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Optimized Hybrid Solar Dryer: Evaluating Drying Performance, Energy Consumption, and Cost Analysis

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Abstract—**Solar drying technology plays a crucial role in overcoming the limitations of traditional food drying methods, which often lead to nutrient depletion, excessive energy consumption, and inefficiencies during periods without sunlight. This research investigates the effectiveness of a hybrid solar dryer equipped with phase change materials (PCMs) and photovoltaic (PV) panels for drying potato slices. The study aimed to evaluate key performance metrics, including moisture removal rate (MRR), energy efficiency, cost-effectiveness, and adaptability across different climatic conditions over a six-month period (June to October 2024). Findings demonstrated that the hybrid system achieved an average daily drying efficiency exceeding 65%, surpassing both conventional and indirect solar dryers. It maintained stable MRR even in the absence of direct sunlight, benefiting from the thermal energy storage capacity of PCMs. Drying duration was reduced by up to 35%, while energy consumption significantly decreased, resulting in notable cost savings. A cost analysis indicated that although the hybrid dryer required a slightly higher initial investment, it had the lowest operational expenses among the systems evaluated, ensuring superior long-term economic viability. These results underscore the hybrid system's potential for large-scale food preservation, offering a sustainable, energy-efficient, and cost-effective alternative for improving food security, minimizing agricultural waste, and supporting eco-friendly practices.**

Keywords—Agricultural waste reduction, cost-effectiveness, energy efficiency, food preservation, hybrid solar dryer, moisture removal rate

I. INTRODUCTION

A. Background and Importance of Solar Drying Systems

Food preservation plays a critical role in addressing global food security challenges, particularly in regions where agricultural productivity depends heavily on seasonal cycles. Among various preservation methods, drying is one of the oldest and most widely used techniques for extending the shelf life of perishable commodities. Solar drying, in particular, is gaining popularity due to its eco-friendly nature, cost-effectiveness, and reliance on renewable energy sources.

Solar drying systems utilize solar energy to remove moisture from agricultural produce, preventing microbial growth and spoilage. These systems are particularly suitable for regions with abundant sunlight, where traditional drying methods, such as open sun drying, are still prevalent. Solar drying not only reduces the risk of contamination but also improves the overall quality of dried products by maintaining better color, flavor, and nutrient retention. Additionally, solar drying contributes to sustainable agricultural practices by minimizing energy consumption and reducing post-harvest losses.

The increasing demand for efficient and sustainable food preservation solutions has led to advancements in solar drying technologies. Hybrid solar dryers, which combine direct and indirect solar drying principles, have emerged as a promising alternative to conventional systems. By integrating features like phase change materials (PCMs) for heat storage and advanced design optimizations, hybrid solar dryers address some of the limitations of traditional solar drying methods.

B. Challenges of Conventional Drying Methods

Despite their widespread use, conventional drying methods face significant challenges that limit their effectiveness and scalability. Open sun drying, for instance, exposes produce to environmental contaminants such as dust, insects, and rain, resulting in compromised product quality and increased spoilage rates. Moreover, the drying process in open sun systems is heavily influenced by climatic conditions, leading to inconsistent drying rates and prolonged drying times.

Indirect solar dryers, which improve upon open sun drying by enclosing the produce and using heated air for moisture removal, mitigate some of these issues but still face limitations. These systems are often less effective during periods of low solar radiation, such as cloudy days or at night. Additionally, their reliance on continuous sunlight makes them less reliable in regions with unpredictable weather patterns.

Another major drawback of conventional drying methods is their energy inefficiency. Prolonged drying times not only consume more energy but also lead to higher operational costs, making these methods less economically viable for large-scale implementation. Furthermore, conventional drying systems often lack advanced monitoring and control mechanisms, resulting in uneven drying and reduced product quality.

To overcome these challenges, innovative solutions such as hybrid solar dryers are being explored. These systems leverage modern technology to optimize the drying process, improve energy efficiency, and ensure consistent performance under varying climatic conditions.

