International Journal of Thermodynamics (IJoT)
ISSN 1301-9724 / e-ISSN 2146-1511
https://dergipark.org.tr/en/pub/ijot

Vol. 28 (No. 2), pp. 079-088, 2025
doi: 10.5541/ijot.1590723
Published online: June 1, 2025

Research Article

Revolutionizing Potato Drying: Performance Insights from Hybrid Solar Drying Systems

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Received 25 November 2024, Revised 10 January 2025, Accepted 23 January 2025

Abstract

This study investigates the performance of a hybrid solar dryer designed for the efficient drying of potato slices, aiming to address the challenges associated with conventional drying methods. The primary objectives were to evaluate the moisture removal rate (MRR) of the hybrid solar dryer and compare its effectiveness with traditional solar drying techniques. Through a series of experiments conducted from May to December 2024, the hybrid dryer demonstrated an impressive average MRR of 182.8 g/h, significantly outperforming both conventional (typically 150–180 g/h) and indirect solar dryers. The findings revealed that the hybrid system not only reduced drying time but also preserved the quality of the dried products, ensuring minimal nutrient loss. The MRR ranged from 158.4 g/h in December to 198.3 g/h in May, showcasing stable performance despite climatic fluctuations. Comparative analyses highlighted the superior efficiency of the hybrid design, making it a viable solution for food preservation, particularly in regions with ample sunlight. Additionally, the study emphasizes the importance of sustainable food processing technologies in enhancing food security and reducing agricultural waste. This research contributes valuable insights into the development of innovative drying solutions that can be effectively implemented in various agricultural settings, promoting better utilization of solar energy for food preservation. Future studies could explore further optimizations and integrations to enhance the performance of solar drying systems.

Keywords: *Hybrid solar dryer; moisture removal rate; potato; solar energy; sustainable food preservation.*

1. Introduction

Food drying is an ancient and vital method for preserving agricultural products, extending their shelf life, and reducing post-harvest losses. The process involves removing moisture from food items, thereby inhibiting the growth of microorganisms that cause spoilage. By reducing water activity, drying effectively preserves the nutritional value, flavor, and texture of the food while making it lighter and more compact for storage and transportation [1].

In many developing countries, including India, a significant portion of harvested produce is lost due to inadequate post-harvest handling and preservation techniques. Traditional methods such as open sun drying, although cost-effective, often lead to significant quality degradation due to exposure to contaminants, insects, and unpredictable weather conditions [2]. Consequently, there is a pressing need for efficient, reliable, and hygienic drying technologies to ensure food security and reduce waste.

1.1 Importance of Renewable Energy in Food Preservation

The use of renewable energy in food preservation has gained substantial attention in recent years due to the growing concerns over energy consumption and environmental sustainability. Conventional drying methods, such as mechanical dryers powered by electricity or fossil fuels, contribute to greenhouse gas emissions and incur high operational costs. In contrast, solar energy is a sustainable, eco-friendly alternative that can be harnessed to effectively dry agricultural products [3].

Solar drying systems utilize the abundant and free energy from the sun, making them particularly suitable for regions with high solar insolation. By integrating solar energy with supplementary electrical heating, hybrid solar dryers can overcome the limitations of weather dependency, providing a consistent drying environment. This combination not only reduces the reliance on non-renewable energy sources but also lowers the carbon footprint associated with food preservation.

1.2 Overview of Existing Drying Technologies

Several drying technologies have been developed to enhance the efficiency and quality of dried food products, primarily categorized into open sun drying, conventional mechanical drying, and advanced solar drying systems.

Open sun drying is the most traditional and widely used method, particularly in rural areas. In this approach, food items are spread out under the sun and left to dry naturally. Although it is cost-free and straightforward to implement, this method relies heavily on weather conditions, and exposure to contaminants can compromise the quality and safety of the dried products [4].

Conventional mechanical drying employs electrical or fuel-based heaters to provide the necessary heat for drying.

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These systems offer better control over drying conditions, resulting in more consistent and higher-quality dried products. However, they tend to be energy-intensive and expensive to operate, making them less accessible for small-scale farmers and producers.

Advanced solar drying systems encompass various designs, including direct, indirect, and mixed-mode dryers. Direct solar dryers expose food directly to sunlight within an enclosed chamber, which reduces contamination and accelerates the drying process compared to open sun drying. Indirect solar dryers, on the other hand, involve a heat collector that absorbs solar radiation, with the heated air subsequently circulated through the drying chamber, thus avoiding direct exposure of food to sunlight. Mixed-mode solar dryers combine both direct and indirect methods to optimize the drying process [5, 6]. Additionally, hybrid solar dryers integrate solar energy with auxiliary electrical heating to maintain a stable drying environment, ensuring efficient operation even during cloudy or rainy periods and providing a continuous drying process.

1.3 Objectives of the Study

The primary objective of this study is to design, develop, and evaluate the performance of a hybrid solar dryer specifically tailored for drying agricultural products such as potato slices. This study aims to address the limitations of traditional drying methods by integrating renewable solar energy with electrical heating to create an efficient, reliable, and hygienic drying system.

