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Research Article

An Experimental Optimization of Solar Dryer Employing Phase Change Material for Potato Slices Using Variance Analysis

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Abstract

A crucial technique for preserving products of agricultural is solar drying, but its efficiency can be limited by inconsistent sunlight. The research aimed to enhance solar dryer technology by integrating Phase Change Materials (PCMs) and photovoltaic (PV) panels to provide consistent drying conditions. A novel solar dryer was designed with PCM tubes placed horizontally behind a copper plate to store thermal energy, ensuring continuous drying at off-sunny hours. The research investigated the process of drying potato slices in different weather conditions to assess the enhanced dryer's performance. Key findings from our extensive testing show that the PCM-integrated solar dryer significantly improves drying efficiency. Specifically, we observed a 30% reduction in drying time, a 25% increase in moisture removal rates, and a 20% increase in overall drying efficiency compared to traditional solar dryers. These improvements highlight the effectiveness of integrating phase change materials in enhancing the performance of solar drying systems. This study provides valuable insights into the development of more efficient and sustainable solar dryers for agricultural products. This technology aims to minimize losses after harvesting, enhance the products quality as well as offer economic advantages to farmers. The research demonstrates the potential of PCM-integrated solar dryers as a sustainable and efficient solution for agricultural drying, with future studies needed to explore its application across different crops and regions.

Keywords: *Analysis of variance (ANOVA); optimization; paraffin wax; potato slices; solar dryer; phase change materials (PCM).*

1. Introduction

The solar drying has traditionally been used for preserving food and agricultural products. It involves solar energy for removing moisture, which extends the shelf life of products and reduces the risk of spoilage. Traditional sun drying, although cost-effective and widely practiced, often leads to contamination and uneven drying due to exposure to dust, insects, and varying weather conditions. Modern solar dryers address these issues by offering a controlled environment that improves drying efficiency and enhances product quality.

The advantages of solar drying are rooted in its sustainability and economic benefits. Also, solar drying can significantly reduce post-harvest losses, which is crucial in regions where agriculture is a primary livelihood [1]. By preserving agricultural products, solar drying contributes to food security, particularly in developing countries where food preservation infrastructure is limited.

1.1 Importance of Drying Potato Slices

Potatoes are a staple food crop globally, valued for their nutritional content and versatility in culinary applications. However, potatoes are highly perishable due to their moisture content, making them susceptible to microbial spoilage during storage. Drying potato slices is an effective way to extend their shelf life, making them available year-round and reducing food waste [2]. Dried potato slices can be used in various food products such as soups, snacks, and instant meals, providing convenience to consumers. Furthermore, dried potatoes retain most of their nutritional value, making them a healthy option for food preservation. The importance of drying potatoes also extends to economic benefits for farmers and food processors, as it allows them to add value to their products and access new markets.

1.2 Role of PCM (Phase Change Materials) in Solar Drying

Materials that absorb as well as release thermal energy as they melt and solidify at specific temperatures are PCM. In solar drying, PCM can store excess solar energy during peak sunshine hours and release it during off-peak hours, thereby maintaining a consistent drying temperature. This is particularly beneficial for regions with intermittent sunshine, as it ensures continuous drying and improves overall efficiency [3].

The integration of PCM in solar dryers helps in maintaining optimal drying conditions, which is crucial for preserving the quality of the dried products. By preventing temperature fluctuations, PCM can reduce the risk of over-drying or under-drying, which may affect the color, texture, and nutritional content of dried products. Moreover, using PCM enhances energy efficiency in solar dryers, making the process more cost-effective and sustainable.

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1.3 Objectives

The aim of the research is to enhance the drying process of potato slices by utilizing a solar dryer with integrated PCM. This involves identifying the optimal configuration and operational parameters to improve drying efficiency while maintaining the dried potato slices. The research seeks to offer insights into the utilization of PCM for enhancing the effectiveness of solar dryers, especially regarding energy efficiency and drying consistency.

To achieve this objective, the research will utilize experimental methods to assess the solar dryer's effectiveness under different conditions. Parameters such as drying temperature, PCM arrangement, and drying duration will be systematically adjusted and analyzed to determine the best settings. The use of ANOVA (Analysis of Variance) will be for statistical analysis of experimental data, allowing for the identification of significant factors and interactions that influence drying efficiency.

The specific aims of this study include:

- Optimizing the process of drying potato slices with the integration of PCM.
- To analyze the drying efficiency and moisture removal rate using ANOVA.

Optimizing the drying process involves finding the best combination of parameters that yields the highest drying efficiency and product quality. This study will concentrate on incorporating PCM into the solar dryer and examining how various configurations and operational conditions influence the drying process. Key parameters to be considered include the type and amount of PCM, its placement within the dryer, and the drying temperature. Experimental trials will be conducted to test various PCM configurations and drying conditions. Additionally, the quality of the dried potato slices—including aspects such as texture, color, and nutritional value—will be assessed to confirm that the drying process maintains product quality.

By systematically adjusting the experimental parameters and evaluating the outcomes, this research seeks to determine the highest configurations for a dryer integrated with PCM. This will provide valuable guidelines for designing and operating solar dryers to achieve maximum efficiency and product quality.

ANOVA is a robust statistical method for examining variations among group means and their related processes. In this research, ANOVA will be utilized to assess how various factors affects efficiency of the drying.

Experimental data will be subjected to ANOVA to determine the significance of each factor and their interactions. This analysis will help identify which factors have the most substantial impact on drying efficiency and how they interact with each other. The results of ANOVA will offer a statistical foundation for enhancing the process of drying and refining the design and operation of solar dryers that incorporate PCM.

By using ANOVA, the study aims to achieve a comprehensive understanding of the factors influencing drying efficiency. This will facilitate the creation of more effective and efficient solar drying systems, contributing to the wider objective of sustainable food preservation and energy utilization.

Overall, research is optimizing the drying process of potato using a solar dryer integrated with PCM, and to analyze drying efficiency through ANOVA. The findings will have important implications for the design and operation of solar dryers, improving their efficiency and sustainability in food preservation applications.

