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Enhancing solar dryer performance with Phase Change Material

P. Durga Prasad[1], K. Jagadeeswara Rao[2], K Leela Kumari[3], N. Durga Sai[4], K. Chandu[5], Dr. K. Siva Prasad[6]

Sivaprasad.k@gmrit.edu.in

[1,2,3,4,5,6] GMR Institute of Technology, Razam. Andhra Pradesh 532127, India

ABSTRACT:

Although solar drying is a sustainable and economical way to preserve food, lengthier drying durations and uneven drying rates are frequently caused by temperature changes and heat loss during off-sunlight hours. This study investigates how to improve heat retention and drying efficiency for mango slices using a Phase Change Material (PCM) combination of paraffin and lauric acid in sun dryers. The inability to sustain ideal drying temperatures after sunset is the fundamental issue with traditional solar dryers, which results in uneven drying and lower-quality products. This was fixed by integrating PCM into the drying chamber, which allowed it to stabilize the drying process by storing extra thermal energy during the hottest parts of the day and releasing it gradually in the evening.

This study set out to examine how PCM affected drying time, temperature stability, and overall thermal efficiency. In comparison to traditional systems, the PCM-regulated drier reduced fast heat loss by maintaining temperatures between 40 and 50°C, according to experimental data. Mango slices' moisture content dropped more quickly from 80–82% to about 12%, which shortened drying periods and enhanced product quality. Furthermore, the system's thermal efficiency increased by 25% to 40%, indicating the PCM's contribution to better energy use and a more reliable drying process. These results imply that the combination of Lauric Acid and Paraffin PCM can greatly enhance the effectiveness of sun drying, making it a more dependable and energy-efficient method of food preservation.

Keywords: Solar drying, Phase Change Material (PCM), Lauric acid, Paraffin, Thermal energy storage, Temperature stability, Moisture reduction, Thermal efficiency, Sustainable food preservation.

Introduction

A major problem in many agricultural areas, particularly those with limited access to traditional preservation techniques, is post-harvest losses in fruits like mangoes. Although solar drying is an economical and environmentally beneficial alternative, its effectiveness is sometimes hampered by erratic temperatures and varying solar radiation. The use of Phase Change Materials (PCMs) into solar dryers offers a viable way around these restrictions. The goal of this research is to improve a solar dryer's performance by adding a eutectic PCM combination of paraffin wax and lauric acid. In order to provide a steady drying environment, these materials store extra thermal energy during periods of high sunshine and release it during periods of low sunlight. Better product quality, consistent drying, and shorter drying times for mango slices are all made possible by the enhanced thermal management. In addition to encouraging sustainable food preservation, this invention provides dependable drying solutions to remote agricultural communities.

2. Problem Formulation

2.1 Drying

Drying is a mass transfer process that involves removing water or another solvent from a solid, semi-solid, or liquid via evaporation. This procedure is frequently employed as the last stage of production prior to product packing or sale. The finished product must be solid, either in the form of a continuous sheet (like paper), long pieces (like wood), particles (like cereal grains or corn flakes), or powder (like salt, washing powder, or milk powder) in order to be deemed "dried." Frequently, a heat source and a solvent to extract the process's vapor are used. In medications like vaccines and bioproducts like food and grains, water is nearly always the solvent that needs to be eliminated. Desiccation can be thought of as an extreme kind of drying or as a synonym for drying.

2.2 Solar energy

Maintaining a constant drying temperature in a solar dryer is the primary issue in order to increase efficiency and shorten drying time. In order to retain extra heat during peak sunlight hours and release it during off-sunshine periods, an efficient thermal energy storage (TES) system is required since solar energy is intermittent. Lauric acid and paraffin wax are examples of Phase Change Materials (PCMs) that have the ability to absorb, store, and release latent heat, creating a steady drying environment even in the event of a drop in solar radiation.