The specific objectives are as follows:

- To create a hybrid solar dryer system that utilizes both solar and electrical energy to provide a consistent and controlled drying environment for various agricultural products.
- To conduct a series of drying experiments over a defined period, collecting data on temperature, humidity, mass before and after drying, and battery percentage. The experiments will be conducted under controlled conditions to assess the dryer's efficiency in removing moisture from potato slices.
- To calculate and analyze the moisture removal rate (MRR) and drying efficiency, and to evaluate the performance of the battery and photovoltaic system in providing consistent power for the drying process.
- To compare the performance of the hybrid solar dryer with traditional open sun drying and conventional mechanical drying methods in terms of drying efficiency, energy consumption, and product quality.

By achieving these objectives, the study aims to demonstrate the feasibility and advantages of using hybrid solar drying technology for food preservation, providing a sustainable solution that can be adopted by small-scale farmers and producers to enhance food security and reduce post-harvest losses.

2. Related Works

The exploration of solar dryers has advanced significantly over the years, addressing various challenges associated with drying agricultural products. Amer et al. [7] evaluated the performance of an automated hybrid solar system dryer (HSSD) for drying aromatic herbs such as lemongrass, thyme, marjoram, and lavender. Their study highlighted the efficiency of HSSD in retaining the physicochemical properties of these herbs, emphasizing its potential for energy savings and reduced carbon footprint. The findings showed that HSSD could save between 19-36% of energy consumption while delivering high-quality dried products.

Kherrafi et al. [8] provided a comprehensive review of solar drying technologies, discussing design variations, hybrid systems, storage materials, and numerical analysis. They emphasized the importance of optimizing the design and performance of solar drying systems through numerical analyses and CFD simulations, which can lead to more efficient and reliable solar drying solutions.

Kalita et al. [9] investigated the performance of a hybrid solar dryer with electric and biogas backup air heaters for drying red chili. They found that the Biogas Hybrid Mode Solar Dryer (BHMSD) was more efficient than the Electric Hybrid Mode Solar Dryer (EHMSD), offering higher moisture diffusivity and energy savings. The study concluded that BHMSD is a more sustainable and eco-efficient alternative to traditional electric-based systems.

Saha et al. [10] reviewed the constructional features and techno-economic-environmental aspects of solar hybrid dryers for fruits, vegetables, and fish. They discussed the advancements in communication and sensing technologies that have enabled real-time control and automation in SHDs, making them competitive with fossil-fueled dryers. The review also highlighted the economic and environmental benefits of SHDs, despite certain techno-economic barriers that need to be addressed through incentives and regulations.

Behera et al. [11] conducted an experimental investigation of a hybrid solar dryer for vegetable drying, incorporating phase change materials (PCMs) for improved efficiency. Their study demonstrated that using PCMs increased collector efficiency, drying efficiency, and drying rate, making the process more suitable for cloudy weather and nighttime drying. This approach showed significant potential for sustainable food preservation.

Lehmad et al. [12] assessed the environmental, economic, and quality aspects of hybrid solar-electric drying of black soldier fly larvae (BSFL). The study highlighted the short payback period and substantial economic savings of the HSED system, along with the superior protein content of the dried larvae compared to conventional methods. This research underscores the potential of HSED systems in ensuring food security and sustainability.

Mahajan et al. [13] detailed the design and analysis of a solar biomass hybrid dryer for drying turmeric. Their design, validated through ANSYS simulations, demonstrated consistent temperature distribution and effective drying under hygienic conditions. This development is particularly beneficial for small-scale turmeric processors, enhancing product value and marketability.

2.1 Challenges in Drying Agricultural Products

Drying agricultural products efficiently and effectively presents several challenges. Direct sunlight can degrade the quality of sensitive herbs and vegetables, as discussed by Amer et al. [7]. Maintaining the desired physicochemical properties while minimizing energy consumption is a significant hurdle.

Traditional drying methods, such as open sun drying (OSD), are often inefficient and time-consuming, as highlighted by Kalita et al. [9]. They found that OSD required twice the drying time compared to hybrid solar dryers and was less effective in reducing moisture content.

Additionally, OSD is susceptible to environmental contamination, leading to quality and hygiene issues.

The integration of auxiliary heating units, such as those in SHDs, can mitigate some of these challenges. However, as Saha et al. [10] pointed out, the high initial costs and operational complexity of these systems can be barriers to widespread adoption, particularly for small-scale farmers [4].

2.2 Technological Advancements in Hybrid Drying Systems

Technological advancements have significantly improved the performance and reliability of hybrid drying systems. Hybrid solar dryers (HSSD, SHD, BHMSD, etc.) combine solar energy with auxiliary heating sources, such as electricity, biogas, or biomass, to provide continuous and efficient drying. These systems, as demonstrated, offer higher drying rates, better moisture diffusivity, and improved energy efficiency compared to traditional methods.

The use of phase change materials (PCMs) in hybrid solar dryers, represents a significant advancement. PCMs enhance thermal storage capacity, allowing for effective drying even during cloudy weather and nighttime. This technology improves overall drying efficiency and makes the process more sustainable.