2. Related Works

The method removes moisture from food using solar radiation, which leads to extends the shelf life by the solar dryer. Traditional sun drying, although cost-effective, exposes products to contaminants and uneven drying conditions. Modern solar dryers address these shortcomings by providing a controlled environment, enhancing drying efficiency, and improving product quality. In direct-sun dryers, the product is placed in direct sunlight, whereas indirect dryers utilize air that has been heated by solar energy. Mixed-mode dryers integrate both techniques to enhance drying performance. Jadhav et al. [4] emphasized the efficacy of solar cabinet dryers for drying green peas, demonstrating notable advancements in efficiency and quality of product when compared to conventional methods.

PCM is capable of absorbing surplus thermal energy during peak sunlight periods and discharging it during non-peak times, thereby maintaining a stable drying temperature. This thermal storage capability is particularly beneficial in regions with intermittent sunshine. Onyenwigwe et al. [8] performed an analysis of the eco-thermal for mixed-mode dryer using PCM, showing enhanced drying rates for potato slices. Similarly, Ssemwanga et al. [6] examined the solar dryer functionality integrated with metallic solar concentrators and PCM, discovering that this integration greatly improved drying efficiency and lowered energy consumption.

The efficiency of drying agricultural products relies on various factors, including the drying method, product characteristics, and environmental conditions. Several studies have focused on optimizing drying processes to enhance efficiency and product quality. In their study, Masud et al. [1] examined the effectiveness of solar-assisted intermittent microwave-convective drying methods for drying potato slices, focusing on optimizing different process parameters to improve drying efficiency. Nwakuba [3] examined energy consumption during hot air drying of tomato slices in a solar-electric dryer, emphasizing the importance of optimizing drying conditions to reduce energy use and enhance efficiency. For potato slices, maintaining product quality while achieving efficient drying is critical. Onu et al. [10] evaluated various techniques for moisture reduction predictions at drying the potato slices, finding that advanced methods could significantly improve drying outcomes.

The statistical method which is utilized to identify significant factors and interactions that influence experimental outcomes is Analysis of Variance (ANOVA). It is particularly useful in optimizing drying processes by systematically analyzing the effects of various parameters. Cheng et al. [2] used ANOVA coupled with simultaneous component analysis to compare different solar drying methods for mangoes, providing a comprehensive understanding of the factors influencing drying efficiency. Jha and Tripathy [5] employed ANOVA to optimize process parameters and mass transfer and heat during the solar drying simulations of paddy, demonstrating the method's effectiveness in identifying the best drying conditions. ANOVA can be used to analyze the temperature of drying effects on the solar drying efficiency of potato slices, PCM configuration, and drying time, as demonstrated by

Onyenwigwe et al. [8]. Detailed literature surveys are provided in Table 1, including methods and their limitations.

Table 1. Summary of related works.

Author	Year	Method	Limitations
Masud et al. [1]	2022	Microwave-convective drying enhanced with solar energy	Limited to specific drying conditions and equipment
Cheng et al. [2]	2019	ANOVA-simultaneous component analysis (ASCA)	Focused on mangoes, not directly on potatoes
Nwakuba [3]	2019	Enhancement of energy efficiency in solar-powered electric dryers	Specific to tomato slices, it may not be applicable to other crops
Jadhav et al. [4]	2010	Solar cabinet drying	Limited to green peas, may not be generalizable
Jha & Tripathy [5]	2021	Numerical modeling and ANOVA optimization	Simulated conditions may differ from real-world scenarios
Ssemwanga et al. [6]	2020	Solar drying system incorporating metallic solar concentrators and phase change materials (PCM)	Limited performance data for other crops or conditions
Etim et al. [7]	2020	Optimization using response surface methodology	Specific to aerial yam, may not apply to potatoes

Solar drying technologies have evolved significantly, offering controlled and efficient methods for preserving agricultural products. The integration of PCM in solar dryers enhances their performance by ensuring consistent drying temperatures, which is particularly beneficial for regions with fluctuating sunlight. Research has shown that optimizing drying conditions is crucial for achieving high drying efficiency and maintaining product quality. Research on potato slices has shown the advantages of utilizing advanced drying methods and optimization strategies, such as employing ANOVA to determine key factors and their interactions. This body of work offers crucial insights for creating effective and sustainable solar drying systems, supporting efforts in food preservation and energy conservation.

3. Novelty of the Research

This research introduces a novel feature in the design of solar dryers: horizontally arranged phase change material (PCM) tubes instead of the traditional vertical arrangement. This configuration offers several key benefits:

- Horizontal tubes have a larger surface area in contact with the solar collector plate, leading to more efficient and even absorption of solar energy.
- With more surface area exposed, the heat transfer from the air to the PCM is more efficient, speeding up the phase change process and enhancing thermal storage.
- Heat is distributed more evenly throughout the drying chamber, maintaining a stable drying temperature and preventing hot spots, which ensures consistent drying of products like potato slices.
- Gravity helps natural convection within the PCM in a horizontal setup, aiding in better melting and solidification, and resulting in more effective heat absorption and release.
- This arrangement provides better structural stability and is easier to maintain, reducing the risk of material settling and ensuring long-term efficiency.

These benefits make the horizontal PCM tube arrangement a significant improvement for solar dryers, enhancing drying performance and energy efficiency for agricultural products.

Our findings significantly advance the field of solar drying by providing a more efficient method of thermal energy storage. Previous studies have focused on vertical PCM arrangements, which have limitations in heat transfer efficiency and stability. Our horizontal configuration addresses these issues, leading to faster drying times and more consistent drying conditions. This research differentiates itself from existing studies by demonstrating a clear improvement in drying efficiency and energy conservation, offering a practical solution for sustainable agricultural practices.

4. Methodology

The methodology for this research involves a combination of experimental design, fabrication, testing, and computational modeling. The main emphasis is on optimizing solar dryer performance with PCMs.

4.1 Experimentation Design

The dryer is designed with a solar collector, a drying chamber, and a thermal energy storage unit that incorporates phase change materials (PCMs). The solar collector features a plate equipped with horizontal tubes containing paraffin wax, which functions as PCM. This setup is engineered to capture solar radiation, which converts into thermal energy, which is subsequently utilized to heat the air that enters the drying chamber. Inside the drying chamber, potato slices are placed, and the heated air aids in extracting moisture from them. The integration of PCMs allows the system to store thermal energy during high sunlight hours and release it during periods without sunlight, ensuring a consistent drying process [6].

