Design, Development and Performance Analysis of Solar-Electric Hybrid Dryer

Dechen Om[1], Phub Tshering[1], Sonam Tashi[1], Aita Bhadur Subba[2], Dileep. G[1*]

[1]Jigme Namgyel Engineering College, Dewathang, Samdrup Jongkhar, Royal University of Bhutan, Bhutan
[2]College of Science and Technology, Phuntsholing, Royal University of Bhutan, Bhutan
E-mail: dileepgopaiakrishna.jnec@rub.edu.bt*

Received: 14 April 2025; Revised :9 June 2025; Accepted:12 July 2025: Published 17 August 2025

Abstract

Bhutan, like any other mountainous country, is facing serious issue in food preservation. Conventionally, open air sun drying is preferred for drying as it is environment friendly and cost-effective. Meanwhile, open-air drying has a few drawbacks, including dust contamination, hardening, discoloration of products and longer drying time. This, in turn, led Jigme Namgyel Engineering College, Bhutan, and Lund university, Sweden, to design and develop an indirect solar dryer. Using solar dryers has many advantages, such as lowering dependency on electricity and fossil fuels and creating a cost-effective and environmentally friendly food preservation solution. Numerous designs were developed every year and many upgrades were done to improve the efficiency of the dryer by which the main intended objective is to make the drying rate even throughout the drying chamber. In the most of dryer model developed, the prime drawback of the dryer was the nonuniform drying rate among the trays in drying chamber owing to many factors such as the number of trays, weather contingencies, tray placements and duration of the drying time. In this study, we present design, development, and performance analysis of a solar-electric hybrid dryer with an integrated heating source that is used to supplement the heated air in sections of the dryer where the drying rate is relatively slow. It also helps maintain the air temperature inside the dryer during cloudy weather conditions. We designed our hybrid solar dryer to be as simple and inexpensive as possible, and better than open sun drying while also shielding the food items from the environment. This work provides useful insights into optimizing airflow, improving component efficiency, and practical recommendations for future advancements, supporting the sustainable preservation of agricultural products in Bhutan and similar regions.

Key Words: *Solar dryer, Food drying, Preservation, Renewable energy*

1. INTRODUCTION

A substantial amount of the world's food supply is affected by post-harvest food losses, which are caused by microbial spoiling, inadequate storage, physical damage, and ineffective handling throughout the supply chain. These losses lead to food insecurity, resource waste, and environmental damage. Post-harvest food losses occur when food quality and quantity decrease between harvest and consumption (Rahman et al., 2025). India ranks second in global fruit and vegetable production, yet only about 2% is processed, and 30 to 40% is wasted due to poor preservation infrastructure (Navale et al., 2015). In mountainous areas like Bhutan, where access to traditional preservation technologies is restricted by climatic and geographic factors, food preservation becomes a major challenge.

Open-air sun drying has historically been popular due to its ease of use, affordability, and environmental friendliness; however, open drying is highly weather-dependent and often unhygienic, exposing food to contaminants and pests. It leads to quality loss in terms of color, taste, and nutrition, and results in high spoilage rates, causing economic losses and food (ITZ Resources, 2025). Sun drying exposes food to sunlight, which can promote bacterial growth and cause chemical changes like fat oxidation, risking food safety and quality (Brown, 2024). Inadequate drying methods often result in mold and fungal infestations on crops, leading to reduced quality and lower export market value. Consequently, enhancing drying techniques could minimize food waste and boost farmers' income through better crop prices (Ruralis, 2024).

Solar drying has emerged as a clean, cost-effective, and eco-friendly solution for food preservation, significantly reducing reliance on electricity and fossil fuels. By extending the shelf life of fruits while retaining their natural flavor, color, and nutrients, solar dryers help maintain food quality and hygiene. Solar drying offers better temperature control, faster drying, and improved hygiene. In a study on fenugreek leaves, solar drying cut drying time by 43%, boosted energy use by 75%, and raised efficiency by 68.12% compared to open sun drying (Navale et al., 2015). Models like indirect dryers further enhance these benefits by preventing direct sun exposure. Additionally, solar drying reduces post-harvest losses and improves farmers' incomes. However, challenges such as uneven drying across trays caused by factors like airflow, tray placement, weather variability, and the number of trays still need to be addressed to optimize efficiency (Ortiz-Rodríguez et al., 2022).