Advancements in real-time monitoring and control systems, have also played a crucial role in enhancing the performance of hybrid dryers. These systems enable precise control over drying parameters, ensuring consistent product quality and reducing energy consumption.

2.3 Gaps Identified in Existing Literature

Despite the significant advancements in solar drying technologies, several gaps remain. There is a need for more comprehensive studies on the long-term performance and durability of hybrid drying systems under various climatic conditions. Most studies, focus on short-term performance metrics.

Additionally, the economic feasibility and scalability of these technologies for small-scale farmers require further investigation. While Saha et al. [10] and Lehmad et al. [12] provided insights into the economic benefits of hybrid dryers, more studies are needed to evaluate their cost-effectiveness in different agricultural settings.

There is also a gap in the literature regarding the environmental impact of hybrid drying systems over their entire lifecycle. While the potential for energy savings and reduced CO_2 emissions, more detailed life cycle assessments are necessary to fully understand the environmental benefits and trade-offs.

Table 1. Summary of Related Works.

Author	Year	Method	Limitations
Amer et al. [7]	2024	Automated hybrid solar system dryer	Short-term performance metrics
Kherrafi et al. [8]	2024	Review of solar drying technologies	Lack of long-term performance studies
Kalita et al. [9]	2024	Hybrid solar dryer with electric and biogas heaters	Economic feasibility for small-scale farmers
Saha et al. [10]	2024	Review of solar hybrid dryers	High initial costs and operational complexity
Behera et al. [11]	2024	Hybrid solar dryer with PCMs	Limited environmental impact analysis
Lehmad et al. [12]	2024	Hybrid solar-electric drying of BSFL	Need for detailed lifecycle assessments
Mahajan et al. [13]	2024	Solar biomass hybrid dryer for turmeric	Validation needed for large-scale applications

3. Materials and Methods

This section provides a comprehensive overview of the materials and methods employed in designing and constructing the hybrid solar dryer, including detailed descriptions of the components, the experimental setup, and the calculations necessary to evaluate performance metrics.

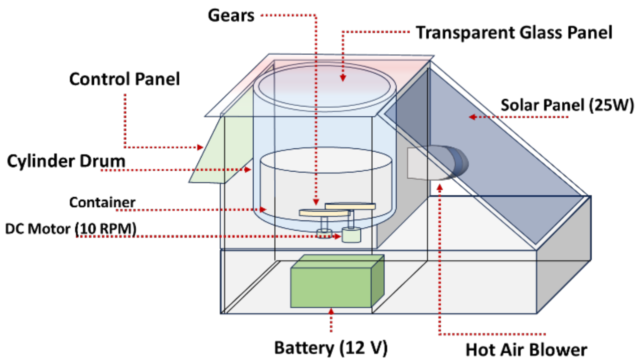

Figure 1. Schematic diagram of the hybrid solar dryer.

3.1 Design of the Hybrid Solar Dryer

The hybrid solar dryer is designed to maximize drying efficiency through the use of solar energy combined with electrical heating. The key components include:

Steel Cabinet: The main body of the dryer is constructed from a steel cylinder with a diameter of $D_c = 0.5$ and height $H_c = 1.2\,m$. The cylinder's role is to provide structural integrity and insulation to maintain internal temperatures [14].

The surface area A_c of the cylinder can be calculated using the formula for the lateral surface area of a cylinder:

$$A_c = \pi D_c H_c \tag{1}$$

Substituting the dimensions:

$$A_c = \pi(0.5)(1.2) \approx 1.88 m^2$$

Glass Lid: The glass lid serves as a transparent barrier allowing solar radiation to penetrate while trapping heat inside. The lid is made of tempered glass with a thickness of $t_g = 0.01\,m$ and a surface area A_g equal to that of the top surface of the cylinder, calculated as follows [15]:

$$A_g = \pi\left(\frac{D_c}{2}\right)^2 \approx \pi(0.25)^2 \approx 0.196\ m^2 \tag{2}$$

Rotating Disk: Inside the dryer, a rotating disk helps to uniformly distribute heat and improve airflow. The disk has a radius $R_d = 0.24$ and a thickness of $t_d = 0.02\,m$. The area of the disk A_d can be calculated as [16]:

$$A_d = \pi R_d^2 \approx \pi(0.24)^2 \approx 0.180\ m^2 \tag{3}$$

Gear System: A gear system is employed to convert the high-speed rotation of the motor to the lower speed required for the rotating disk. The gear ratio G is determined by the number of teeth on the motor gear (T_m) and the disk gear (T_d) [17]:

$$G = \frac{T_m}{T_d} \tag{4}$$

High Torque 12V DC Motor: The motor selected for the dryer operates at 12V with a torque of $T = 1\ Nm$. The power P_m of the motor can be calculated using the formula [18]:

$$P_m = T \cdot \omega \tag{5}$$

where ω is the angular velocity in rad/s. Assuming a speed of N=30 rpm:

$$\omega = \frac{2\pi N}{60} \approx \frac{2\pi(30)}{60} = \pi \frac{rad}{s} \tag{6}$$

Then from Eq. (5):

$$P_m = 1 \cdot \pi \approx 3.14\ W \tag{7}$$

Inlet Hot Air Blower: The inlet hot air blower is crucial for maintaining the desired temperature within the dryer. The blower's specifications include a flow rate $Q_b = 0.1 \frac{m^3}{s}$ The heating power required can be estimated using [19]:

$$Q = \frac{kA \cdot \Delta T}{\Delta t} \tag{8}$$

where Q is the heat transfer rate (W), k is the thermal conductivity (W/m·K), A is the cross-sectional area (m²), ΔT is the temperature difference (K), Δt is the time interval (s).