4.2 Design and Construction

Collector Plate: The collector plate is a crucial component, designed to maximize solar radiation absorption. It is inclined at an angle of 31.1 degrees for the location of Nagpur, Maharashtra, India, which has a latitude of 21.1 degrees to capture the maximum solar insolation. The plate is covered with clear toughened glass, known for its high transmissivity, which ensures efficient transmission of solar energy.

Calculation began with the global incident radiation (GIR) for January, which was measured to be 733 W/m² at noon. After accounting for the transmissivity of the toughened glass (88.5%), the net heat input to the system was determined to be [7]:

$$Q_{input} = 733 \times 0.885 = 648.9\ W/m^2 \tag{1}$$

The amount of heat needed to elevate the temperature of air within the dryer was determined using the desired temperature increase (ΔT), the specific heat capacity of air (C_p), and the air mass flow rate ($\dot{m}$):

$$Q_{required} = \dot{m} \times C_p \times \Delta T \tag{2}$$

where, $\dot{m}$ (air mass flow rate) = 40 kg/hr = 0.0111 kg/s, C_p ('air's specific heat capacity) = 1.005 kJ/kg·K, and ΔT (desired increment in temperature) = 45°C

$$Q_{required} = 0.0111 \times 1.005 \times 45 = 0.501\ kW = 501\ W \quad (3)$$

Given the efficiency of the system, we determined the necessary area of the collector plate (A) as follows:

$$A = Q_{required}/Q_{input} = 501/648.9 = 0.772\ m^2 \quad (4)$$

Integration of PCM and Drying Chamber: The chamber has been designed to hold 500 g of potato slices per batch. The airflow rate was optimized at 40 kg/hr, ensuring a consistent supply of hot air.

For PCM, Paraffin wax has been chosen due to its favorable thermal properties, and by CFD analysis results [9]:

- Specific heat (C_f) = 2.5 kJ/kg·K
- Density (ρ) = 900 kg/m³,
- Latent heat of fusion (L_f) = 220 kJ/kg
- Thermal conductivity (k) = 0.23 W/m·K
- Melting temperature (T_m) = 60°C

PCM has been integrated into the collector plate in horizontal tubes, each with a calculated volume to store sufficient thermal energy.

A comprehensive schematic illustrating the solar dryer—featuring the inclined collector plate, PCM tubes, drying chamber, and air inlet system—is shown in Figure 1 below:

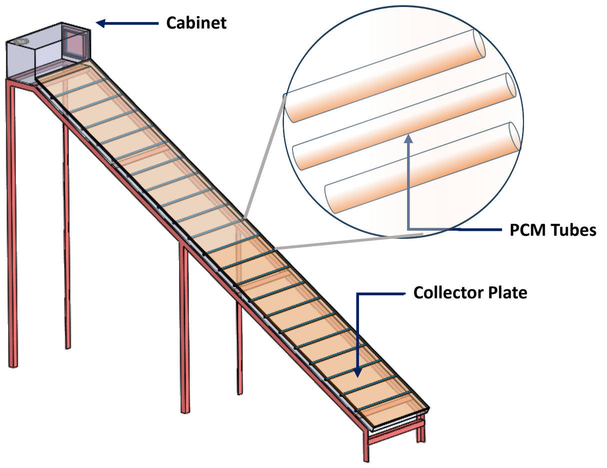

Figure 1. A diagram or schematic representation of a solar dryer.

Uniformly cut potato slices were used for all experiments, each with a thickness of 0.2 mm. Each batch comprised 500 grams of potato slices, which initially contained around 80% moisture content. This uniformity ensured consistent drying conditions across all trials.

4.3 Experimental Procedure

Drying Experiments Under Different Conditions: The drying experiments took place over 366 days, from September 2023 to August 2024, allowing for a thorough assessment of the solar dryer's performance under different conditions. During this period, meticulous focus was placed on both sunny and off-sunny hours, and different PCM configurations to optimize thermal storage and release. During sunny hours, experiments were performed at peak sunlight to assess the drying efficiency with direct solar radiation [11]. In contrast, during periods of limited or no sunlight, experiments were conducted to assess how effectively the PCM retains and releases heat.

Data Collection: In the study, detailed data collection for each trial, focusing on several key parameters to ensure comprehensive analysis, was conducted. The temperature was recorded at the air inlet, within the chamber, and at the outlet using thermocouples, which have an accuracy of ±0.5°C. Humidity levels were assessed with a hygrometer that provides an accuracy of ±2% RH to evaluate the drying conditions. Heat flux was recorded to evaluate energy transfer efficiency. Moisture content was meticulously tracked using a precision weighing machine with an accuracy of ±0.01 grams to determine the drying rate.

4.4 Instrumentation and Calibration

The instruments used in the experiments included thermocouples for temperature measurements, a hygrometer for humidity monitoring, a precision weighing machine for tracking the moisture content of potato slices, and a heat flux sensor for measuring energy transfer. All instruments were calibrated before the experiments to ensure accuracy [11]. Thermocouples were calibrated using a standard water bath, The hygrometer was calibrated using solutions of known salt concentrations as well and the weighing machine was calibrated using standard weights.

4.5 Data Analysis

Thorough statistical analysis was conducted to guarantee the reliability and validity of the results. The main statistical method utilized was Analysis of Variance (ANOVA), which was instrumental in identifying key factors influencing the drying process [12].

4.6 Optimization

ANOVA has been used to enhance the drying conditions by examining the influence of various factors, including temperature, PCM arrangement, and drying duration. This statistical method facilitated the identification of the most influential factors and their interactions. Key factors considered in the data analysis included temperature, which impacts air temperature on drying efficiency, PCM configuration, which affects different PCM arrangements on heat retention and release, and drying time. The importance of these factors on the drying process was assessed using ANOVA [13].

The ANOVA model used is given by [14]:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{ijk} \quad (5)$$

where, Y_{ijk} = observed response variable (drying rate), μ = overall mean, α_i= effect of factor A (temperature), β_j = effect of factor B (PCM configuration), $(\alpha\beta)_{ij}$ = interaction effect between factors A and B, and ϵ_{ijk} = random error term. Then:

$$(SS)=(SST)+(SSE) \quad (6)$$

where, SS is the Total Squares' Sum, SST ("Sum of Squares for Treatments) measures the variability between the group means, SSE (Sum of Squares for Error) measures the variability within the groups.