Although several indirect solar dryers were previously developed by Jigme Namgyel Engineering College in collaboration with Lund University, issues such as uneven drying and poor performance during cloudy conditions remained unresolved. To address these challenges, this study introduces and explores a newly developed solar-electric hybrid dryer. The hybrid system integrates an auxiliary electric heating source to maintain consistent internal temperatures, especially in low-sunlight conditions or areas with limited airflow.

Designed to be efficient, affordable, and user-friendly, this new approach aims to improve drying uniformity and is particularly suited for rural and remote communities. The paper presents the design, development, and performance evaluation of the hybrid dryer, offering valuable insights into advancing sustainable food preservation in Bhutan and similar contexts.

1.1 Project Background

Over the years, various solar dryers have been developed to overcome the limitations of earlier models. One notable and recent advancement was the solar dryer built at Jigme Namgyel Engineering College, which showed marked improvements in both efficiency and drying rate. However, the issue of uneven drying remained unresolved. This challenge was highlighted in the research paper, *"Enhancing Post-Harvest Preservation through Improved and Even Solar Drying: A Case Study in Bhutan*" (Müller, 2024).

The current study builds upon this work, introducing a hybrid solar-electric dryer that integrates heating elements as an upgrade to the previous design, aiming to enhance performance and ensure more uniform drying across all trays. By incorporating an electric heating system, the hybrid dryer ensures consistent performance and functionality even during cloudy or non-sunny days, making it more reliable for continuous post-harvest processing.

2. METHOD

The hybrid dryer was developed by modifying an existing solar dryer previously built at Jigme Namgyel Engineering College. While based on the earlier design, the hybrid dryer is not identical, as it includes several physical rearrangements, additional components, and improved features. The original dryer relied solely on solar radiation, which led to several complications, particularly uneven drying rates. To address these issues, the hybrid design incorporates enhancements aimed at improving performance. Data collection was carried out to evaluate its effectiveness compared to the previous and other conventional solar dryers, with a focus on achieving more uniform drying.

The refurbishment of the Hybrid Solar-Electric Dryer involved repairing and replacing all damaged or worn-out components of the original solar dryer. Special attention was given to sealing any air leakages, which were effectively eliminated using glue and other adhesives. To minimize heat loss, a double layer of insulation was applied to the outer surfaces of the dryer.

All temperature sensors were carefully calibrated in advance, and additional sensors were installed to enhance data accuracy and coverage. Following thorough research on various heating elements, ceramic heaters were selected due to their ability to efficiently heat the surrounding air through conduction and convection, an ideal feature for the intended drying application. Also, the ceramic heating cols were easily available and cost effective.

2.1 Working of the previous Solar-Dryer

The solar-dryer, depicted in Fig.1, operates by drawing in fresh air through an external fan at the bottom inlet (1). The air first passes through a heat exchanger (2) at the base, then moves through the absorber (3), where it is further heated before entering the drying chamber by the heat storage (4). Inside the chamber, the warm air flows across multiple drying trays (5) and exits through the chamber exhaust (6). It then circulates through the hot side of the heat exchanger before finally exiting the dryer at the back (7).

To enhance airflow and drying uniformity, an internal fan (8) is positioned between the two sections of the dryer. This fan improves circulation within the chamber without increasing overall airflow, promoting better convective heat transfer and reducing temperature variations across the trays. Without this fan, uneven drying occurs since hot air over-dries the first tray while cooler, moist air reaches the later trays.

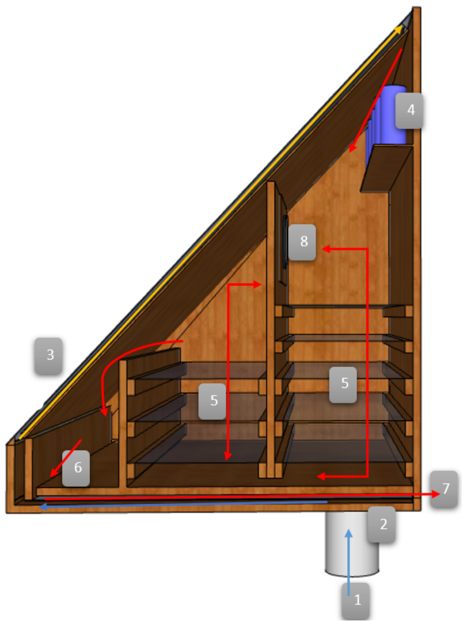

Fig. 1: Previous solar dryer setup (Müller, 2024)

2.2 Hybrid Solar-Electric Dryer

What distinguishes this system as a hybrid dryer is the integration of 2 (1 pair of) ceramic electric heating elements. The pair is placed at the bottom of the front chamber near last tray (Tray 6) as shown in Fig. 2 for the initial days of the drying and later it was shifted to the bottom of the back chamber near Tray 4 which is also the bottom most tray of the back chamber. These heaters ensure stable internal temperatures during cloudy weather or limited solar radiation, improving overall performance and reliability.

