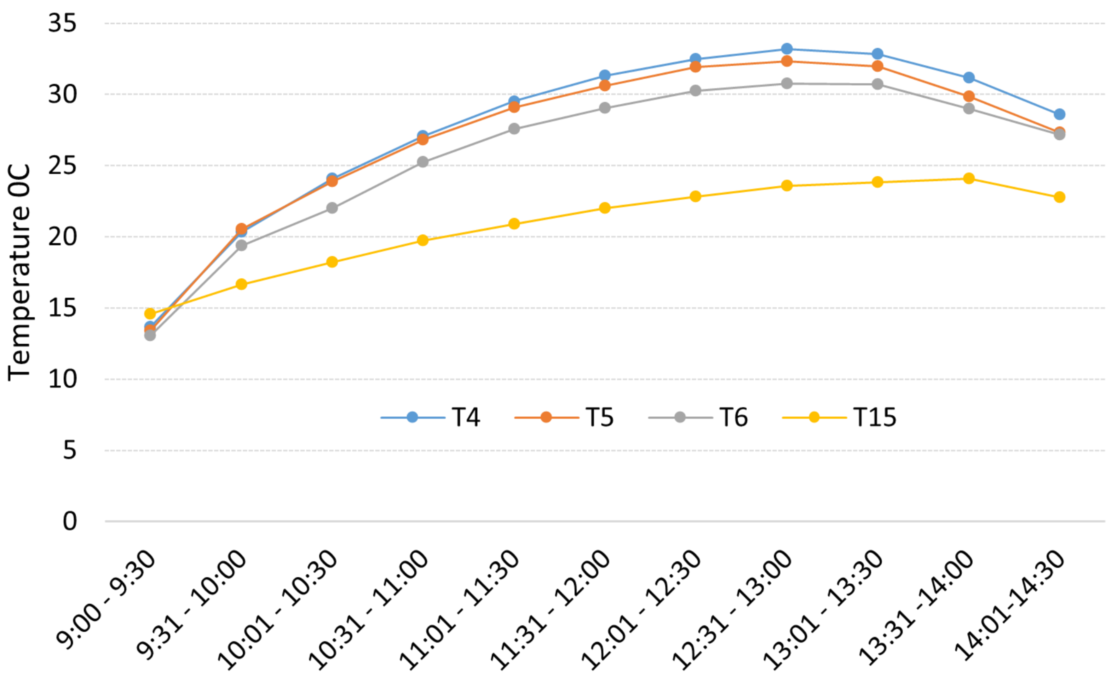

Figure 14: Showing temperature difference between exchanger inlet and outlet

4 Conclusion and Recommendation

The central aim of this research is to keep the solar dryer design simple and to analyze its performances enabling better understanding for reproducing a similar system at lower cost in rural areas. The design of the heat exchanger is not a primary focus here as detailed study on this aspect was conducted in Bhutan and Nepal in 2022 [7]. The conclusion and recommendations as follows:

- In the drying chamber, sufficient heat is generated to remove moisture from the product with the internal temperature reaching a maximum of 45.70C while the ambient temperature was 22.80C at noon. Due to this significant temperature differences, there is high chance of heat loss will occur through exposed plywood surfaces. The recommendation to minimize conductive heat loss, the exposed surface should be insulated with 25 mm thick expanded polystyrene, which is expected to reduce heat loss up to 80%.

- A significant temperature difference between the inlet and outlet of the solar collector is achieved with a maximum difference of 210C. Additionally, the air temperature within the collector is higher than the air temperature inside the drying chamber. To further increase the efficiency of the solar collector, it is recommended to optimize the collector's tilt angle based on the specific location. The tilt angle should ideally be adjusted to maximize solar energy collection during winter as processing usually takes place towards the end of the year.

- A significant temperature difference between the inlet and outlet of the solar collector is achieved with a maximum difference of 210C. Additionally, the air temperature within the collector is higher than the air temperature inside the drying chamber. To further increase the efficiency of the solar collector, it is recommended to optimize the collector's tilt angle based on the specific location. The tilt angle should ideally be adjusted to maximize solar energy collection during winter as processing usually takes place towards the end of the year.

- The results indicate that selecting the appropriate airflow is crucial for optimizing both heat ex changer and collector efficiencies. Although the temperature of the incoming air to the drying chamber is lower at higher flow rates, the greater energy carried by the increased airflow results in a faster drying rate. It is therefore, recommended to use a fan capable of supplying an air flow of 10 to 12 l/sec [1] and to maintain a constant flow rate for operational simplicity. Additionally, to improve air circulation within the chamber, a low-volume airflow fan can be used.

- The heat exchanger functions effectively in the dryer, as the results indicated an air temperature difference between the inlet and outlet is 3 to 100C over the drying period of five and half hours. Therefore, it is recommended to continue with same design heat exchanger but different materials with higher thermal conductivity to further increase the heat exchange rate.

The solar dryer was found to be effective compared to the conventional drying process as reported by experienced staff at KNC based on visual inspection of the product's color, aroma and texture. Moreover, the dryer is low-cost, easily fabricated from locally available materials and also readily available materials in the local market. In terms of complexity, it is simple and easily operable.

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