2.3Heat

The mass, specific heat, and temperature fluctuations of an item all affect how much heat is required to raise or reduce its temperature. This may be expressed as follows:

$Q = mc (T2 - T1)$

Where;

Q = heat (J)

m = object mass (kg)

c = specific heat (J/kgK)

ΔT = temperature change

2.4 Heat Transfer

The flow of energy in the form of thermal energy between physical systems as a result of temperature differences is called heat transfer. Numerous scientific, technical, and environmental applications—such as solar dryers, temperature control systems, and industrial operations—rely heavily on this phenomenon.

2.4.1 Conduction

Conduction is the process by which energy, such as heat or electricity, moves from one item to another when they come into direct touch. A molecule acquires energy and begins to vibrate during conduction. Until all of the energy in the body has been transmitted, this energy is then passed on to the other molecules in the vicinity. The equations that can be used are as follows:

$$q = - kA\, dT/dx$$

Where:

q = heat transfer rate (watts)

-k = thermal conductivity (W/mk)

A = heat transfer area (m^2)

dT = temperature difference

dx = distance (m)

2.4.2 Convection

Convection is the mechanism by which heat is transferred by the bulk movement of molecules in fluids, including liquids and gases. Conduction facilitates the first heat transfer between the fluid and the object, but the fluid's motion causes the bulk heat transfer. The equations that can be used are as follows:

$$q = h \times A \times \Delta T$$

Where;

h = material convection coefficient (W/m2 C)

A= cross-sectional area of the surface (m2)

ΔT = temperature difference

2.4.3 Radiation

Heat radiation is the movement of heat by electromagnetic waves from high temperatures to lower temperatures without the use of a medium. One type of heat radiation with a unique wavelength distribution is solar radiation. The Stefan-Boltzman rule is the fundamental formula behind the idea of radiant heat transport. The following is an expression for the Stefan-Boltzman law:

$$r = \varepsilon \sigma A \Delta T 4$$

where;

surface emissivity is represented by ε.

T = body's absolute temperature, K

A = m2 of surface area

qr = watts of convection heat transfer rate

σ is the Stefan-Boltzman rate. 5.669 x 10-8 W/m2.K4

2.5 solar dryer efficiency

The degree to which a solar dryer effectively transforms available solar energy into usable thermal energy for extracting moisture from a product is known as drying efficiency. It shows the proportion of solar energy received to the energy utilized for moisture evaporation.

$$\eta dry = \frac{mw \times hfg}{I \times A \times t} \times 100$$

ηdry = Drying efficiency (%)
mw = Mass of water evaporated (kg)
hfg = Latent heat of vaporization of water (kJ/kg)
I = Solar radiation intensity (kW/m²)
A = Collector/dryer area (m²)
t = Drying duration (s)

2.6 Phase change materials

Phase Change Materials (PCMs) are substances that absorb or release significant amounts of thermal energy during phase transitions, typically from solid to liquid or vice versa. They help regulate temperature by storing heat when it's available and releasing it when needed. PCMs are widely used in thermal energy storage systems, including solar dryers, to enhance efficiency and stability.

2.6.1Organic

Organic PCMs, such fatty acids and paraffin waxes, provide long-term dependability, high temperature stability, and non-corrosiveness. They experience little supercooling during phase transitions and have a modest thermal conductivity. Commonly employed in sun dryers, they provide continuous thermal energy storage with safe, non-toxic qualities.

2.6.2 Inorganic

Inorganic PCMs, such as salt hydrates, offer superior thermal conductivity and significant latent heat storage. Although they may experience phase segregation and supercooling, they are appropriate for applications involving medium-to-high temperatures. Because they are corrosive, they frequently need to be encapsulated or have chemicals added to optimize function over time.

2.6.3Eutecticmixture

Two or more component combinations that melt and solidify at a single, high temperature are known as eutectic PCMs. They may be customized from organic, inorganic, or mixed materials and provide accurate heat control. For uses like solar drying that require steady and reliable temperature control, these PCMs are perfect.

2.1 OBJECTIVES

The main goal of this experiment is to improve the efficiency of a solar dryer for drying mango slices by employing phase change material (PCM), a eutectic combination of paraffin and lauric acid. The particular goals consist of:

Enhance Thermal Stability: To minimize temperature swings and maintain a constant drying temperature, PCM should be incorporated into the solar dryer.