***Table 1** Specifications of the Components used for Hybrid Dryer*

Component	Specifications
Gross Dimension	1300mm x 1000mm x 1000mm
Heat Exchanger (steel core)	800 mm x 1000 mm x 0.25 mm
Absorber Area	1450 mm x 1000 mm x 0.25 mm
Airflow Mode	Forced Convection
Airflow channel (Absorber)	10mm (Each Side)
Airflow channel (Heat Exchanger)	10mm (Each Side)
Ceramic Heating Coils	2000W x 4 nos

Table 1 lists the key components used in the construction of the Hybrid Solar-Electric Dryer. These components were primarily selected based on their affordability and local availability, with the goal of minimizing the overall cost of the dryer without compromising functionality. Emphasis was placed on using materials that are easy to source and maintain, making the design more practical and accessible for small-scale or rural users. Additionally, the choice of components aimed to ensure energy efficiency, ease of assembly, and compatibility with the existing modified structure of the dryer.

The experiments were conducted outdoors at Jigme Namgyel Engineering College under natural solar irradiation conditions, with a constant airflow rate maintained throughout the testing period to ensure consistent drying performance. Temperature measurements were recorded using thermocouples connected to a Campbell Scientific CR1000 data logger with an AM 16/32 multiplexer, strategically placed at key locations including the dryer inlet (cold side of heat exchanger), absorber inlet, absorber outlet, drying chamber outlet (hot side of heat exchanger inlet), final dryer outlet and different positions inside the dying chamber. Airflow velocity was precisely measured at the dryer inlet duct using a Testo 416 anemometer with ±0.1 m/s accuracy.

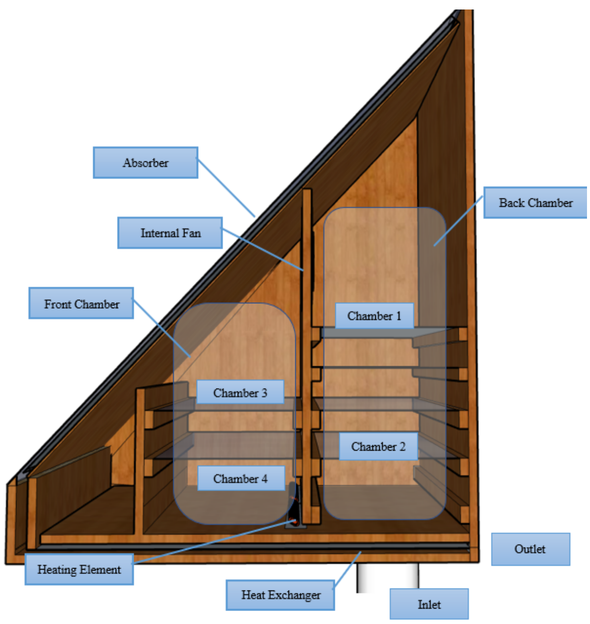

***Fig. 2:** Hybrid Solar-Electric Dryer with its components*

Fresh pumpkin slices served as the drying material as shown in Fig. 3 and Fig. 6 in experimental runs using six trays to evaluate system performance under different conditions of temperature. The data acquisition system recorded measurements at 30-second intervals, with minute-averaged values stored for subsequent analysis. This outdoor testing setup provided realistic performance data of the hybrid solar-electric dryer under actual operating conditions. The constant airflow regulation and comprehensive sensor network enabled detailed analysis of the system's thermal behavior and drying efficiency in natural solar exposure.