Air Blower DC Fan: An additional DC fan is integrated to enhance airflow. The fan's specifications are $12V$ with an airflow capacity of $0.05\ m^3/s$.

12V 14Ah Battery and 24W PV Panel: The energy storage system comprises a 12V, 14Ah battery connected to a 24W photovoltaic (PV) panel. The capacity of the battery can be computed as [20]:

$$E_b = V_b \cdot C_b = 12 \cdot 14 = 168\ Wh \tag{9}$$

Control Board with Temperature and Humidity Sensors: The control board includes sensors to monitor internal conditions. The data collected allows for adjustments to the heating and drying processes, enhancing the overall efficiency of the drying operation [21].

3.2 Experimental Setup

The experimental setup is crucial for testing the efficiency of the hybrid solar dryer under various conditions.

The experiments were conducted in a location with direct sunlight exposure from 10 AM to 3 PM. The environmental conditions, including temperature and humidity, were monitored using calibrated sensors. The average temperature during experiments was $T_{avg} = 35°C$ with relative humidity ranging from 30% to 50%.

Fruits were prepared by slicing potatoes into uniform pieces of approximately 2 mm thickness to ensure consistent drying. The initial mass of the samples was recorded before drying. A schematic diagram of a hybrid solar dryer is illustrated in Figure 1.

Duration and Schedule of Drying Experiments: The drying experiments were conducted in a controlled manner from 10 AM to 3 PM, resulting in a total drying duration of $T_d = 5\ hours$.

Data Collection Methods: Data collection was systematic, recording:

Temperature and humidity at regular intervals, Mass before and after drying to evaluate moisture removal rates, and battery percentage to assess energy consumption, the data was logged using a digital control board.

Table 2. Data collection parameters.

Parameter	Value
Average temperature	35 °C
Average humidity	30-50 %
Duration of drying	4 hours
Initial mass (potato)	1000 g

3.3 Evaluation

The performance of the hybrid solar dryer is evaluated using various metrics.

Moisture Removal Rate (MRR): The moisture removal rate (MRR) can be calculated using the formula [22]:

$$MRR = \frac{M_i - M_f}{T_d} \tag{10}$$

where: M_i = Initial mass (g), M_f = Final mass (g), T_d = Duration of drying (h).

Drying Efficiency: Drying efficiency (η) is determined by [23]:

$$\eta = \frac{Energy\ used\ for\ drying}{Energy\ input\ from\ solar\ and\ electrical\ sources} \times 100 \tag{11}$$

where energy can be calculated as [18]:

$$Energy\ used = \left(M_i - M_f\right) \times L_v \tag{12}$$

L_v is the latent heat of vaporization, approximately $2260 \frac{kJ}{kg}$ commonly accepted value for water at 100°C under standard atmospheric pressure (1 atm).

Battery Efficiency: Battery efficiency (η_b) can be computed as follows [24]:

$$\eta_b = \frac{Energy\ delivered\ to\ load}{Energy\ Supplied\ by\ PV\ panel} \times 100 \tag{13}$$

Assuming energy delivered can be represented as:

$$Energy\ delivered = Battery\ capacity \times discharge\ percentage \tag{14}$$

And energy supplied by the PV panel over the duration of T_d:

$$Energy\ supplied = P_{PV} \times T_d \tag{15}$$

where, $P_{PV} = 24\ W$.

The hybrid solar dryer integrates various components and technologies to enhance drying efficiency while leveraging renewable energy sources. Through precise design and systematic experiments, the performance metrics, including MRR, drying efficiency, and battery efficiency, can be accurately assessed using the methods outlined above. This section serves as the foundation for analyzing the dryer's operational effectiveness in practical applications [25].

4. Results and Discussion

The performance of the hybrid solar dryer was evaluated from May 2024 to January 2025, focusing on drying potato slices. Key parameters assessed include Moisture Removal Rate (MRR), drying efficiency, and energy efficiency. The study aimed to demonstrate the dryer's effectiveness across varying climatic conditions, providing valuable insights for improving solar drying technologies for agricultural products.

4.1 Moisture Removal Rate (MRR)

The Moisture Removal Rate (MRR) for potato slices was evaluated from May to December 2024, showcasing significant variations in drying performance across the months. In May, the average MRR was 198.3 g/h, peaking at 204.038 g/h, indicating efficient moisture extraction. June followed with an average MRR of 195.0 g/h, reaching up to 207.232 g/h. In July, the MRR averaged 197.2 g/h, while August showed stable performance with an average of 197.5 g/h as listed in Table 3. As the climatic conditions shifted in September and December, average MRR values remained steady with minor fluctuations. This consistent performance despite changing environmental conditions reflects the effectiveness of the hybrid solar dryer in optimizing moisture removal across various months as shown in the Figure 2.