Improve Drying Efficiency: By keeping the drying temperature higher and more constant, mango slices' moisture content may be removed more quickly.

Evaluate Performance: To evaluate the drying properties of mango slices in a solar dryer with and without PCM with respect to drying duration, moisture absorption, and productivity.

3 Methodology

3.1 Place and Time of Implementation

A solar dryer test will be carried out for about one week starting in march 2025, from 9:00 a.m. to 5:00 p.m., at the Faculty of Mechanical EngineeringGMR institute of technology rajam, which is located at rajam gmr nagar, Vizianagaram district, andhara Pradesh.

3.2 Classifications of pcm

Three major categories may be used to classify PCMs:

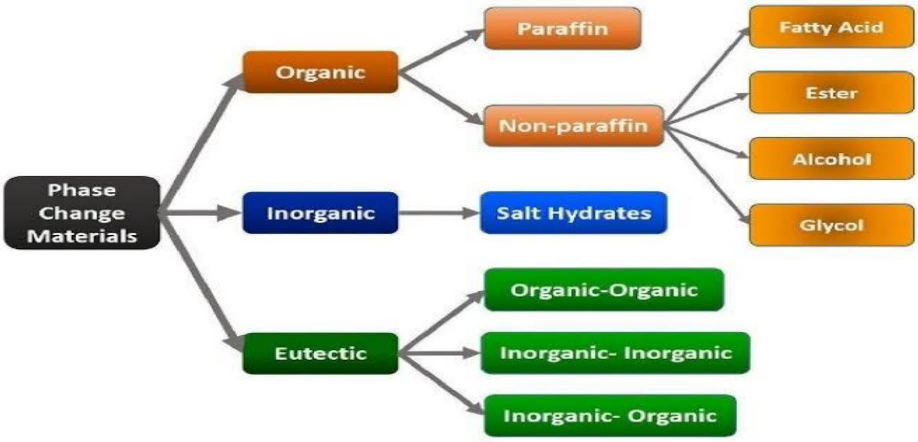

FIG.1 Classifications of PCM

3.3Experimental Procedure

Properties Of PCM

Fig.2 Paraffin wax

Properties Of Paraffin wax
1. Chemical Formula: CnH2n+2
2. Molecular Weight: 300-500 g/mol
3. Melting Point: 44-70°C
4. Thermal conductivity (solid): 0.20-0.25 w/mk .25
w/mk
5. Thermal conductivity (liquid): 0.10-0.15 w/mk
6. Density: 0.9 g/cm3

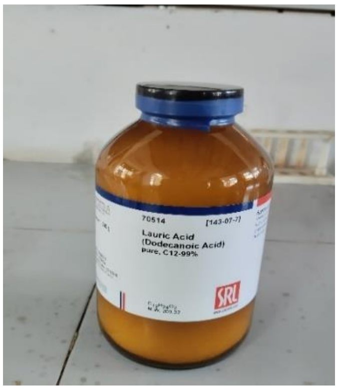

Fig.3 Lauric acid

Properties Of Lauric acid

1. Chemical Formula: $C_{12}H_{24}O_2$
2. Molecular Weight: 200.32 g/mol
3. Melting Point: 43-44°C
4. Thermal conductivity (solid): 0.20-0.24 w/mk
5. Thermal conductivity (liquid): 0.15-0.18 w/mk
6. Density: 0.88 g/cm3

Step 1: Weigh the Components

1. Measure **500g of Paraffin wax** using a weighing balance.
2. Measure **500g of Lauric acid** using a weighing balance.

Step 2: Prepare a Eutectic PCM

3. Fill a lauric acid and paraffin wax mix each one **500g beaker** place it on a **hot plate**.

Fig.4 Mixing of Lauric and Paraffin Wax

Step 3: Melt the Substances

Fig.5 Heating the PCM on Hot Plate

4. Place **lauric acid and paraffin wax** in a beaker.
5. Stir gently with a **glass rod** to ensure proper mixing.

Fig.6 Stirring the PCM with Glass Rod

Step 4: Cooling and Observation

6.Once the mixture is completely molten and mixed after that quenching the pcm and poured into the storage box.