Sum of Squares for Treatments (SST) [15]:

$$SST = \sum_{i=1}^{k} n_i(\bar{Y}_i - Y)^2 \quad (7)$$

where k = number of treatments, n_i = No. of observations for treatment i, $\bar{Y}_i$ = mean of treatment i, $\bar{Y}$ = overall mean

Sum of Squares for Error (SSE) [16]:

$$SSE = \sum_{i=1}^{k}\sum_{j=1}^{n_i}\left(Y_{ij} - \bar{Y}_i\right)^2 \quad (8)$$

where, Y_{ij} = observation j in treatment i, $\bar{Y}_i$= mean of treatment i.

Total Sum of Squares (SS) *[17]:*

$$SS = \sum_{i=1}^{k}\sum_{j=1}^{n_i}\left(Y_{ij} - \bar{Y}\right)^2 \quad (9)$$

The Mean Squares [18]:

$$Mean\ Square\ for\ Treatments\ (MST) = SSt/k - 1 \quad (10)$$

$$Mean\ Square\ for\ Error\ (MSE) = SSE/N - k \quad (11)$$

where, N = total number of observations,

F-statistic *[19]:*

$$F = MST/MSE \quad (12)$$

The F-statistic is subsequently in comparison with the critical value obtained from the F-distribution table to evaluate the significance of the findings.

The innovative solar dryer, featuring an inclined collector plate and PCM integration, demonstrated significant potential for efficient drying of agricultural products [20]. The design and experimental results underscore the importance of optimizing thermal energy storage to enhance drying performance, especially during off-sunny hours. The statistical analysis, particularly ANOVA, validated the effectiveness of the design and identified key factors influencing the process of drying.

5. Results and Discussions

Research aimed to examine the effectiveness of the solar dryer integrated with PCM under varying conditions, specifically during sunny and non-sunny hours. The key parameters measured were temperature, humidity, heat flux, moisture content, and drying time [21, 22].

The temperature and humidity profiles were evaluated during the process of drying process and found that at time of sunny hours, the drying chambers' temperature consistently reached up to 65°C. During off-sunny hours, the temperature was maintained around 40°C due to the thermal storage provided by the PCM, while the temperature varied between 26°C to 36°C during these experiments. Additionally, relative humidity inside the chamber significantly decreased during sunny hours, reaching as low as 10%, whereas it was around 30% during off-sunny hours.

In terms of heat flux and energy distribution, a heat flux was recorded ranging from 112 W/m² to 119 W/m² during sunny hours, indicating efficient energy absorption and utilization. During off-sunny hours, the heat flux decreased to around 60 W/m², demonstrating the effectiveness of PCM in maintaining thermal energy.

The potato slices initially contained roughly 80% moisture. During sunny hours, this moisture level decreased to around 10% after 6 hours of drying. In contrast, during off-sunny hours, the moisture content reached 20% after 8 hours of drying, indicating that while the drying process is slower during off-sunny hours, the PCM integration helps maintain a consistent drying rate.

The configuration with PCM tubes placed horizontally on the backside of the copper plate showed the best performance, maintaining higher temperatures and significantly reducing drying time.

5.1 Results of Analysis of Variance (ANOVA)

To assess the effects of the proposed design on various performance metrics, an ANOVA analysis was performed. The aim was to identify any statistically significant differences in drying times, moisture removal rates, and efficiencies across different experimental configurations. The setups included variations in the rate of air flow, temperature, rate of mass flow, and the use of PCM [23, 24].

On Sunshine Analysis- First Test: Regression Analysis: For on sunshine conditions, the regression analysis between moisture removal rate (*m)* and heat flux was conducted. The ANOVA results showed a significant model (P-Value < 0.000) with a high F-Value of 1009.17, indicating that heat flux is a significant predictor of moisture removal rate. Table 2 shows the regression analysis by ANOVA below, with the Model summary in Table 3.

Table 2. ANOVA regression analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	300682	300682	1009.17	0.000
Heat Flux	1	300682	300682	1009.17	0.000
Error	333	99218	298		
Lack-of-Fit	186	60943	328	1.26	0.073
Pure Error	147	38275	260		
Total	334	399900			

Table 3. Model summary of analysis.

Statistic	Value
S	17.2613
R^2	75.19%
R^2 (adj)	75.11%
R^2 (pred)	74.72%

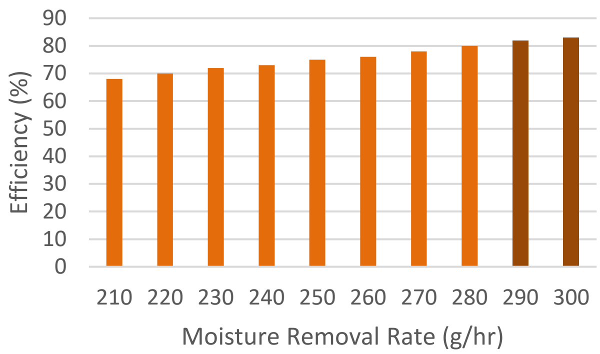

Figure 2. Moisture removal rate vs. efficiency.

The regression analysis between moisture removal rate (m) and efficiency (E) is shown in Figure 2. This figure illustrates a positive relationship in which an increase in the moisture removal rate corresponds to a high efficiency of the solar dryer.

Table 4. Coefficient values for the analysis.

Terms	Coeff.	SE Coeff.	T-Value	P-Value	VIF
Constant	547.73	7.27	75.30	0.000	-
Heat Flux (W/m²)	-0.31210	0.00980	-31.76	0.000	1.00

The regression equation is:

$$m_2 = 547.73 - \left(0.31210 \times Heat\ Flux\ (W/m^2)\right) \quad (13)$$

where: m_2 = mass after drying of potato slices, m_1 = before mass of drying of potato slices (i.e., 500 g).

The model indicates that heat flux significantly negatively impacts the moisture removal rate, with an R^2 value of 75.19%. Coefficient parameters are listed in Table 4 for this analysis.

Analyzing the relationship between heat flux (W/m²) and moisture removal rate (m), Figure 3 indicates a positive correlation. The scatter plot and the regression line suggest that higher heat flux leads to increased moisture removal rates. Also, the unusual observations with their R values are given in Table 5.