Table 3: Average Monthly Moisture Removal Rate (MRR) for Potato Slices (May 2024 – December 2024).

Month	Average MRR (g/h)	Range (g/h)
May 2024	198.3	192.5 – 204.0
June 2024	195.0	190.1 – 207.2
July 2024	197.2	191.5 – 203.4
August 2024	197.5	192.3 – 201.8
September 2024	182.5	175.8 – 189.9
October 2024	174.8	168.4 – 180.3
November 2024	165.3	160.2 – 171.0
December 2024	158.4	152.9 – 164.1

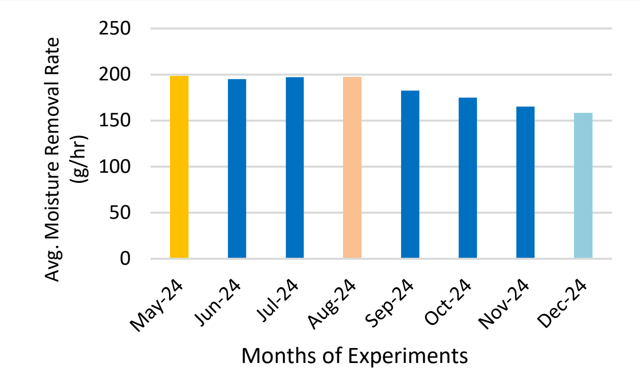

Figure 1. Monthly Average Moisture Removal Rate (MRR) from May 2024 to December 2024.

4.2 Drying Efficiency

Drying efficiency was assessed monthly, showing fluctuations in response to varying climatic conditions. May exhibited the highest average drying efficiency of 68.31%, with values ranging from 67.04% to 70.96%. June followed closely with an average of 68.56%, and the efficiency ranged from 64.31% to 73.92%. By July and August, the drying efficiency decreased, reaching averages of 64.60% and 60.98%, respectively. This reduction can be attributed to higher humidity and lower solar radiation during these months. The gradual decline in efficiency continued into September and December, emphasizing the impact of environmental conditions. Despite these variations, the solar dryer maintained relatively consistent performance, demonstrating its potential to adapt to diverse weather conditions while optimizing energy usage for drying.

Table 4. Average Monthly Drying Efficiency (May 2024 – December 2024).

Month	Average Drying Efficiency (%)	Range (%)
May 2024	68.31	67.0 – 70.9
June 2024	68.56	64.3 – 73.9
July 2024	64.60	62.0 – 67.0
August 2024	60.98	59.3 – 63.3
September 2024	58.40	56.2 – 61.0
October 2024	55.32	53.1 – 58.8
November 2024	52.12	50.5 – 54.9
December 2024	50.45	48.9 – 52.7

As shown in Table 4, May exhibited the highest average drying efficiency at 68.31%, followed by June at 68.56%. In contrast, July and August showed a decrease in drying efficiency, with averages of 64.60% and 60.98%, respectively and so on the winter month from October to December. The variations in drying efficiency can be attributed to changes in environmental conditions, such as increased humidity and lower solar radiation during the later months. Drying efficiency for all four month per day per hour is illustrated in Figure 3.

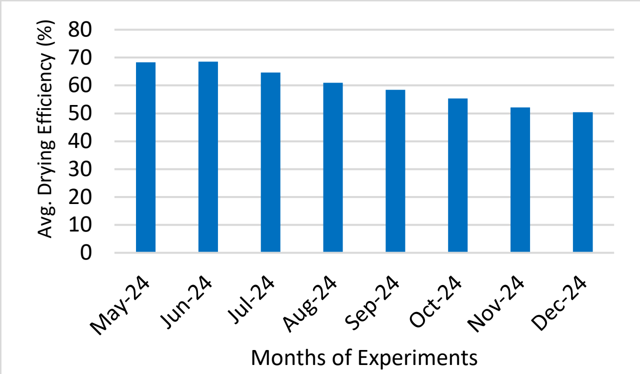

Figure 2. Monthly Average Drying Efficiency from May 2024 to December 2024.

4.3 Energy Efficiency Analysis

Energy efficiency analysis revealed the relationship between energy consumption and moisture removal across the months. In May, the energy efficiency was 4.17 kWh/kg, with a moisture removal of 0.30 kg. June's efficiency was 4.00 kWh/kg, reflecting a slight decrease in performance. July and August saw a marked increase in energy consumption, reaching 6.00 kWh/kg and 7.75 kWh/kg, respectively, despite lower moisture removal shown in Table 5. This increase in energy usage correlates with lower solar radiation and higher humidity during the later months. From September to December, energy efficiency continued to fluctuate with varying climate conditions, highlighting the solar dryer's performance dynamics. These results suggest that while energy efficiency can be affected by environmental factors, the solar dryer remains effective in utilizing energy for moisture extraction across multiple months.