***Fig. 3:** Hybrid Solar-Electric Dryer with heating element installed in the front Chamber*

2.2 Coils Placements in the Dryer

The study involved testing two different coil placements within the dryer to improve heat distribution and overall drying efficiency. Initially, the coil was placed at the bottom of the front chamber, directly beneath tray 6, as shown in Fig. 4. This specific placement aimed to address a major issue observed in previous solar dryers that was the uneven drying, particularly on the lower trays of the chamber. These trays often received less heat and airflow, resulting in slower and inconsistent drying. By positioning the coil beneath tray 6, the study sought to enhance heat circulation at the bottom of the chamber and reduce temperature variation across all tray levels.

Later, the coil was repositioned to the bottom of the back chamber, directly beneath tray 4, as shown in Fig. 5. This adjustment was made in response to uneven drying observed in the lower trays of the back chamber. The internal fan primarily circulated air from the back to the front chamber, causing heat to accumulate mainly in the front section and resulting in inadequate heating at the rear. To achieve a more balanced temperature distribution across all trays and improve overall drying uniformity, this relocation was necessary for identifying the optimal coil placement. Data for each coil placement were collected separately and analyzed further in the paper.

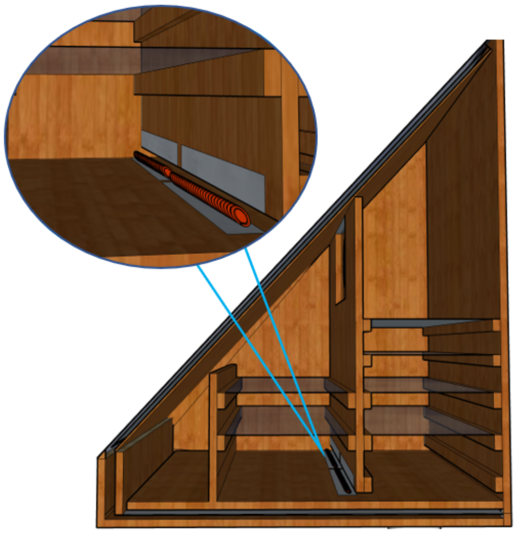

***Fig. 4:** Solar-Electric Hybrid dryer setup with heating coils installed in the front chamber*

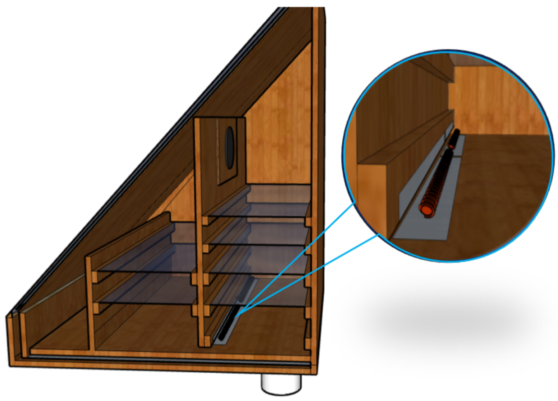

***Fig. 5:** Solar-Electric Hybrid dryer setup with heating coils installed in the back chamber*

2.2 Data Collection and Analysis

Fresh pumpkin was prepared by peeling, deseeding, and slicing it uniformly before weighing and evenly distributing the pieces across the trays as shown in Fig. 6. The loaded trays were then placed inside the dryer, and the internal and external fans were switched on. Data collection started with the logger recording temperatures, relative humidity, and solar irradiance.

Throughout the experiments, only one variable was altered at a time (e.g., position of the heating elements). Weight measurements were taken periodically, where pumpkin slices were weighed with their trays after every hour to track moisture loss. Airflow rate at the inlet was verified multiple times to ensure consistency. In order to maintain experimental integrity, the same number of pumpkin slices were used in each trial, and every effort was made to keep all other parameters, such as slice thickness, drying time, and environmental conditions, as constant as possible. Approximately four sets of data were collected for each change in the experimental variable to ensure consistency and continuity, allowing for more accurate and reliable results.

Fig. 6: *Pumpkin slices placement on the trays*

This controlled approach helped minimize variability and allowed for meaningful comparisons between different conditions and dryer configurations. The total drying time was computed by analyzing the pumpkin's moisture content reduction per hour throughout the dehydration process.

3 RESULTS

To achieve higher-quality data, researchers installed a network of twenty temperature sensors and two humidity detectors at strategic points inside the drying chamber as shown in Fig. 7.

