Design and Development of a Modified Solar Dryer Integrated with Thermal Energy Storage

Abstract

This study presents the design, development, and evaluation of a modified solar dryer integrated with a thermal energy storage system for enhanced food dehydration performance. The system incorporates copper fins for increased thermal conductivity and paraffin wax as Phase Change Material (PCM) for storing latent heat. The solution addresses key limitations in conventional solar dryers, such as dependency on sunlight, poor heat retention, and uneven drying. A fully functional prototype was developed and tested using green chilies under variable solar radiation conditions. The results demonstrate improved temperature stability, reduced drying time, and increased energy efficiency, establishing the proposed system as a viable solution for sustainable agricultural drying.

1. Introduction

Post-harvest drying is a critical step in agricultural processing, aimed at reducing moisture content to prevent microbial spoilage and extend shelf life. Traditional drying methods—such as open sun drying—are inefficient, weather-dependent, and prone to contamination. Solar dryers offer an eco-friendly alternative but still suffer from limitations such as temperature fluctuations and inadequate heat storage. The current research aims to overcome these challenges by integrating an energy storage system into a modified solar dryer using Phase Change Material (PCM).

2. Problem Statement

Conventional solar dryers face several operational limitations:

- Inability to retain heat after sunset, resulting in incomplete drying
- Irregular temperature distribution causing product quality degradation.
- Inadequate heat transfer in flat plate collectors.
- Extended drying time and increased risk of spoilage during cloudy conditions.

There is a need for a dryer that ensures consistent drying performance, better heat retention, and higher efficiency under varied environmental conditions.

3. Objective

The primary objective of this research is to design and prototype a modified solar dryer with:

- Copper fins for improved heat transfer efficiency.
- Paraffin wax-based PCM for thermal energy storage.
- A forced air circulation system to achieve uniform drying conditions.

This dryer is aimed at achieving continuous drying operation, reduced dependency on sunlight, and improved product quality.

4. Literature Review (Summary)

Past studies have validated the role of PCM in improving solar drying systems:

- **Vigneshkumar et al.** reported that paraffin-based PCM improved the drying efficiency of potato slices by over **5%.**
- **Swami et al.** found that PCM integration reduced the drying time of fish by **2 hours**, indicating better heat retention.
- **Esakkimuthu et al.** demonstrated that PCM-based air heaters maintained a **consistent heating effect**, essential for uniform drying.

This research builds on those findings by incorporating thermal energy storage and improved heat conduction using copper fins in a single prototype.

5. Methodology

The research followed a structured design and prototyping approach:

- **Design**: Optimized airflow and thermal flow using CAD tools.
- **Material Selection**: Copper for high thermal conductivity and paraffin wax for latent heat storage.
- **Fabrication**: Constructed using wood, PVC, copper sheets, and transparent glass.
- **Testing**: Conducted experimental tests on green chilies under varying solar intensities over two days.

6. System Design:

- **Solar Air Collector**: Copper fins on a flat plate to enhance heat transfer.
- **PCM Storage Unit**: Cylindrical chamber filled with paraffin wax for thermal storage.

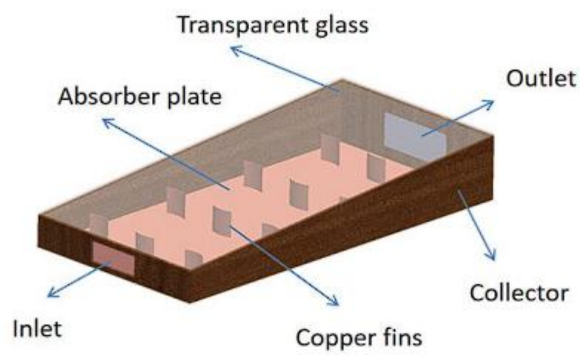
- **Drying Chamber**: Multi-tray design with forced air for uniform drying.
- **Transparent Glass Cover**: Maximizes solar absorption and minimizes heat loss.