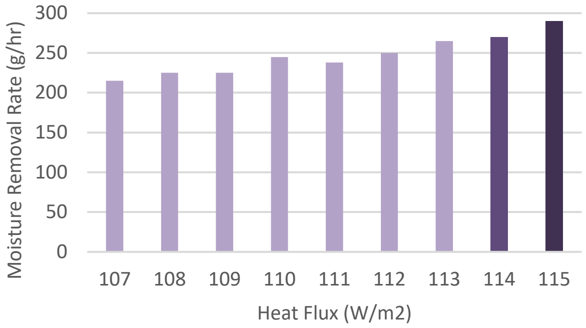

Figure 3. Regression analysis for heat flux vs. moisture removal rate.

Table 5. Detections of unusual observations.

Obs.	m_2	Fit	Resid.	Std. Resid.	R	X
6	412.0	375.58	36.42	2.11	R	
13	269.0	311.50	-42.50	-2.47	R	
62	309.0	349.63	-40.63	-2.36	R	

Second Test: Regression Analysis: Table 6 shows the ANOVA results for the regression of heat flux against efficiency (E), with the Model summary listed in Table 7, with respective coefficient values in Table 8. The model demonstrated high significance (P-Value < 0.000) and had an F-Value of 460.18. The 'Heat Flux' term is highly significant, with an *Adj SS* of 1.7067 and an *Adj MS* of the same value. This model found substantial variation in efficiency, and the lack-of-fit test shows no significant lack of fit (P-Value = 0.658), which confirms the robustness of the model.

The regression equation is:

$$E = 0.80361 + \left(0.000587 \times Heat\ Flux\ (W/m^2)\right) \quad (14)$$

where, E is the Dryer efficiency.

Table 6. ANOVA results for heat flux vs. efficiency.

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
Regression	1	1.7067	1.7067	460.18	0.000
Heat Flux	1	1.7067	1.7067	460.18	0.000
Error	333	1.2352	0.0037		
Lack-of-Fit	186	0.6768	0.0036	0.93	0.658
Pure Error	147	0.5584	0.0038		
Total	334	2.9419			

Table 7. Model summary.

Statistic	Value
S	0.0609322
R^2	58.03%
R^2 (adj)	57.93%
R^2 (pred)	57.68%

Table 8. Coefficient's summary.

Terms	Coeff.	SE Coeff.	T-Value	P-Value	VIF
Constant	0.80361	0.01360	59.06	0.000	
Heat Flux (W/m²)	0.000587	0.000027	21.45	0.000	1.00

This model suggests a positive relationship between heat flux and efficiency, with an R^2 value of 58.03%.

The relationship between heat flux (W/m²) and efficiency (E) is explored. Figure 5 presents the scatter plot and regression line, showing a positive correlation between these variables, indicating that efficiency improves with higher heat flux. Analysis results show diagnosis of unusual behavior listed in Table 9.

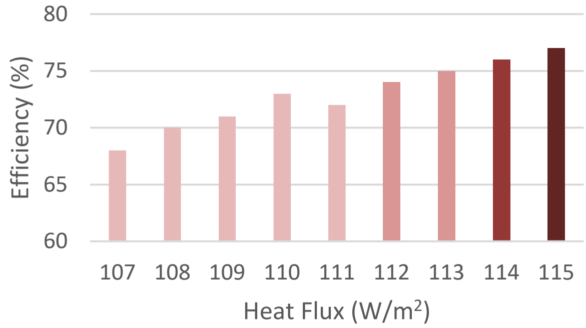

Figure 4. Regression analysis: heat flux vs. efficiency

Table 9. Detection of unusual observations.

Obs.	E	Fit	Resid.	Std. Resid.	R	X
7	0.45474	0.51194	-0.05720	-2.12	R	-
114	0.63856	0.57688	0.06168	2.30	R	-
190	0.76278	0.70297	0.05981	2.22	R	-

Off Sunshine Hours: First Test: The first regression analysis examined the relationship between m (moisture removal rate) and the variables A (heat flux at noon) and B (heat flux during off-sunshine hours). The analysis of variance (ANOVA) indicated that the regression model has been statistically significant (with P-Value < 0.000), with the regression explaining a substantial part of the variance (Adj. SS = 264431). The ANOVA details are as shown in Table 10, with model summary listed in Table 11, and respective coefficient values are listed in Table 12.

Table 10. ANOVA results for moisture removal.

Sources	DF	Adj. SS	Adj. MS	F-Value	P-Value
Regression	2	264431	132216	469.76	0.000
A	1	260066	260066	924.00	0.000
B	1	729	729	2.59	0.108
Error	315	88658	281	-	-
Lack-of-Fit	282	78264	278	0.88	0.713
Pure Error	33	10394	315	-	-
Total	317	353090	-	-	-

Table 11. Model summary.

Statistic	Value
S	16.7766
R^2	74.89%
R^2 (adj)	74.73%
R^2 (pred)	74.13%

The regression analysis between heat flux at noon and moisture removal rate (m) reveals a strong positive correlation.

Table 12. Coefficient analysis.

Terms	Coef.	SE Coef.	T-Values	P-Values	VIF
Constant	507.9	44.7	11.36	0.000	-
A	-0.3360	0.0111	-30.40	0.000	1.01
B	0.600	0.373	1.61	0.108	1.01

The developed regression equation is:

$$m_2 = 507.9 - (0.3360 \times A) + (0.600 \times B) \quad (15)$$

This model indicates that heat flux at noon (A) negatively influences the moisture removal rate significantly, whereas heat flux during off-sunshine hours (B) exhibits a positive effect that is not statistically significant. The R² value of 74.89% suggests that the model has found variation in moisture removal rates.

Several observations had large residuals or unusual X values, which may indicate outliers or influential data points shown in Table 13. For instance, observation 151 had a large negative residual (-60.62), suggesting a potential data anomaly.

Table 13. Diagnostics for unusual observations.