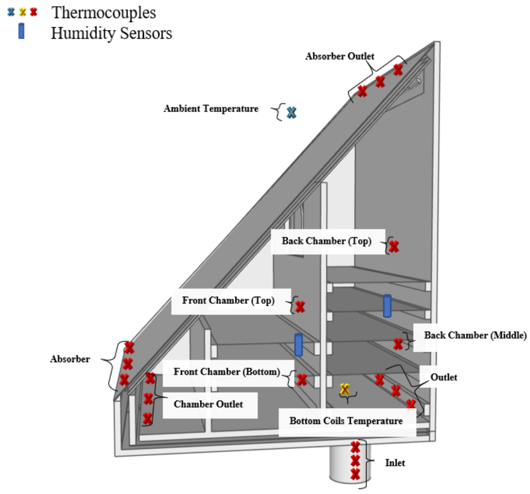

Fig. 7: *Sensors Placements*

3.1 Temperature Chart for Drying Chambers with Bottom Coils in the Front

Fig. 8. illustrates temperature variations over time in various chambers of the hybrid solar dryer, along with the bottom coil. While both the chambers and the coil exhibit a steady rise in temperature throughout the drying period, noticeable differences in temperature levels exist between the chambers. These variations suggest a need for improvements in airflow distribution or design modifications to achieve more consistent and uniform drying conditions across all chambers.

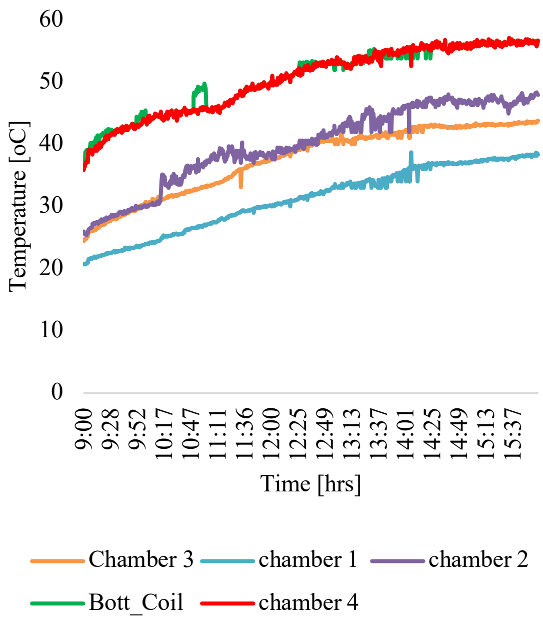

Fig. 8: *Temperature chart of chambers and heating element*

3.2 Temperature Chart for Drying Chambers with Bottom Coils at the Back

Fig. 9. displays steady increase in temperature across four chambers and two coils (at the bottom) as shown in figure 2. from 8:00 AM to 1:00 PM, ranging from around 30–40°C initially to about 55–60°C by the end. All components exhibit a similar upward temperature trend, with Chamber 1 and Chamber 4 recording slightly higher values due to their locations, Chamber 1 being close to the absorber outlet and Chamber 4 situated near the heating coils. Overall, the system demonstrates a uniform rise in temperature over time, indicating efficient thermal distribution.