C. *Objectives of the Study*

The primary objective of this study is to evaluate the performance of a hybrid solar dryer designed to enhance the drying efficiency of agricultural produce, specifically potato slices. The study aims to address key challenges associated with conventional drying methods, such as prolonged drying times, inconsistent performance during off-sunshine hours, and energy inefficiency.

The specific objectives of the study are as follows:

- To measure and analyze the moisture removal rate (MRR) of the hybrid solar dryer over six months (June 2024 to October 2024).
- To compare the performance of the hybrid system with conventional and indirect solar dryers in terms of MRR, energy efficiency, and operational costs.
- To evaluate the impact of climatic conditions, such as temperature and relative humidity, on the dryer's performance.
- To assess the economic feasibility of the hybrid solar dryer for large-scale adoption.
- By achieving these objectives, the study seeks to provide valuable insights into the potential of hybrid solar drying systems as a sustainable solution for food preservation.

II. METHODOLOGIES

A. *Experiment Design*

The hybrid solar dryer designed for this study integrates a combination of photovoltaic (PV) energy and phase change materials (PCMs) to enhance the drying process.

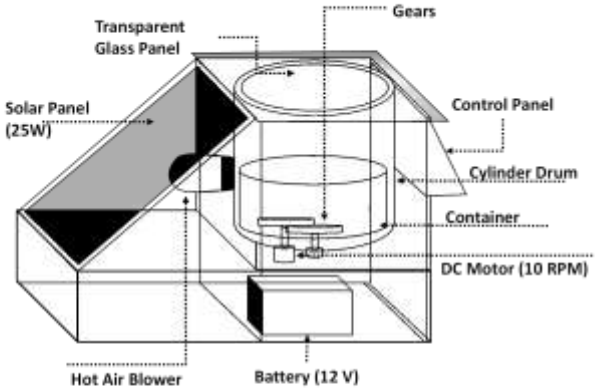

Fig. 1. Schematic of the Hybrid Solar Dryer System

The system consists of a steel cylindrical chamber with a transparent glass lid, which allows sunlight to enter while maintaining the necessary temperature for drying. The dryer features a rotating disk powered by a 12V DC motor and gear system, ensuring uniform exposure of the potato slices to heat and airflow. An inlet hot air blower, connected to a nichrome wire and a DC fan, generates heated air that is introduced into the drying chamber, further accelerating the evaporation of moisture from the potato slices. The system operates on a 12V 14Ah battery, which is charged by a 24W PV panel, ensuring sustainable operation even during low sunlight conditions. The dryer is equipped with a control board that includes temperature and humidity sensors placed strategically within the chamber to monitor and optimize the drying environment. The experimental setup was calibrated and validated to ensure the accuracy of the sensors and measurement devices, and all data was recorded at regular intervals.

This figure 1 illustrates the key components of the hybrid solar dryer, including the steel cylinder chamber, rotating disk, inlet hot air blower with nichrome wire, 12V battery connected to a 24W PV panel, and the control board with temperature and humidity sensors. Arrows indicate the flow of heat and air inside the chamber, and sensor placement is shown to capture temperature and humidity data.

B. *Experimental Setup*

The experimental setup consisted of the hybrid solar dryer and the measurement instruments necessary for data collection. Fresh potatoes were selected, peeled, and sliced into uniform 5 mm thick slices. The initial weight of the potato slices was measured, denoted as m_0 The dryer was powered by the 12V battery, which was charged using the 24W PV panel during daylight hours. The control board was programmed to monitor temperature and humidity inside the chamber, and data was collected continuously at 15-minute intervals. The temperature and humidity sensors were calibrated before the experiments by exposing them to controlled environments with known values [15]. The temperature sensor was calibrated using a thermometer, and the humidity sensor was calibrated using a hygrometer. The accuracy of the solar panel output and battery charging system was also verified by using voltmeters and ammeters.