7.Allow it to cool naturally for rapid solidification8.

Fig.7 Poured the melted PCM into Storage box

8. Observe the cooling pattern and note the **solidification temperature** using a thermometer.

Indirect Solar Dryer with PCM:

Uses a *separate solar collector* to heat air, which is then directed into the drying chamber. PCM is integrated within the collector or drying chamber walls to maintain a stable temperature. Ensures *better product quality* by preventing direct sunlight exposure.

An indirect solar dryer is a drying system where the product is not exposed to direct sunlight but instead dried using heated air from a separate solar collector. This method prevents color degradation, nutrient loss, and contamination, making it ideal for drying fruits, vegetables, grains, herbs, and fish The system consists of a solar air collector that absorbs solar radiation and heats the air, which is then directed into a well-insulated drying chamber. Air circulation can occur through natural convection (hot air rises naturally) or forced convection (using fans). Phase Change Materials (PCM) can be integrated into the collector or chamber to store excess heat, ensuring a continuous drying process even after sunset.

Fig.8 Indirect solar dryer

RESULTS AND CALCULATIONS

Based on temperature control, moisture content reduction, and increased thermal efficiency, the performance of the solar dryer improved with PCM (Lauric Acid + Paraffin) was evaluated. The outcomes unequivocally show the benefits of using PCM in solar drying applications.

4.1 Temperature Regulation in the Drying Chamber

One of the main conclusions of this study is that the PCM effectively regulates temperature. In a traditional solar dryer without PCM, the drying chamber temperature varied greatly during the day, peaking at 55–56°C at midday and then rapidly dropping to 30–32°C by evening. This rapid cooling has a detrimental effect on the drying rate, particularly after sunset.

However, during the course of the drying process, the temperature profile of the solar drier with PCM remained more consistent. Even when nighttime sun energy dropped, the chamber temperature stayed within a regulated range of 42–49°C. This illustrates PCM's capacity for heat storage, which ensures continual drying by absorbing surplus heat during peak hours and releasing it gradually during off-peak hours. Without causing harm to the mango slices, the steady temperature improves the drying process and avoids overheating.