7. Working Principle

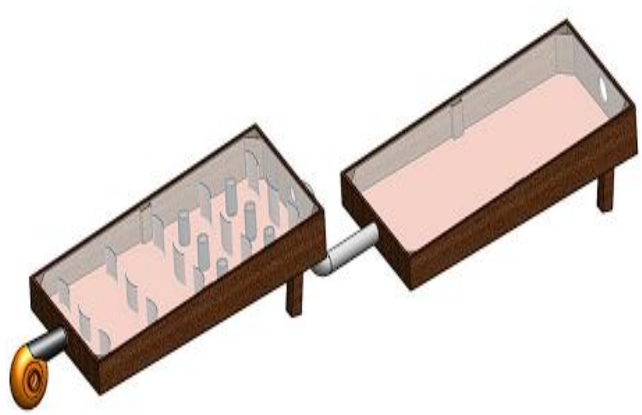
During daylight, solar energy is absorbed by the copper plate and stored in the PCM. The blower circulates the air which is heated and passed through the drying chamber. After sunset, the PCM releases the stored heat, maintaining chamber temperature and allowing continuous drying.

9. Experimental Design

Design of Solar Collector:



Design of Complete setup of Modified Solar Dryer:



Fabrication of the Modified Solar Dryer:

8. Experimental Setup

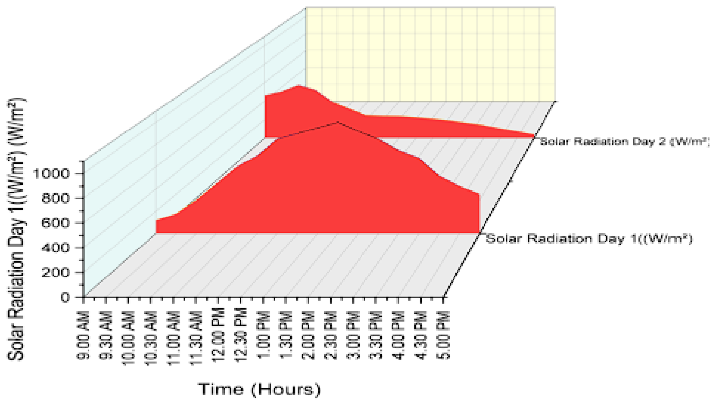
The prototype was tested using green chilies (500g) across two days. Parameters measured included solar radiation, outlet air temperature, chamber temperature, and moisture content.

9. Results and Discussion

Global Solar Radiation on Experimental Days:

The global solar radiation on the experimental days was depicted in Fig. 8.1. The solar radiation is recorded from 9 AM to 7 PM (IST) on Day 1 and 9 AM to 5 PM (IST) on Day 2 at half an hour time interval. The maximum solar radiation was recorded on day 1. Whereas the day 2 is affected by the rain after 5 PM. Which helps to evaluate the performance of the system during both solar radiation and low solar radiation periods. The peak solar radiation of 1000 W/m2 was recorded at 1.30 PM (IST) on day 1. Whereas on day 2, the peak solar radiation was 572 W/m2 at 10 AM. The ambient temperature for both days' ranges between 18.8 °C to 30 °C.

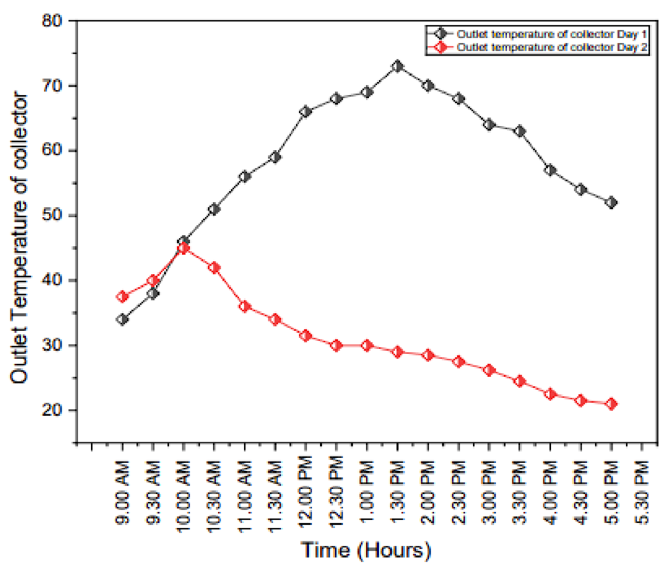
Comparison of solar radiation on day 1 & 2:



Outlet temperature of the solar collector on experimental days:

The outlet temperature of the solar collector was depicted in Fig. 8.2. The outlet temperature is also recorded, similar to the solar radiation from 9 AM (IST) to 7 PM on Day 1 and 9 AM to 5 PM (IST) on Day 2 at half an hour time interval. The graph states that the relationship between solar radiation and the outlet temperature of the collector. When the solar radiation decreases, the overall outlet temperature of the collector also decreases. But the modified solar collector has a better moisture content removal and drying chamber temperature than the conventional dryer on day 2.

Comparison of outlet temperature of the collector on day 1 & 2:



Comparing the moisture content of green chilly on the solar dryer and the conventional dryer on experimental days:

The moisture content of green chilly was analyzed to compare the performance of the modified solar dryer with a conventional dryer using the wet basis method

$$MC_W = \frac{W_i - W_f}{W_i} \times 100$$

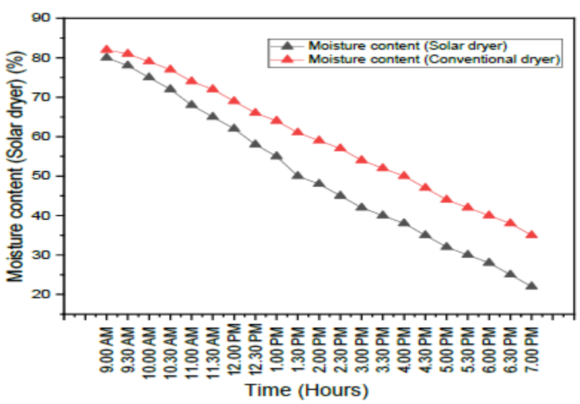
MC_W = Moisture content on the wet basis (%).

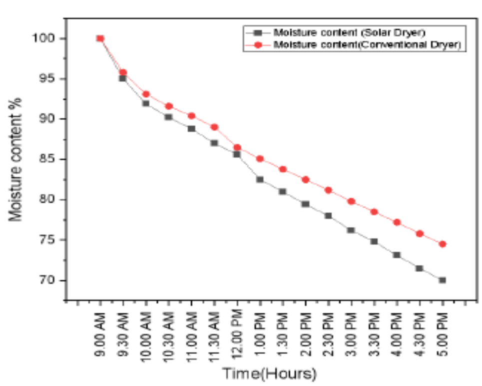
W_i = Initial Weight of the sample before drying.

W_f = Final Weight of the sample after drying.

On Day 1, 500g of green chilly was dried to 139g (22%) in the solar dryer and 162g (35%) in the conventional dryer. On Day 2, despite lower sunlight, the solar dryer reduced the weight to 350g (70%) compared to 362.5g (74.5%) in the conventional dryer. The plots show better drying efficiency in the modified solar dryer on both days.