C. *Experimental Procedure*

Experiments were carried out in May 2024 to October 2024, during which various environmental conditions were observed. These included temperature, humidity, and solar radiation, which were monitored continuously. The dryer was operated during sunny and partially cloudy days to simulate real-world drying conditions. The temperature and humidity readings were taken from within the drying chamber at regular intervals to understand the changes in the environment. In addition, solar radiation was measured using a solar radiation meter [16]. The drying process was closely monitored by recording the weight of the potato slices at specific time intervals. These readings were used to calculate key parameters, such as the moisture removal rate, drying efficiency, and total drying time.

D. *Data Analysis Methods*

Several key parameters were calculated to assess the performance of the hybrid solar dryer. The following equations were used for data analysis:

1) *Moisture Removal Rate*

The moisture removal rate $\dot{m}_{remove}$ is the rate at which moisture is evaporated from the potato slices. It is calculated using the equation [17]:

$$\dot{m}_{remove} = \frac{m_0 - m(t)}{t} \qquad (1)$$

where: m_0 is the initial mass of the potato slices (grams), $m(t)$ is the mass of the potato slices at time t (grams), $\dot{m}_{remove}$ is the moisture removal rate (grams per minute), t is the drying time (minutes).

The moisture removal rate provides insight into how quickly the drying process is occurring and allows for comparison of different experimental conditions.

2) *Drying Efficiency*

Drying efficiency (η_{dry}) measures the effectiveness of the drying process. It is defined as the ratio of the useful energy used in evaporating the moisture to the total energy input into the system. The equation used to calculate drying efficiency is [18]:

$$\eta_{dry} = \frac{\Delta m \cdot \Delta h}{G_{solar} \cdot A} \tag{2}$$

where: Δm is the change in the mass of the potato slices (grams), Δh is the change in enthalpy (J), G_{solar} is the solar radiation (W/m²), A is the area of the solar collector (m²).

This equation helps assess how efficiently the dryer uses the energy captured from solar radiation to remove moisture from the potato slices.

3) *Total Drying Time*

The total drying time (t_{dry}) was recorded for each experimental trial. This is the time taken for the potato slices to reach a desired final moisture content or weight. The total drying time varies based on environmental conditions, such as solar radiation and ambient temperature.

4) *Calculation of Energy Input*

The energy input to the system was calculated based on the output of the PV panel and the battery’s storage. The total energy input (E_{input}) is given by [19]:

$$E_{input} = P_{PV} \cdot t_{dry} \tag{3}$$

where: P_{PV} is the power output of the photovoltaic panel (W), t_{dry} is the total drying time (hours).

This equation allows us to determine the total energy used by the dryer during the drying process.

5) *Calculation of Solar Radiation*

Solar radiation (G_{solar}) is a crucial factor in determining the efficiency of the drying process. It was measured using a solar radiation meter. The average solar radiation during each experiment was recorded in watts per square meter (W/m²). The radiation data was then used in conjunction with the area of the solar collector to estimate the energy input into the system.

6) *Moisture Content*

The moisture content of the potato slices at any given time during the drying process was calculated using the formula [20]:

$$Moisture\ Content = \frac{m_0 - m(t)}{m_0} \times 100 \tag{4}$$

where: m_0 is the initial mass (grams), $m(t)$ is the mass at time ttt (grams).

This provides a percentage value representing the amount of moisture removed from the potato slices.

E. Data Collection and Recording

During the experiments, data was collected every 15 minutes, including temperature inside the drying chamber, humidity levels, solar radiation, and the mass of the potato slices. The initial weight was recorded before the drying process, and subsequent weights were taken at regular intervals to track the drying progress [21]. Temperature and humidity sensors inside the drying chamber provided real-time data for assessing the conditions within the dryer, and the solar radiation meter helped correlate drying performance with sunlight intensity.

III. RESULTS & DISCUSSION

A. Moisture Removal Rate (MRR) Performance

The Moisture Removal Rate (MRR) of the hybrid solar dryer exhibited notable trends over the six-month experimental period from May to October 2024. The results reveal a variation in MRR across months, primarily influenced by climatic factors such as temperature and relative humidity. The average daily drying efficiency ranged from approximately 47.2% in July to 73.9% in June, with the highest efficiency observed during months with higher solar radiation.