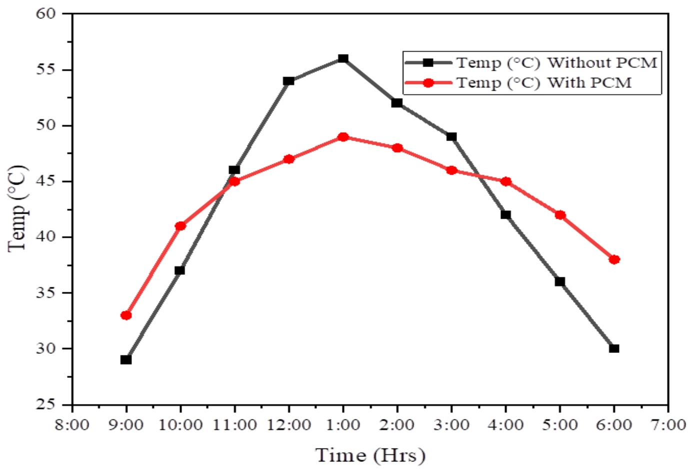

Fig.9 Day-1 Temperature Difference With & Without PCM

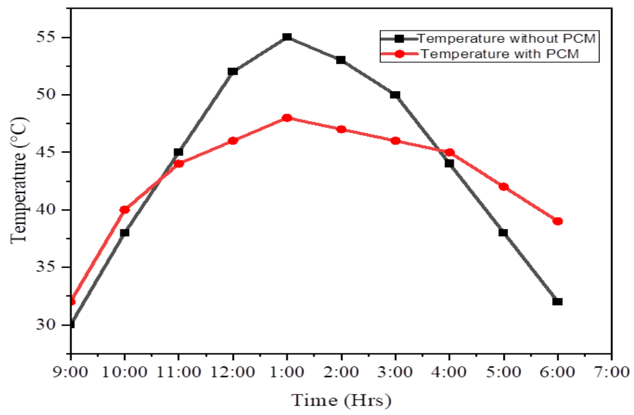

Fig.10 Day-2 Temperature Difference With & Without PCM

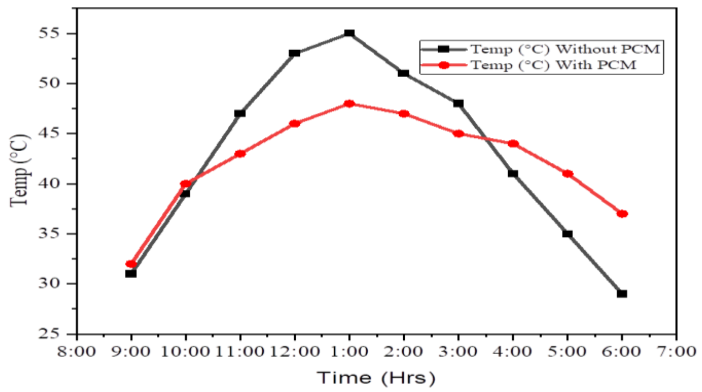

Fig.11 Day-3 Temperature Difference With & Without PCM

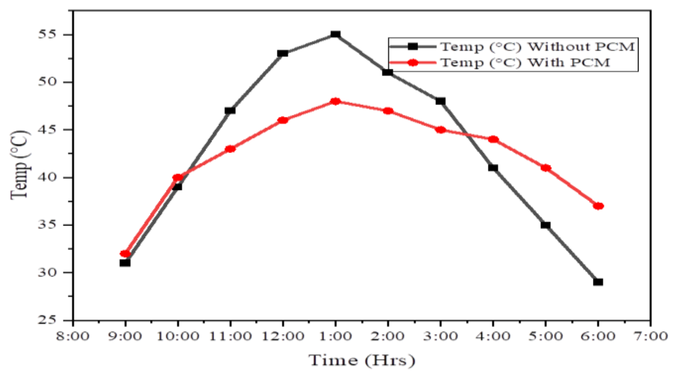

Fig.12 Day-4 Temperature Difference With & Without PCM

4.2 Moisture Content Reduction Over Time

The drying method' efficacy was also assessed by looking at how much moisture was removed from mango slices. The mango chunks had an initial moisture content of 80–82%, and the drying process was carried out until the moisture content dropped to a safe storage level of about12–15%.

The drying process was comparatively slower in the solar dryer without PCM, and by 6:00 PM, the final moisture content had reached 14–17%. On the other hand, the moisture content decreased more quickly in the solar dryer with PCM, reaching 12% at the same time. The PCM's constant heat supply, which preserved ideal drying conditions even when the sun's strength dropped in the evening, is responsible for the increased drying efficiency.