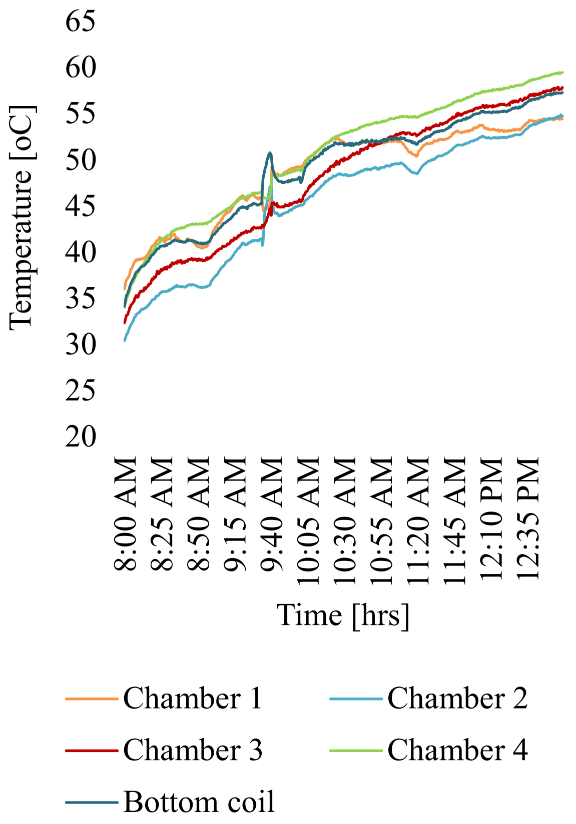

Fig. 9: *Temperature chart of Chambers and heating elements of 29th March, 2025*

3.3 Temperature and Solar Irradiance variations

Fig. 10. depicts the relationship between solar irradiance and various temperature parameters of the Solar-Electric Hybrid Dryer from 8:00 AM to 1:00 PM of the dryer setup shown in Fig 4. Solar irradiance rose sharply in the morning, peaking above 400 W/m² around 11:00–12:00 AM, which corresponded with a noticeable increase in absorber outlet and chamber average temperatures, indicating effective solar heat capture.

The absorber outlet consistently remained higher than the inlet, reflecting a clear thermal gain. After 10:30 AM, as solar irradiance began to decline, the chamber temperature remained relatively stable, suggesting that the electric heating elements were activated to maintain the desired internal conditions. Inlet and ambient temperatures showed minimal variation throughout the period, indicating stable external environmental conditions. This demonstrates the dryer's ability to efficiently sustain internal temperatures using both solar and auxiliary electric heating sources.

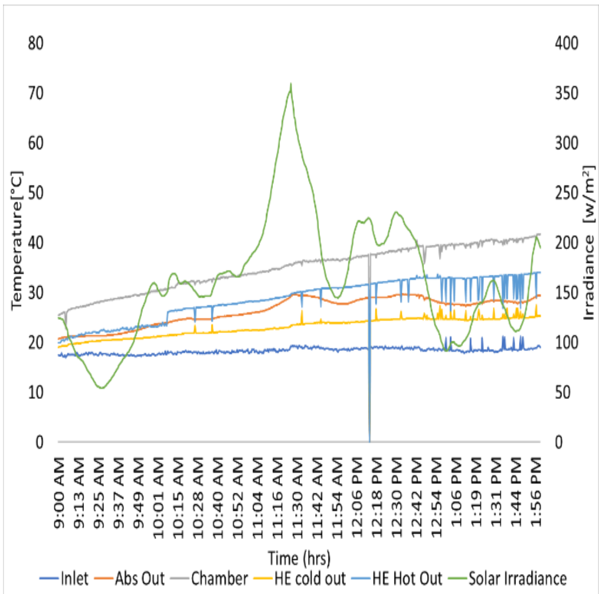

Fig. 10: *Temperature and Solar Irradiance chart of 12th March,2025*

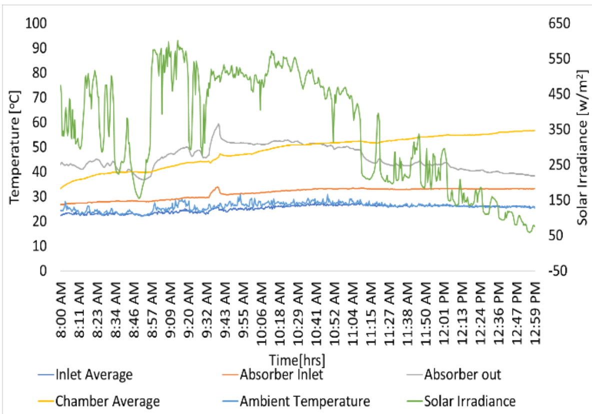

Fig. 11: *Temperature and Solar Irradiance chart of 29th March, 2025*

Fig. 11. demonstrates the relationship between solar irradiance and various temperature parameters of the Solar-Electric Hybrid Dryer

from 8:00 AM to 1:00 PM. Solar irradiance increased sharply in the morning, peaking above 600 W/m² around 9:00–10:00 AM as maximum sunlight was received during this hour for this particular experiment, which led to a rise in absorber outlet and chamber average temperatures, indicating effective heat collection. The absorber outlet remained higher than the inlet, showing clear thermal gain. As solar irradiance declined after 10:30 AM due to weather changes and cloud cover, the chamber temperature remained steady due to the activation of heating elements, which maintained the required thermal conditions.

Meanwhile, the inlet and ambient temperatures showed minimal variation, indicating stable external environmental conditions. This further demonstrates the dryer's efficiency in sustaining internal temperatures independently of solar input and alternative heating element.