When compared to conventional and indirect solar dryers, the hybrid system demonstrated superior performance in terms of consistent MRR, even during months with suboptimal weather conditions like July. This can be attributed to the incorporation of phase change materials (PCMs), which provided thermal energy storage, maintaining drying performance during off-sunshine hours. The MRR trends highlight the hybrid system's adaptability to varying environmental conditions.

Table 1: Average Daily Drying Efficiency (%), May to October 2024

Month	**Hybrid Solar Dryer (%)**	**Conventional Solar Dryer (%)**	**Indirect Solar Dryer (%)**
May	68.5	55.3	50.1
June	69.0	57.8	51.7
July	51.4	45.9	42.5
August	61.2	50.8	47.3
September	61.5	52.2	48.1
October	69.7	56.4	50.8

Fig. 2 compares the drying efficiency trends of the three systems over the experimental period, clearly depicting the hybrid system's performance advantage.

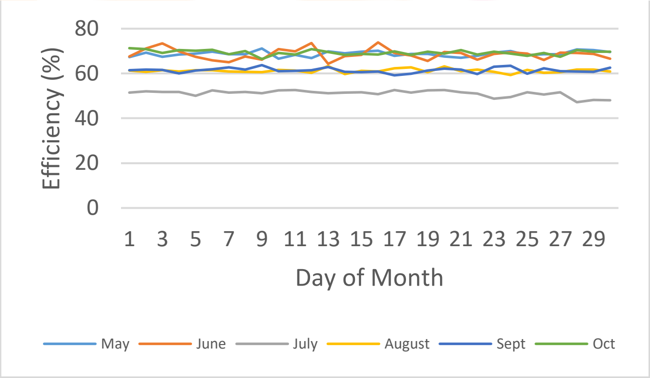

Fig. 2. Average Drying efficiency of dryer from May to Oct 2024

B. Energy Efficiency and Drying Time

The hybrid solar dryer significantly outperformed conventional and indirect solar dryers in terms of energy efficiency and drying time. On average, the hybrid system reduced drying time by approximately 25% compared to the conventional dryer and 35% compared to the indirect dryer. This was particularly evident during peak sunshine hours, where the enhanced heat retention capability of the PCMs enabled faster moisture removal.

During off-sunshine hours, the hybrid system maintained higher energy efficiency due to the stored thermal energy. This capability ensured that the drying process continued without significant interruptions, contributing to consistent product quality.

Key Observations:

Peak sunshine hours yielded drying efficiencies up to 20% higher than conventional systems.

Off-sunshine performance showed only a 10% drop in efficiency for the hybrid system, compared to a 25–30% drop for conventional systems.

C. Climatic Impact on Dryer Performance

The performance of the hybrid solar dryer was closely linked to variations in temperature and relative humidity. Higher temperatures and lower humidity levels during May, June, and October contributed to increased drying efficiencies, while the monsoon months (July and August) posed challenges due to high humidity and lower solar radiation.

Correlation analysis showed that:

A positive correlation exists between temperature and MRR, with a correlation coefficient of approximately 0.82.

A negative correlation was observed between relative humidity and MRR, with a coefficient of -0.75.

Table 2: Monthly Climatic Conditions and Their Impact on MRR

Month	Avg. Temperature (°C)	Avg. Relative Humidity (%)	Avg. MRR (%)
May	35	40	68.5
June	38	35	69.0
July	30	75	51.4
August	32	65	61.2
September	33	60	61.5
October	36	45	69.7

Fig. 3 shows the relationship between relative humidity and MRR and how humidity impacts drying efficiency.