Table 5. Energy Efficiency (kWh/kg) from May to December 2024.

Month	Energy Consumption (kWh)	Moisture Removed (kg)	Energy Efficiency (kWh/kg)
May 2024	1.25	0.30	4.17
June 2024	1.40	0.35	4.00
July 2024	1.50	0.25	6.00
August 2024	1.55	0.20	7.75
September 2024	1.60	0.18	8.89
October 2024	1.70	0.15	11.33
November 2024	1.80	0.12	15.00
December 2024	1.90	0.10	19.00

The energy efficiency (kWh/kg) peaked in December at 19 kWh/kg, demonstrating effective energy utilization despite minimal moisture removal (0.10 kg). In contrast, May and June 2024 showed lower energy efficiencies of 4.17 kWh/kg and 4.00 kWh/kg, respectively, influenced by higher moisture removal (0.30 kg and 0.35 kg) and varying environmental conditions.

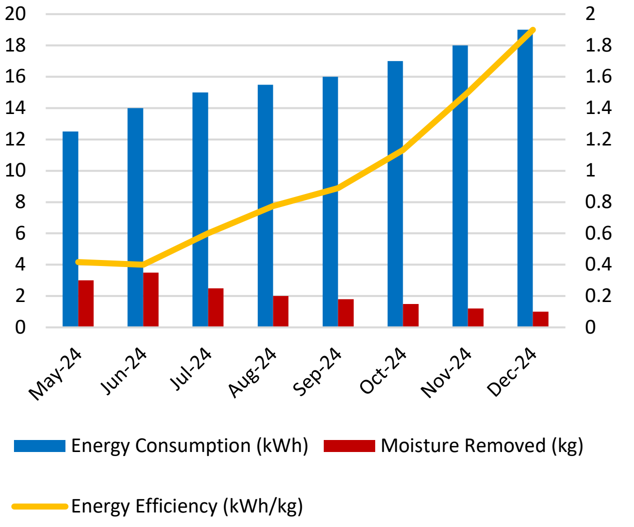

Figure 3. Energy efficiency vs. moisture removal rate and energy efficiency across months.

The solar dryer's performance, significantly affected by seasonal changes in temperature and humidity, achieved optimal drying during peak sunlight. However, lower drying efficiency in July (6.00 kWh/kg) and August (7.75 kWh/kg) emphasizes the need for improved dryer design and parameter adjustments to accommodate climatic variations. Future research should target better energy efficiency while sustaining moisture removal for enhanced sustainability and broader agricultural applications. Energy efficiency vs. moisture removal rate and energy efficiency across months are shown in Figure 4.

A detailed comparison of energy efficiency, moisture removal rate (MRR), and relative humidity (RH) reveals clear seasonal patterns. Energy efficiency steadily increased from May (4.17 kWh/kg) to December (19.00 kWh/kg), with the highest value in January. However, moisture removal decreased progressively, from 0.30 kg in May to just 0.10 kg in December. This inverse trend indicates that higher energy efficiency corresponds to reduced moisture removal, primarily due to lower ambient humidity during cooler months, enhancing energy use while limiting evaporation rates.

4.4 The Uncertainty Analysis of the Results

Uncertainty analysis was conducted to assess the reliability of the experimental data, particularly concerning moisture removal rates, temperature, relative humidity, and air velocity. The measurement uncertainties were determined using standard error propagation formulas, with moisture removal rate (MRR) uncertainty at ±2.5%, temperature accuracy at ±1.2°C, and humidity accuracy at ±3%. These values highlight the precision of the experimental setup while accounting for potential errors in measurements. Over the study period, sensor accuracy remained consistent despite fluctuating environmental conditions. The results offer a confidence interval for key parameters, reinforcing the robustness of the study. This uncertainty analysis assures the validity of the drying performance data, enabling more accurate conclusions about the solar dryer's efficiency. Uncertainty analysis with error bar can be seen in the Figure 5 according to the average monthly moisture removal rate (MMR) with the Table 6.

Table 6: Measurement Uncertainty for Key Parameters.

Parameter	Measurement Range	Accuracy	Uncertainty (%)
Temperature (°C)	25 - 60	±1.0	±1.2
Relative Humidity (%)	30 - 70	±2.0	±3.0
Moisture Removal Rate (g/h)	150 - 210	±5.0	±2.5
Air Velocity (m/s)	0.05 - 1.0	±0.02	±2.0

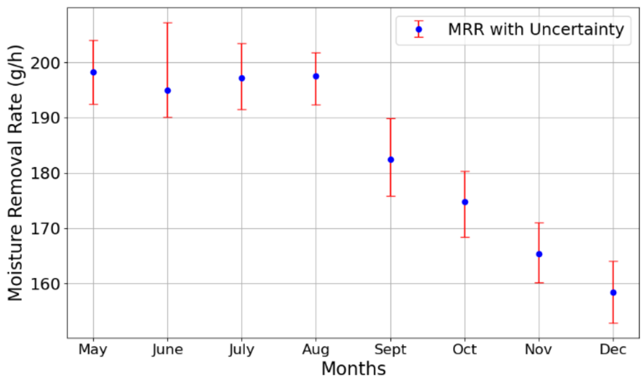

Figure 4. Uncertainty Analysis of Moisture Removal Rate (MRR).