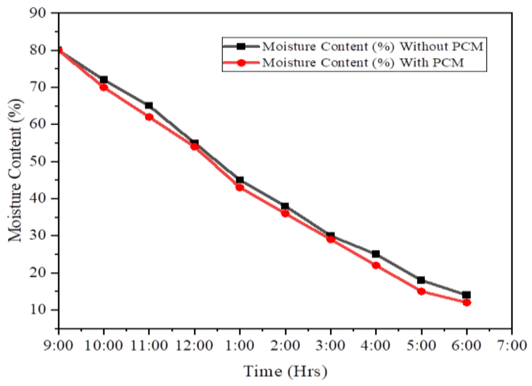

Fig.13 Day-1 Moisture Difference With & Without PCM

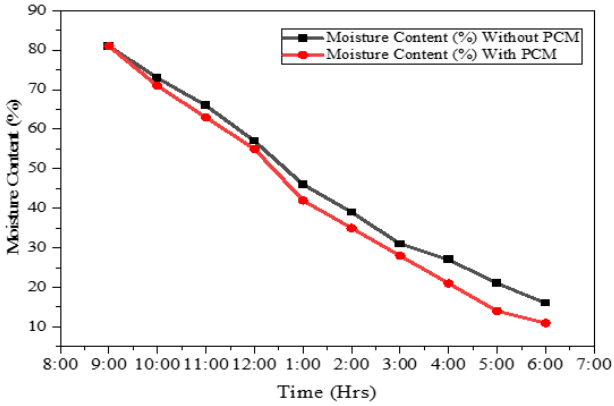

Fig.14 Day-2 Moisture Difference With & Without PCM

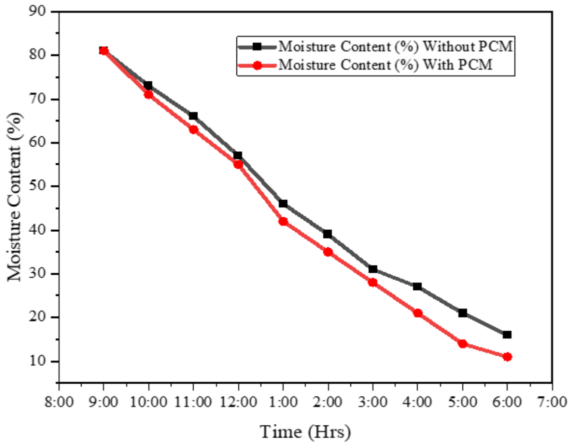

Fig.15 Day-3 Moisture Difference With & Without PCM

Thermal Efficiency Improvement

The solar dryer's thermal efficiency is another significant factor that was assessed in this investigation. The capacity of a solar dryer to efficiently convert and use solar energy determines its efficiency. Depending on the time of day, the thermal efficiency in the dryer without PCM ranged from 20% to 39%. Because of heat losses and the lack of stored energy, efficiency was lower in the morning and evening.

The thermal efficiency increased dramatically with the addition of PCM, rising from 28% to 55% throughout the drying phase. This rise is the result of improved heat retention and progressive release, which decreased energy waste and prolonged drying times. The efficiency gain implies that sun drying becomes more sustainable and energy-efficient with PCM inclusion.