3.4 Heating Coil Temperature Variation with Solar Irradiance

Fig. 11. shows that while ambient temperature stays fairly constant around 20°C, the bottom coil temperature steadily rises throughout the day, reaching about 55°C. Solar irradiance peaks around midday and then declines, with noticeable fluctuations. The increase in coil temperature corresponds to solar irradiance, indicating effective solar heating.

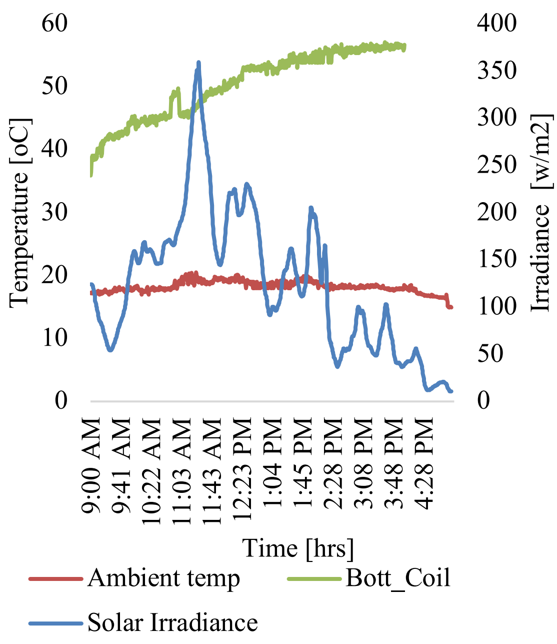

Fig.12: *Solar Irradiance and Heating Coils' Temperature for 12th March,2024*

From 8:00 AM to 1:00 PM, bottom coil temperatures steadily increased, reaching nearly 60°C, while the ambient temperature remained around 25°C. Solar irradiance fluctuated significantly in the morning, peaking around 600 W/m², then gradually declined after 11:00 AM. Despite the fluctuations in solar input, the coil temperatures continued to rise, indicating effective heat absorption.

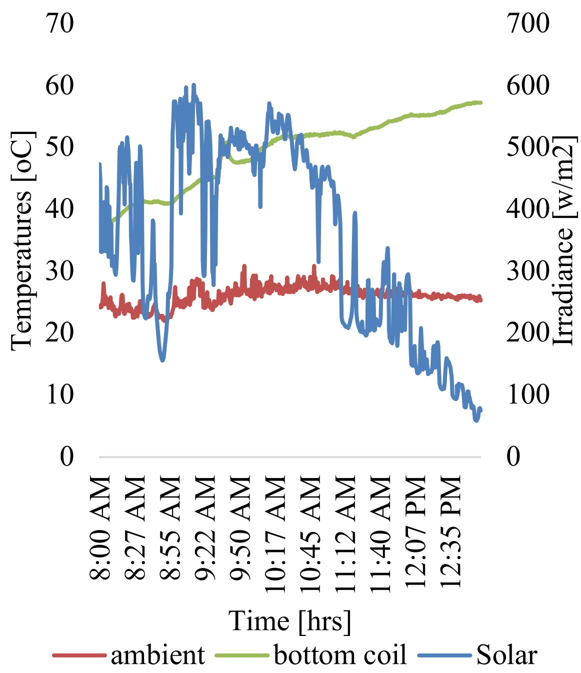

Fig.13: *Solar Irradiance and Heating Coils' Temperature*

3.5 Pumpkin Drying Percentage

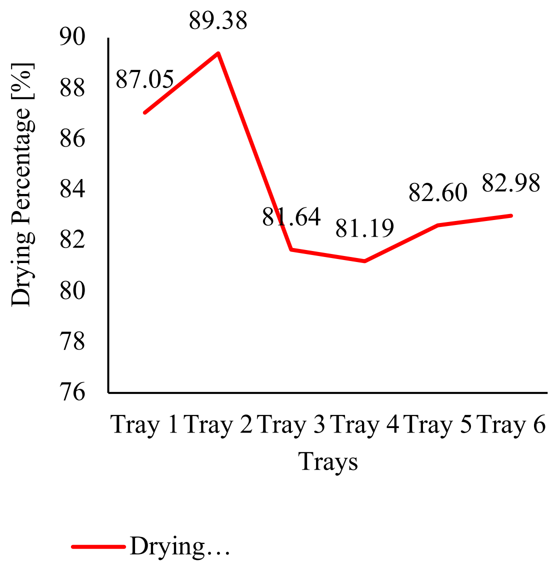

Fig. 14: *Drying Percentage of different trays*

Fig. 14. shows the drying percentages across six trays, labeled Tray 1 through Tray 6. Tray 2 shows the highest drying efficiency at 89.38%, while a significant decrease is seen at Tray 3 (81.64%) and Tray 4 (81.19%). A modest improvement follows in Tray 5 (82.60%) and Tray 6 (82.98%). Overall, the graph highlights performance fluctuations, providing a clear view of drying consistency among the trays.

