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Conference paper

Enhancing Energy Storage and Drying Efficiency in a Cabinet Solar Dryer Using Nano-Enhanced PCM with FMWCNT

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ABSTRACT

This study investigates the thermal performance of cabinet-type solar dryer using paraffin wax-based NEPCM enhanced with 0.5% functionalized multi-walled carbon nanotubes (FMWCNT). The addition of nanoparticles significantly improves the thermal conductivity and energy storage capacity of the PCM. NEPCM was integrated into the dryer walls and baffle plates beneath the trays. The system, combined with a parabolic solar concentrator, was tested for mushroom drying. Moisture content and thermal parameters were monitored throughout the process. Results showed that NEPCM effectively stored heat, maintaining dryer temperatures for 2 to 3 hours after sunlight was unavailable. The collectors' energy efficiency ranges from 51.02% to 67.45% for without PCM, from 53.02% to 85.09% for PCM, and from 58.77% to 77.52 % for NEPCM. The thermal efficiency of the dryer reached up to 22% and 27%, The energy efficiency of the NEPCM Solar Dryer drying chamber found 6.61% for without PCM, 6.85% for PCM., and 7.40% for NEPCM. The drying rate improved notably, reducing the moisture content from 17.45 to 0.0515 g water/g dry matter. Overall, incorporating FMWCNT-enhanced PCM into the solar dryer significantly enhanced energy storage and drying performance, making it a promising solution for extending drying hours and optimizing solar energy use.

1. INTRODUCTION

Agriculture remains the backbone of India's economy, with nearly 65–70% of the population depending on it for their livelihood (Ndukwu et al., 2023). However, post-harvest losses, especially in moisture-rich produce such as mushrooms, grapes, and leafy greens continue to pose a major challenge. A key reason for this is the lack of efficient and reliable preservation methods. While solar drying has emerged as a promising and eco-friendly solution compared to traditional open sun drying, its effectiveness is often limited by fluctuating solar radiation, ambient temperatures, and unpredictable weather conditions

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(Rouzegar et al., 2023). These variations frequently lead to uneven drying and reduced system performance, particularly during cloudy periods or in the late afternoon.

To tackle these limitations, researchers have increasingly explored the integration of thermal energy storage (TES) in solar dryers. Among the various TES techniques, latent heat storage using phase change materials (PCMs) like paraffin wax has gained attention for its ability to store large amounts of energy and maintain thermal stability (Shalaby et al., 2016). However, paraffin wax has a drawback: its low thermal conductivity (around 0.25 W/m·K), which slows down both the charging and discharging of stored heat. This limits how effectively the system can respond to changing drying demands.

To improve the thermal performance of PCMs, recent research has focused on nano-enhanced PCMs (NEPCMs) where high-conductivity nanoparticles are dispersed within the PCM to boost heat transfer. For instance, Kabeel et al. (2020) reported that adding graphene oxide nanoparticles to paraffin wax in a solar still increased energy storage efficiency by 30–40%. Similarly, Sharma et al. (2022) reviewed the use of nanomaterials like aluminum oxide, copper oxide, and carbon-based nanoparticles, showing they significantly enhance both thermal conductivity and overall drying rates.

In applied settings, Demir and Sacilik (2010) highlighted the importance of thermal uniformity in solar tunnel dryers used for tomatoes, while Sundari (2013) showed how integrating latent heat storage with evacuated tube collectors extended drying hours and improved temperature stability. Building on this, Rouzegar et al. (2023) combined PCM with copper nanoparticles and internal fins in a hybrid solar dryer, leading to faster heating and more consistent drying across trays.

Among these nanomaterials, functionalized multi-walled carbon nanotubes (FMWCNTs) are particularly promising due to their high thermal conductivity, excellent dispersion properties, and large surface area. However, as Tosun et al. (2022) caution, adding too much typically beyond 0.5 wt% can cause particle agglomeration, reduce system stability, and drive up costs. Finding the optimal nanoparticle concentration is therefore crucial for achieving both technical performance and cost-efficiency.