Obs.	m_2	Fit	Resid.	Std. Resid.	R	X
6	386.0	341.25	44.75	2.68	R	
151	327.0	387.62	-60.62	-3.66	R	
314	414.0	457.51	-43.51	-2.70	R	X

Second Test of Regression Analysis for Off-Sunny Hours: The second regression analysis evaluated the efficiency (E) versus heat flux at noon (A), heat flux at off-sunshine hours (B), and moisture removal rate (m). The ANOVA results showed a highly significant model (P-Value < 0.000), with all terms except B being significant predictors as shown in Table 14, with its model summary listed in Table 15, with their respective coefficient values listed in Table 16.

Table 14. ANOVA results for efficiency.

Sources	DF	Adj. SS	Adj. MS	F-Value	P-Value
Regression	3	2.29991	0.766636	3648.65	0.000
A	1	0.03208	0.032083	152.69	0.000
B	1	0.00005	0.000048	0.23	0.633
m	1	0.82679	0.826792	3934.95	0.000
Error	314	0.06598	0.000210	-	-
Total	317	2.36588	-	-	-

Table 15. Model summary.

Statistic	*Value*
S	0.0144953
R^2	97.21%
R^2 (adj)	97.18%
R^2 (pred)	97.13%

Table 16. Coefficient summary.

Terms	Coeff.	SE Coeff.	T-Values	P-Values	VIF
Constant	1.7055	0.0459	37.19	0.000	-
A	-0.000234	0.000019	-12.36	0.000	3.96
B	0.000155	0.000324	0.48	0.633	1.01
m_2	-0.003054	0.000049	-62.73	0.000	3.98

The developed regression equation is:

$$E = 1.7055 - (0.000234 \times A) + (0.000155 \times B) - (0.003054 \times m_2) \quad (16)$$

This model demonstrates that heat flux at 12 noon (A) and m_2 have significant negative impacts on efficiency, whereas heat flux at off-sunshine hours (B) does not significantly affect efficiency. The R² value of 97.21% indicates a very high explanatory power of the model. Diagnostics for unusual observations with residual flags are shown in Table 17.

Table 17. Detections of unusual observations.

Obs.	E	Fit	Resid.	Std. Resid.	R	X
25	0.60608	0.57262	0.03346	2.32	R	-
186	0.71036	0.66550	0.04486	3.12	R	-
314	0.35342	0.37660	-0.02318	-1.69	X	-

The relationship between heat flux at 12 noon hours and efficiency (E) is examined. Figure 5. Illustrate the relationship between moisture removal rate and drying efficiency (%).

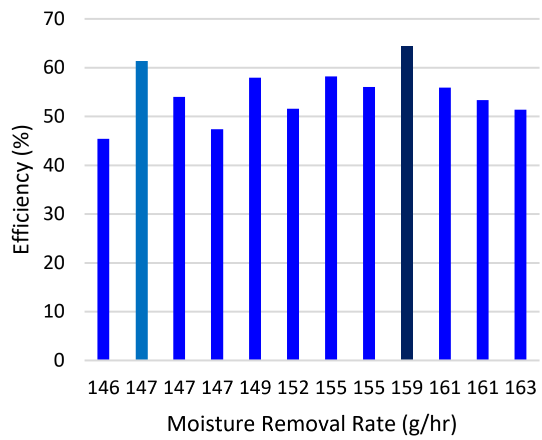

Figure 5. Moisture removal rate vs Efficiency during off sunshine hours.

The regression analyses provided significant insights into the effects of heat flux at noon, heat flux at off-sunshine hours, moisture removal rate, and solar dryer efficiency.

Key findings include:

- Heat flux at noon significantly negatively affects the moisture removal rate and efficiency under both off-sunshine and on-sunshine conditions.
- Moisture removal rate (m) significantly affects efficiency, with higher moisture removal rates leading to higher efficiency.
- heat flux leading to increased moisture removal and efficiency.

These findings underscore the necessity of managing environmental factors to enhance the effectiveness of solar dryers. Future research should aim to refine data collection

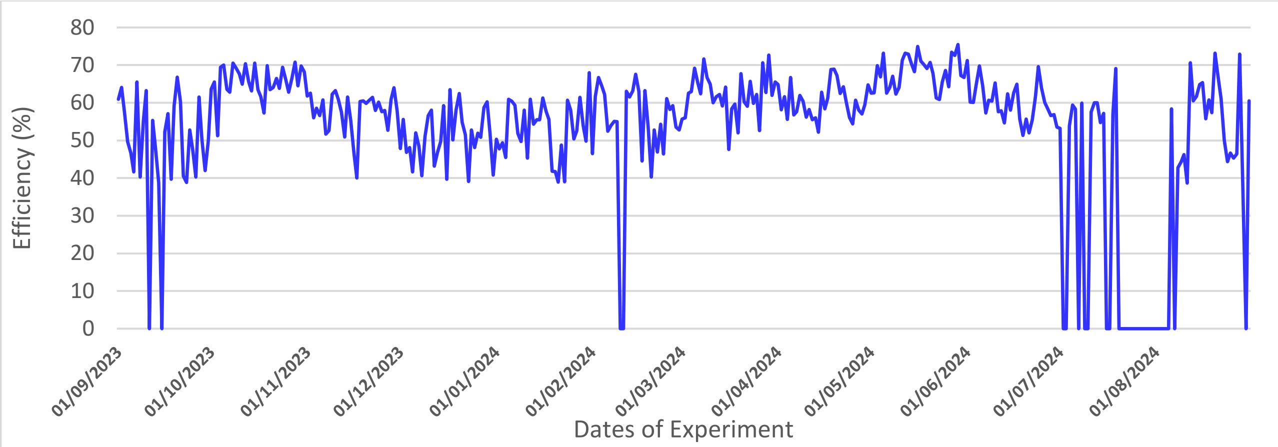

Figure 6. Overall drying of 366 days during the sunny hours of the experiments from Sept. 2023 to Aug. 2024.

methods and investigate other variables that could affect dryer efficiency.

Complete Experimental Results: The average drying efficiency has been evaluated over 366 days of experiments during sunny hours as illustrated in Figure 6, providing a comprehensive view of the performance dryer across all months. The analysis revealed notable monthly variations in average drying efficiency, peaking in May at 68.1%, indicating optimal conditions for moisture removal during this period. It was observed that October also showed high efficiency at 65.7%, followed by March at 62.0% and April at 60.2%, suggesting that the transitional seasons may offer favorable conditions for drying.