Fig. 13. illustrates the drying percentage of trays numbered 1 through 6 over three dates: 29th, 30th, and 31st March. It shows fluctuations in drying efficiency across the trays, with each date following a similar trend, Tray 1 starts with high percentages (around 85-86%), dips at Tray 2 (reaching as low as 78% on 29th March), then steadily increases, peaking near 88% for Tray 6.

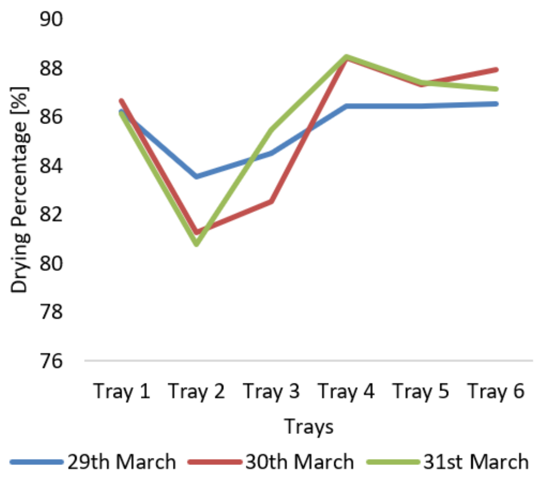

Fig.15: *Drying Percentage of different trays for different days*

4 CONCLUSION

The integration of electric heating elements into the solar-electric hybrid dryer significantly improved drying uniformity across trays, addressing one of the major limitations of previous solar dryer models that was the uneven drying among the trays. By strategically placing the heating coils near trays with slower drying rates and combining this with optimized airflow through internal fan, the system maintained consistent temperatures throughout the drying chamber, even during fluctuating solar irradiance.

Data from temperature and drying percentage graphs clearly show reduced variation in drying efficiency between trays, especially when the heating coils were relocated from the front to the back chamber. This enhancement ensures more uniform moisture removal, improving the overall quality of dried products and making the dryer more reliable and suitable for continuous post-harvest food processing in regions with variable weather conditions like Bhutan.

REFERENCES

Brown, J. (2024, December 31). The sun's impact on food: What happens when food is exposed to sunlight? EasyHealthyFoods. https://easyhealthyfoods.com/what-happened-to-the-food-exposed-to-sunlight/

Müller, L. C. (2024). Enhancing post-harvest preservation through improved and even solar drying: A case study in Bhutan (Master's thesis, Lund University). Lund University Publications. https://lup.lub.lu.se/

Navale, S. R., Harpale, V. M., & Mohite, K. C. (2015). Comparative study of open sun and cabinet solar drying for fenugreek leaves. International Journal of Renewable Energy Technology Research, 4(2), 1–9. http://ijretr.org

Ortiz-Rodríguez, N., Condorí, M., Durán, G., & García-Valladares, O. (2022). Solar drying technologies: A review and future research directions with a focus on agroindustrial applications in medium and large scale. Applied Thermal Engineering, 215, 118993. https://doi.org/10.1016/j.applthermaleng.2022.118993

Problems of traditional open drying – ITZ resources. (2025). ITZ Resources. https://itzresources.com/2025/02/09/hello-world/

Rahman, M. A., Hasnain, S. M. M., Paramasivam, P., Zairov, R., & Ayanie, A. G. (2025). Solar drying for domestic and industrial applications: A comprehensive review of innovations and efficiency enhancements. Global Challenges, 9(2). https://doi.org/10.1002/gch2.202400301

Ruralis - Institutt for rural- og regionalforskning. (2024). SolarFood: Reducing post-harvest losses through improved solar drying. Ruralis. https://ruralis.no/en/projects/solarfood-reducing-post-harvest-losses-through-improved-solar-drying/