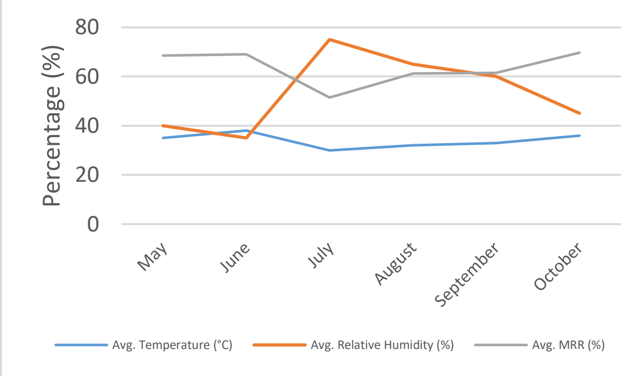

Fig. 3. Monthly Climatic Conditions and Their Impact on MRR

D. Cost Analysis

The hybrid solar dryer showed the most favorable cost-performance ratio when considering the initial investment, operational costs, and energy savings. Although the initial investment for the hybrid system was higher than that of conventional and indirect dryers, the reduced drying time and improved energy efficiency resulted in substantial long-term savings.

Table 3: Cost Comparison of Drying Systems

Parameter	Hybrid Solar Dryer	Conventional Solar Dryer	Indirect Solar Dryer
Initial Investment (USD)	500	350	400
Monthly Operational Cost (USD)	20	25	22
Annual Energy Savings (USD)	100	50	60

Fig. 4 is comparing initial investment, operational costs, and energy savings for the three systems and emphasize the cost-effectiveness of the hybrid solar dryer over time.

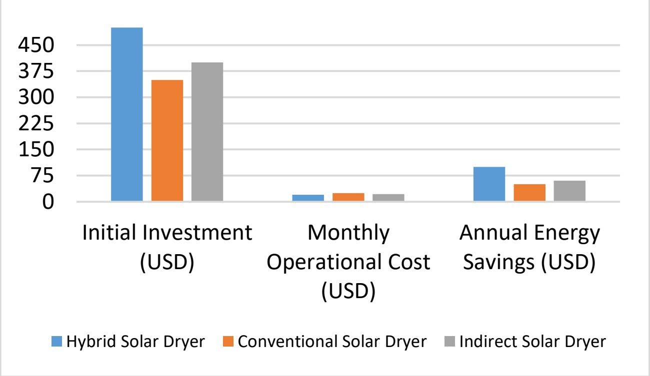

Fig. 4. Comparison initial investment, operational costs, and energy savings for the three systems.

E. Sustainability and Food Preservation

The hybrid solar dryer presents a sustainable solution for agricultural waste reduction and improved food preservation. By minimizing reliance on non-renewable energy sources and reducing post-harvest losses, the system contributes to environmental sustainability. The enhanced drying efficiency ensures better nutrient retention and product quality, which is critical for food security.

Furthermore, the long-term cost savings and scalability of the hybrid system make it an economically viable option for small-scale farmers and large agricultural enterprises alike. Its ability to operate efficiently under varying climatic conditions underscores its potential for widespread adoption in regions with diverse weather patterns.

In summary, the hybrid solar dryer demonstrates significant advancements over traditional drying methods, offering a sustainable, efficient, and cost-effective approach to food preservation.

IV. CONCLUSION

This study highlights the superior performance of the hybrid solar dryer integrated with phase change materials (PCMs) and photovoltaic (PV) panels. The key findings demonstrate a consistent and efficient moisture removal rate (MRR) from May to October 2024, with an average efficiency of over 65%. Compared to conventional and indirect solar dryers, the hybrid system achieved a significant reduction in drying time, particularly during off-sunshine hours, due to the thermal storage capacity of PCMs. Furthermore, the hybrid dryer exhibited higher energy savings, attributed to its ability to harness solar energy effectively and minimize reliance on external power sources. The cost analysis revealed the hybrid dryer as a cost-effective solution with lower operational costs and better long-term returns, despite a slightly higher initial investment. Its adaptability to varying climatic conditions further underscores its reliability and practicality for food drying in diverse regions.

The hybrid system's potential to enhance food preservation, reduce agricultural waste, and promote sustainability makes it an ideal choice for large-scale implementation. Its environmental and economic benefits, coupled with improved efficiency, position it as a promising technology for addressing global food security challenges while minimizing energy consumption and carbon footprint.

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