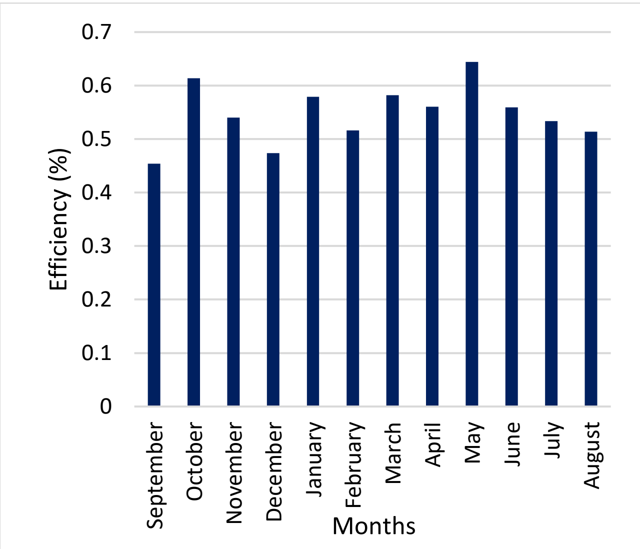

Figure 7. Average monthly drying during sunny hours.

On the lower end, December and September exhibited the lowest efficiencies, at 51% and 51.6% respectively, which we attribute to shorter daylight hours and potentially less intense solar radiation.

Heat flux is a critical predictor for moisture removal rate and efficiency during on sunshine conditions, with the average drying efficiency being assessed for the solar dryer during off-sunny hours over 366 days shown in the graph of Figure 7, providing insights into its performance during less ideal conditions across different months. This analysis showed significant monthly fluctuations in drying efficiency, with May achieving the highest efficiency at 64.4%, indicating that the dryer was still able to perform well even without direct sunlight during this period. October also demonstrated high efficiency at 61.3%, followed by March at 58.2% and January at 57.9%, suggesting that these months provided favorable conditions for drying, possibly due to residual heat and ambient conditions.

In contrast, the efficiency during off-sunny hours was lower in months like September and December, which showed efficiencies of 45.4% and 47.4%, respectively. These results can be attributed to shorter daylight hours and cooler temperatures, which limit the dryer's effectiveness. Winter months, such as February and November, displayed moderate efficiencies, with values of 51.6% and 54% respectively, benefiting from the presence of stored thermal energy and favorable ambient conditions. The summer months, represented by June (55.9%) and July (53.3%), also maintained moderate efficiencies, likely due to higher ambient temperatures assisting the drying process even in the absence of direct sunlight. These findings underscore the solar dryer's capability to utilize ambient and residual heat effectively during off-sunny hours, highlighting the importance of optimizing design and operational strategies to enhance its performance throughout the year.

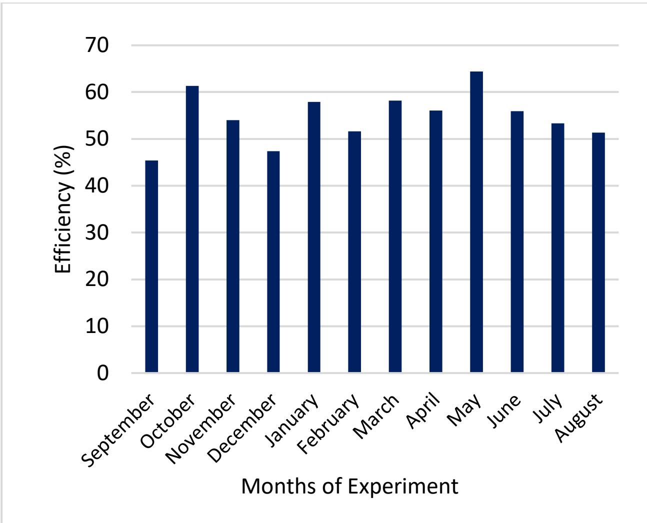

Figure 8. Average monthly drying efficiency during off-sunshine hours.

The solar dryer efficiency analysis over a span of 366 days for sunshine hours reveals several insights, as shown in the graph of Figure 8. The data we have collected indicates that the dryer efficiency fluctuates throughout the year, with notable peaks such as 64% on October 28, 2023, and 70.5%

on October 8 and 15, 2023. The graph illustrating these variations over the year highlights the efficiency of the solar dryer, with trends suggesting that specific days achieve optimal performance, likely due to favorable environmental conditions. This comprehensive year-long data provides valuable insights into the operational dynamics and potential for optimizing solar dryer performance.

5.2 Uncertainty Analysis

The ANOVA results demonstrated significant effects of heat flux and PCM integration on the performance metrics of the solar dryer. The regression model was highly significant (P-Value < 0.000), with an F-Value of 460.18, and explained a substantial portion of the variance in moisture removal rates (R^2 = 74.89%). Heat flux at noon had a significant negative impact on both moisture removal rate and efficiency, whereas heat flux during off-sunshine hours had a positive but non-significant impact.

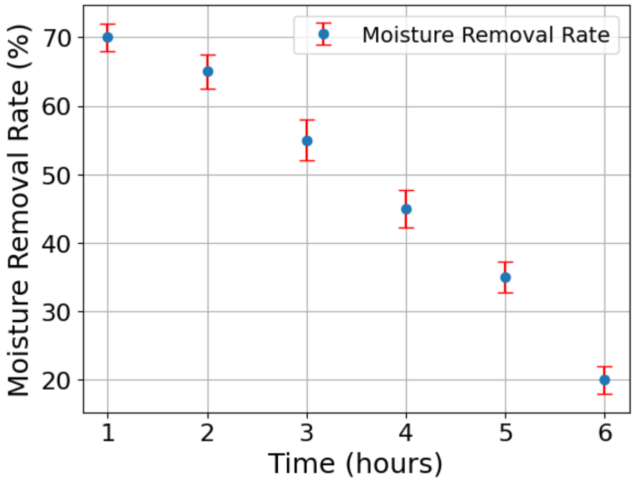

Figure 9. Moisture removal rate vs time with uncertainty.