Comparison of moisture content of solar dryer and conventional dryer on day 1 & day 2:

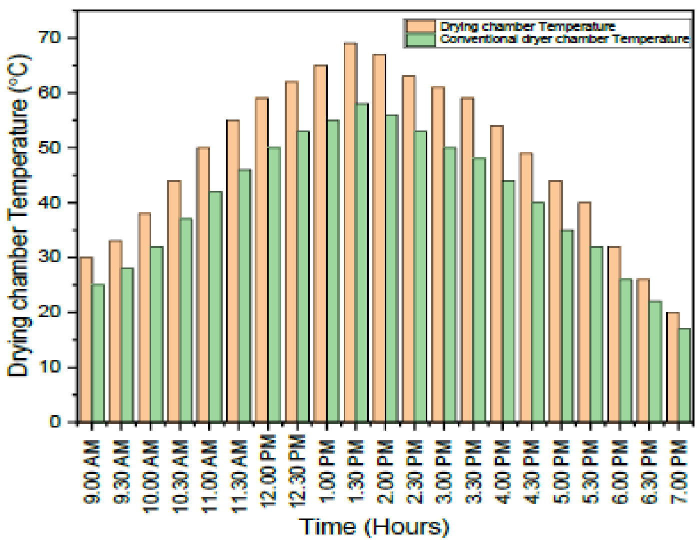


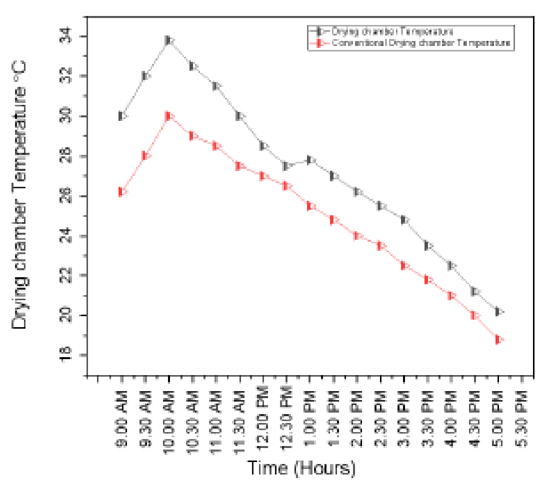


Drying Chamber Temperature :

The drying chamber temperature for both dryers was recorded to understand the thermal efficiency. On Day 1, during peak solar radiation at 1:30 PM, the modified solar dryer reached a temperature of 69°C, 11°C higher than the conventional dryer, which reached 58°C. On Day 2, despite lower solar radiation, the modified dryer maintained a temperature of 30°C, while the conventional dryer reached only 33.8°C. The modified dryer consistently provided higher chamber temperatures, even in lower radiation periods, ensuring more efficient drying and making it more reliable for off-grid applications and variable climates.

Comparison of drying chamber temperature of solar dryer and conventional dryer on day 1 & day 2:





Overall Drying Performance :

The overall performance of the modified solar dryer was evaluated by calculating the moisture content reduction in green chilies and comparing temperatures in both dryers. The modified solar dryer, incorporating copper fins and PCM, showed a significant improvement in moisture removal and thermal efficiency. On both experimental days, the modified dryer dried the green chilies faster and more efficiently than the conventional dryer, especially during periods of reduced solar radiation. This demonstrates that the modified dryer is more reliable and effective, ensuring superior drying performance and product quality in diverse weather conditions.

Comparison of drying performance in modified and conventional dryer:

Moisture and temperature of chilies both dryers were measured:

The green chilly’s drying performance in both dryers on experimental days:

10. Conclusion

The modified solar dryer with copper fins and PCM improves heat transfer and reduces drying time. It shows better moisture removal than the conventional dryer, even under low solar radiation. A temperature difference of 11 °C was observed at 1000 W/m², and 3.8 °C during low sunlight, indicating efficient heat retention. The system offers stable drying, prevents overheating, ensures uniform drying, and reduces reliance on conventional energy.

11. References

1. Vigneshkumar et al., Materials Today Proceedings, 2021.
2. Swami et al., Journal of Energy Storage, 2018.
3. Esakkimuthu et al., Solar Energy, 2013.
4. Murugesan et al., Journal of Energy Storage, 2024.
5. Getahun et al., Solar Energy, 2021.