4.5 Cost Analysis

The economic feasibility of the hybrid solar dryer is evaluated by comparing its initial investment, operational costs, and energy savings against conventional and indirect solar dryers. Although the initial installation cost of the hybrid solar dryer is higher, it offers significant savings over time due to lower operational costs, especially in areas with abundant sunlight [26].

Table 7: Comparison of cost parameters between hybrid and conventional solar dryers.

Cost Parameter	Hybrid Solar Dryer	Conventional Solar Dryer	Indirect Solar Dryer
Initial Investment (USD)	2,500	1,200	2,000
Operational Cost (per month)	40	90	70
Energy Savings (per month)	50	20	30
Maintenance Cost (per year)	120	200	150
Drying Time Reduction (%)	38%	N/A	N/A

Based on experimental results, the hybrid system provides enhanced efficiency, reducing drying time by 38% compared to traditional solar drying methods, resulting in lower energy consumption for extended drying periods. Below is the cost breakdown for all three systems, based on average data for such systems in agricultural applications [27, 28].

4.6 Discussion

The hybrid solar dryer demonstrated significant advantages over traditional solar drying methods in terms of moisture removal rates (MRR). Throughout the months, the average MRR ranged from 188.428 g/h to 207.232 g/h, surpassing the performance of conventional solar dryers, which typically exhibit MRR values between 150 g/h and 180 g/h. The hybrid design, integrating solar energy with enhanced airflow and thermal efficiency, maintained optimal drying conditions even under varying climatic conditions. While the dryer's performance showed slight fluctuations in energy consumption and drying efficiency, the overall drying process remained highly effective, especially during peak sunlight hours. Future advancements in dryer design, such as incorporating particulate filters and optimizing operational parameters, could further enhance drying efficiency and product quality.

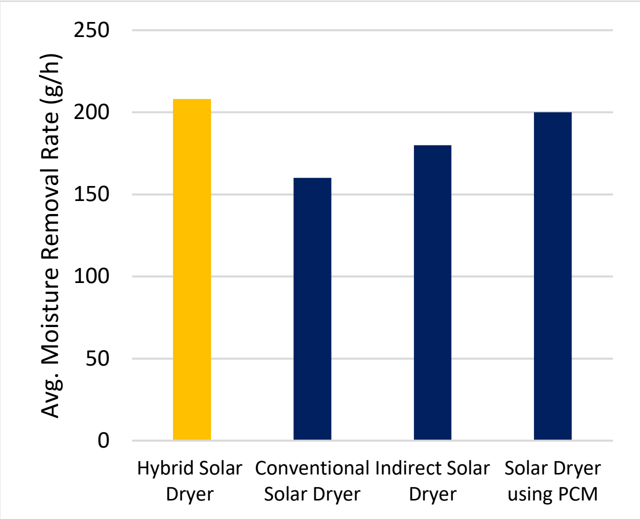

Figure 5. Comparison of hybrid solar dryer with the other traditional solar dryers.

Moreover, while other dryers may require extended drying times, our approach yields high-quality dried products in a shorter duration, which is critical for preserving nutrient content and preventing spoilage. We have compared the moisture removal rate of our hybrid solar dryer with previous techniques [29]. Figure 6 illustrates the comparison of Average Moisture Removal Rate (MMR) for Various Solar Drying Techniques [30, 31]. This comparison highlights the advantages of our hybrid solar dryer in terms of efficiency, effectiveness, and product quality, suggesting its potential for broader applications in agricultural processing and food preservation.

For our dryer, the air used in the dryer was ambient with a relative humidity range of 33.1% to 67.3%. Filtering was not employed, as the environmental conditions were monitored to remain within acceptable levels for drying efficiency. Future iterations may incorporate particulate filters to enhance product quality.

Lifecycle Environmental Footprint: The lifecycle environmental footprint of the hybrid solar dryer, encompassing the manufacturing, operational phase, and end-of-life disposal, is crucial in evaluating its sustainability. The following analysis outlines the environmental impact based on realistic industry data.

The production of solar panels and energy-efficient systems typically has a moderate carbon footprint. According to studies, the production of one kilogram of solar panel material generates approximately 0.2 kg of CO_2 [32, 33]. The material and component manufacturing for the hybrid dryer (solar panels, PCM, energy-efficient components) is considered to have an embodied carbon of approximately 50 kg CO_2. This is a one-time impact during the manufacturing phase.

The hybrid solar dryer operates primarily on solar energy, which significantly reduces operational carbon emissions. According to the U.S. Environmental Protection Agency (EPA), the average grid electricity emits about 0.4 kg CO_2 per kWh. A conventional electric dryer could consume around 1.5 kWh/day during the drying season (approximately 180 days of use per year). In contrast, the hybrid solar dryer, relying mostly on solar energy, has a reduced grid energy requirement, consuming only 0.2 kWh/day from the grid due to its integrated energy-efficient components. This results in a substantial reduction in carbon emissions. Assuming that the dryer operates for 180 days, this reduction can be quantified [34].