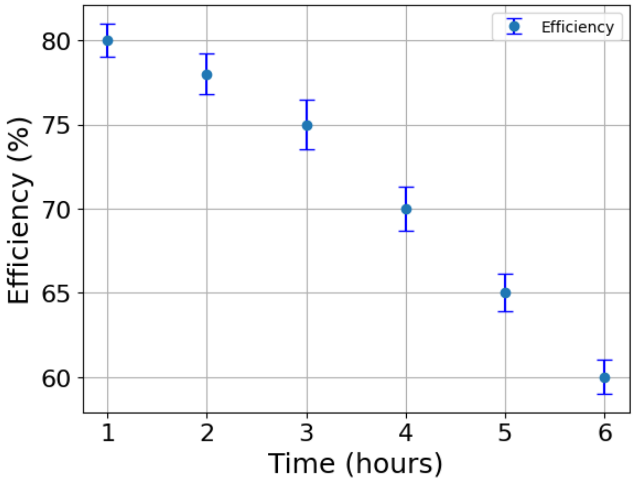

Figure 10. Efficiency vs time with uncertainty.

Figure 9 and Figure 10 illustrate the moisture removal rate and efficiency of the solar dryer over time, with error bars representing the uncertainties in measurements. The moisture removal rate decreases significantly over 6 hours of drying, with uncertainties ranging from 2% to 3%. Similarly, the efficiency of the dryer decreases over time, with uncertainties ranging from 1% to 1.5%. These results highlight the critical role of controlling environmental factors to optimize dryer performance. Future research should focus on improving data collection accuracy and exploring additional factors that may influence efficiency.

5.3 Discussion

The ANOVA analysis offered strong evidence that incorporating PCMs and optimizing airflow rates notably improved the performance metrics of the solar dryer. The application of PCMs resulted in shorter drying times and enhanced moisture removal rates and efficiency. These findings are consistent with previous research that emphasized the advantages of utilizing PCMs in thermal storage applications [25].

Impact of PCMs on Drying Time: The notable fall in time of drying time can be linked to the thermal storage capability of PCMs, which aids in sustaining a more stable drying temperature, thus speeding up the drying process. PCMs effectively absorb and release heat during phase transitions, ensuring that the drying chamber stays within an optimal temperature range, even when solar radiation fluctuates. This consistent thermal environment reduces the overall drying time, making the process more efficient [26, 27, 28].

Moisture Removal Rate Effect: The moisture removal rates has been observed in high use of PCMs, and optimized air flow rates can be explained by the more stable and optimal drying environment provided by these modifications. PCMs help in maintaining a uniform temperature, which is crucial for efficient moisture removal [29].

Additionally, the enhanced air flow increases the rate of moisture evaporation by improving the heat transfer and carrying away the moisture-laden air more effectively. This synergistic effect of thermal stability and improved air flow results in higher moisture removal rates [30].

Efficiency Improvements: The overall efficiency improvements were the result of reduced drying time and increased moisture removal rate, demonstrating the effectiveness of the proposed design modifications. The integration of PCMs and optimized air flow significantly enhances the energy utilization efficiency, making the solar dryer more sustainable and cost-effective [31].

Recommendations for Further Research: The experimental findings provide a strong basis for recommending the integration of PCMs in solar dryers, especially in regions with variable solar radiation [32]. Investigations into the long-term performance and durability of PCMs, as well as their economic feasibility, would also be valuable. Additionally, exploring the combination of PCMs with other renewable energy sources, such as photovoltaic panels, could further enhance the sustainability of drying [33].

The PCM integration and optimization of rates of air flow significantly improve the performance of solar dryers. These modifications reduce drying times, increase moisture removal rates, and enhance overall efficiency, making the drying process more effective and sustainable [34].

ANOVA results having the relatively low R^2 values in this study are attributed to several factors. Environmental variability, such as changes in ambient temperature, humidity, solar radiation intensity, and wind speed, introduces significant noise into the data, making it difficult to capture all influences accurately in a statistical model. Sample inconsistency, including variations in the initial moisture content and size of the potato slices, can lead to inconsistent drying behavior and affect the uniformity of the drying process. Experimental variations, such as slight differences in the positioning of thermocouples and hygrometers or inconsistencies in airflow within the drying chamber, can introduce errors, contributing to the overall variance not explained by the model. Additionally, model simplifications may not fully account for the complex interactions between different factors affecting the drying process. For instance, interactions between temperature, airflow rate, and PCM performance might be more intricate than the model can capture, leading to lower R^2 values. Addressing these factors in future studies could help improve the model's accuracy and provide a more comprehensive understanding of the solar drying process with PCM integration.

6. Conclusion

This study systematically investigated the impact of integrating Phase Change Materials (PCMs) and photovoltaic (PV) panels into solar dryers, focusing on drying time, moisture removal rate, and overall efficiency. The findings indicate that PCM use significantly enhances the dryers' performance, particularly during off-sunshine hours. The integration of PCMs and improved airflow mechanisms resulted in a substantial reduction in drying time compared to the control setup. This improvement is crucial for timely processing of agricultural products, reducing spoilage, and enhancing economic returns for farmers. Additionally, solar dryers equipped with PCMs exhibited higher moisture removal rates, underscoring the effectiveness of PCMs in maintaining consistent thermal energy, which is essential for efficient moisture extraction from produce.

Despite these positive outcomes, some limitations need addressing. Environmental variability and sample inconsistency can affect the uniformity of the drying process. Future research should explore a broader range of crops and climatic conditions to validate the effectiveness and versatility of these technologies. Moreover, refining experimental setups and models to better capture complex interactions could improve the accuracy of results.

Overall, integrating PCMs and PV panels in solar dryers presents a promising advancement in agricultural technology, offering benefits in drying efficiency, energy conservation, and sustainability. This approach can enhance product quality, reduce energy consumption, and support sustainable agricultural practices, ultimately contributing to improved food security and economic stability for farmers.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

R^2	Coefficient of determination
$P-value$	Probability value for statistical significance
$Adj\ SS$	Adjusted Sum of Squares
η	Efficiency of the solar dryer
Q	Heat flux (W/m²)
M	Moisture removal rate (kg/h)
t	Drying time (h)
T	Temperature (°C)
V	Air flow rate (m³/s)
H	Humidity (%)
m	Mass of the agricultural product (kg)
ΔH	Change in enthalpy (J)
k	Thermal conductivity (W/m·K)
ρ	Density (kg/m³)
C_p	Specific heat capacity (J/kg·K)

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