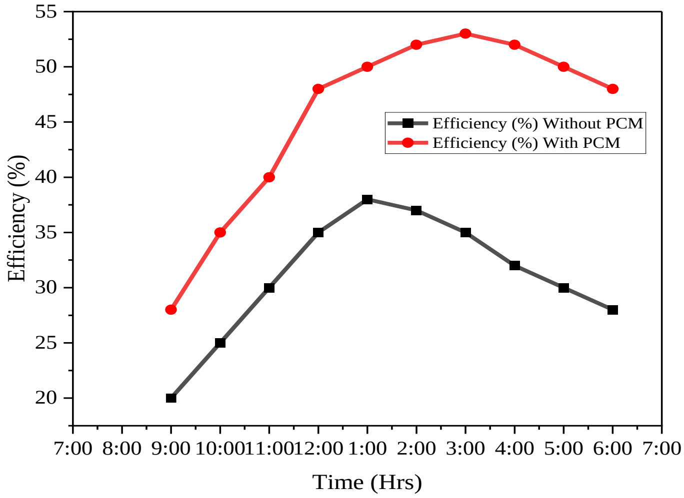

Fig.17 Day-1 Efficiency Difference With & Without PCM

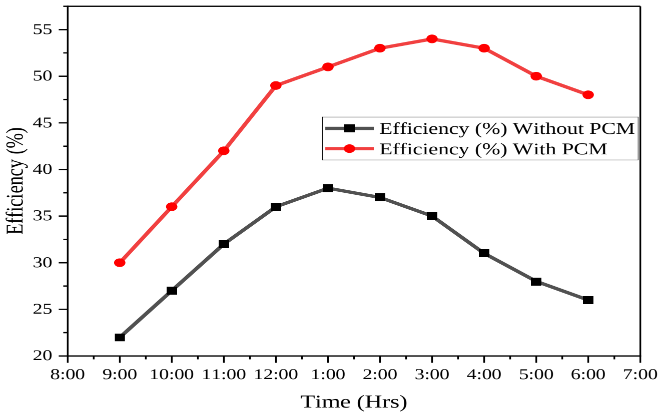

Fig.18 Day-2 Efficiency Difference With & Without PCM

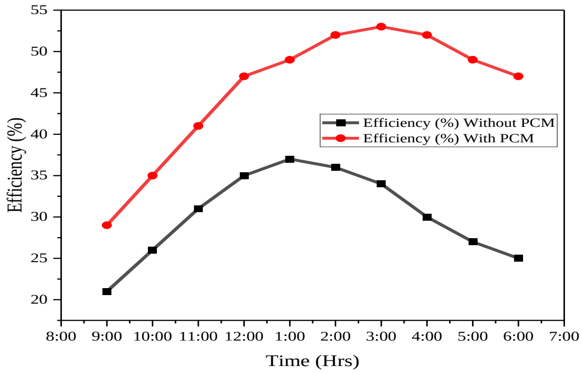

Fig.19 Day-3 Efficiency Difference With & Without PCM

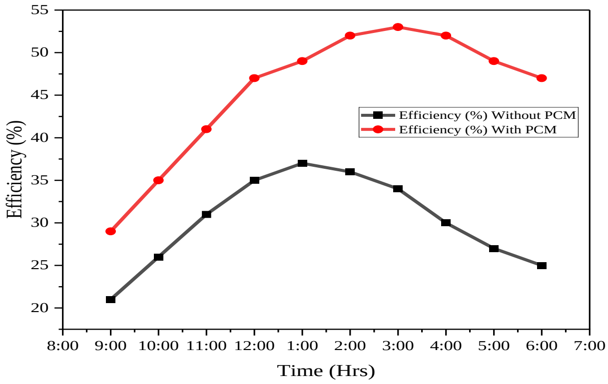

Fig.20 Day-4 Efficiency Difference With & Without PCM

CALCULATIONS

Here we calculate the one value based the experiment. The experiment done at 25-03-2025 (12:00 pm) in GMRIT, Rajam.
Data:
Solar radiation: I= 800 W/m^2
Collector area: A= 0.6 m^2
Time duration: t= 1 hr
Mass flow rate of air: m_w= 0.0122 kg/s
Specific heat capacity of air: C_p= 1.005kJ/kg.k
Inlet temperature: T_{in}= 40^0C
Outlet temperature (With PCM): T_{out}=55^0C
Step 1: Calculate Q_s
Q_s= 800 ×0.6 ×3600
Q_s= 1728 KJ
Step 2: Calculate Q_u:
Q_u= 0.0122 ×1.005 × (55-40) ×3600
Q_u= 662.094 KJ

Step 3: Calculate Efficiency

$$\eta = \frac{662.094}{1728} \times 100$$

$$\eta = 38\%$$

CONCLUSION

The experimental investigation showed that adding phase change material (PCM) (paraffin + lauric acid) greatly improves the drying performance of solar dryers for mango slices. Important conclusions include:

- **Better Thermal Stability:** The PCM reduced variations and prolonged the effective drying duration past sunlight hours by maintaining a steady drying temperature (42–49°C).
- **Increased Drying Efficiency:** When compared to the system without PCM, the solar dryer with PCM removed more moisture at a faster rate and took around 25 to 40 percent less time to dry.
- **Improved Product Quality:** Because of the carefully regulated drying conditions, the dried mango slices maintained their superior color, texture, and nutritional value.
- **Sustainable Energy Solution:** Solar drying is an effective and environmentally beneficial drying method that is made more reliable by the use of PCM, even in the face of variable weather.

Lauric acid + paraffin PCM is a viable option for sustainable food preservation since it greatly increases the sun drying system's efficiency, drying rate, and product quality.

Future Scope:

1. **Optimization of PCM Composition:** To optimize thermal performance and energy storage capacity, more study can examine various lauric acid to paraffin ratios.

2. **Better Heat Transfer Mechanisms:** Heat absorption and release rates can be increased by employing heat exchangers or improving PCM encapsulation processes.
3. **Expanding for Commercial Uses:** The financial possibility of using PCM-enhanced solar dryers on a large scale for industrial food processing may be examined.
4. **Application to Other Agricultural Products:** The advantages of PCM-enhanced dryers can be increased by extending their application to other perishable fruits, vegetables, and medicinal herbs.

By improving these factors, sun drying technology can become more accessible, economical, and efficient, promoting sustainable food preservation and lowering losses after harvest.

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