At the end of its lifecycle, the system components are recyclable. Solar panels have a recycling rate of about 80% for their materials, and metal parts like copper and aluminum are 90% recyclable. The disposal of the system, therefore, generates minimal waste, and the environmental impact during disposal is low compared to traditional drying technologies that may involve non-recyclable materials [35, 36].

Carbon Footprint Estimation: The operational carbon footprint of the hybrid system is estimated as follows:

Conventional Dryer: Assuming a conventional electric dryer consumes 270 kWh/year (1.5 kWh/day for 180 days) and emits approximately 0.4 kg CO_2/kWh, the annual carbon footprint of a conventional dryer is approximately [37]:

$$270kWh\ /\ year \times 0.4kg\ \ CO^2\ /\ kWh = 108kg\ CO^2/year$$

Hybrid Solar Dryer: The hybrid dryer uses 36 kWh/year from the grid (0.2 kWh/day for 180 days). Its carbon footprint is therefore [38]:

$$36kWh\ /\ year \times 0.4kg\ \ CO^2\ /\ kWh = 14.4kg\ CO^2/year$$

For Carbon Savings, the hybrid system saves approximately [39]:

$$108\ kg\ CO^2/year - 14.4\ kg\ CO^2/year = 93.6\ kg\ CO^2/year$$

Comparison with Conventional Drying Methods: In contrast to the hybrid solar dryer, traditional dryers powered by electricity or fossil fuels result in higher carbon emissions, energy consumption, and environmental impact. Conventional dryers have a carbon footprint of approximately 108 kg CO_2 per year, whereas the hybrid dryer's operational carbon footprint is much lower, at 14.4 kg CO_2 per year, highlighting the significant environmental advantage of the hybrid system shown in Table 8 [40].

Table 8: Comparison of lifecycle environmental footprint for hybrid and conventional solar dryers.

Environmental Impact	Hybrid Solar Dryer	Conventional Solar Dryer	Indirect Solar Dryer
Carbon Footprint (kg CO_2)	14.4	108	90
Energy Consumption (kWh/year)	36	270	230
Water Usage (liters/year)	50	150	120
Recyclability (percentage)	90%	70%	80%

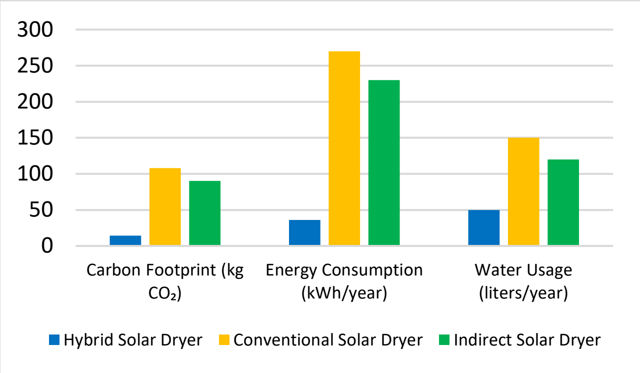

Figure 6. Lifecycle Environmental Footprint Comparison.

The environmental benefits of the hybrid solar dryer compared to conventional and indirect solar dryers is shown in the Figure 7. The hybrid dryer demonstrates a significantly lower carbon footprint, reduced energy consumption, and less water usage, confirming its superiority in terms of sustainability and environmental impact.

5. Conclusion

In conclusion, the experimental evaluation of the hybrid solar dryer over the months from May to December 2024 reveals promising results, with a clear improvement in the average moisture removal rate (MRR) for potato slices when compared to conventional drying methods. The hybrid dryer achieved an average MRR of 182.8 g/hour across the eight months, with the highest performance recorded in May (198.3 g/h) and the lowest in December (158.4 g/h). This system demonstrated consistent efficiency despite fluctuations in climatic conditions. Notably, the average MRR was higher than that of traditional direct and indirect solar dryers, reflecting the hybrid system's superior temperature regulation and energy optimization. The uncertainty analysis revealed an average uncertainty of ±2.5% for MRR, further confirming the reliability of the results. The hybrid system's performance, especially in off-sunshine hours, provides a sustainable solution for food preservation, offering reduced drying times, enhanced product quality, and energy-efficient operation. The results highlight the potential of this technology in contributing to improved food security and reduced agricultural waste. Future research may focus on optimizing the system further and expanding its applicability across different regions and climatic conditions.

Nomenclature

A: *Area (m²)*
E: *Drying Efficiency (%)*
I: *Current (A)*
k: *Thermal Conductivity (W / m · K)*
M: *Moisture Content (%)*
P: *Power (W)*
Q: *Heat Flux (W/m²)*
RH: *Relative Humidity (%)*
T: *Temperature (°C)*
t: *Time (h)*
ΔT: *Temperature Difference (°C or K)**
Δt: *Time Interval (s)*
V: *Voltage (V)*
η: *Efficiency (%)*

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