Despite these advancements, there are still gaps in the literature. Very few studies have tested NEPCMs in real-world solar dryers, especially with PCM integrated directly into the dryer walls and baffle plates**.** Also missing are systematic comparisons between dryers using no PCM, conventional PCM, and NEPCM under the same environmental and operational conditions. This makes it hard to quantify the real advantages of nano-enhanced materials in practical drying systems.

This study aims to address those gaps. It presents the design and experimental evaluation of a cabinet-type solar dryer enhanced with NEPCM, where paraffin wax is doped with 0.5% FMWCNT. The nano-enhanced material is embedded into the dryer's side walls and baffle plates for efficient heat retention, and a 1.2 meter diameter parabolic concentrator is used to intensify solar input. Experiments were conducted under field conditions in Amravati, India, using mushrooms as the drying sample. The system's performance was assessed across three setups without PCM, with paraffin wax, and with NEPCM to demonstrate the benefits in terms of thermal stability, energy efficiency, and drying effectiveness. The results contribute to the development of more efficient and compact solar dryers suitable for decentralized agricultural use.

2. PREPARATION OF MATERIALS AND EXPERIMENTAL SETUP

2.1 Preparation of PCM with NWCNT

The NEPCM was prepared in the Chemistry Lab of Sipna COET in India. The phase change material (paraffin wax) and nanomaterial (FMWCNT) of size 3 nm to 10 nm were directly procured from a dealer in Nagpur city. NEPCM was then prepared in the lab using equipment such as a weighing machine with a 0 to 50 g limit and another with a 1 to 300 kg limit, a hot plate to melt the wax, a magnetic stirrer to mix the nanoparticles and wax, and an ultra-sonicator machine for the sonication process. Initially, the wax was measured and melted on the hot plate, then stirred for 10 minutes. The nanomaterial, along with a surfactant, was added in the desired proportion and stirred again for 30 minutes. Finally, sonication was carried out for 1 hour. FMWCNT was mixed in 0.1%, 0.5%, and 1% proportions by weight in paraffin wax. In the current study, a performance comparison is made between paraffin wax without FMWCNT, paraffin wax with 0.1% FMWCNT, paraffin wax with 0.5% FMWCNT, and paraffin wax with 1% FMWCNT. Samples made in the lab are shown in Fig. 1.

Fig 1. NEPCM with added MWCNT in different proportion.

The properties of the PCM are tabulated in Table 1. The addition of nanomaterial beyond 0.5% was found to be no longer beneficial for the PCM. Further addition leads to agglomeration, and FMWCNT becomes difficult to disperse; moreover, it increases the cost of the final product. Although thermal conductivity increases after 0.5% addition, it also results in a higher rate of heat loss. Therefore, based on the application and its requirements, PCM with 0.5% FMWCNT is preferred and selected for experimentation, offering a 40 to 45% enhancement in thermal conductivity.

Table 1. Thermal properties for paraffin wax (Shalaby et al., 2016), (Haji-Sheikh et al. 1982)

Property	Actual value found	Value
Density (Kg/m^3)	841 / 766	818 / 760
Melting temperature ^{o}C	53	56
Heat capacity / Kg (J/Kg^{o}K)	2790	2950 /2500
Thermal conductivity (W/mK)	0.25	0.24

2.2 Experimental Setup

In this article, the focus is on NEPCM and its use in a solar dryer to heat air for drying. The effect of heat addition to the NEPCM, present inside the side walls and baffle plates of the drying chamber, and its mechanism are discussed here. Drying racks with suitable channels and even spacing were housed in the cabinet as shown in fig 2. Metal handles were attached to each tray for easy handling and sliding within the chamber. To avoid contamination of the dried product, each tray was provided with a stainless steel wire mesh.

Experimentation was conducted from November 2023 to June 2024 in Amravati. The average solar radiation in the city is 4.8 kWh/day in winter and 4.95 kWh/day in summer. The solar concentrator collects heat at a focal point located 1 meter away and increases the temperature of the air. The hot air then passes through the drying chamber. During the daytime, heat stored in15kg NEPCM is around 2.87 kW and is released during cloudy weather or after sunshine hours for approximately 2 to 3 hours depending on the solar radiation intensity, passing clouds and weather conditions. This is made possible by the parabolic concentrator, 1.2 meters in diameter, which is attached to heat the air. This setup helps the dryer achieve a high temperature range in a shorter time.

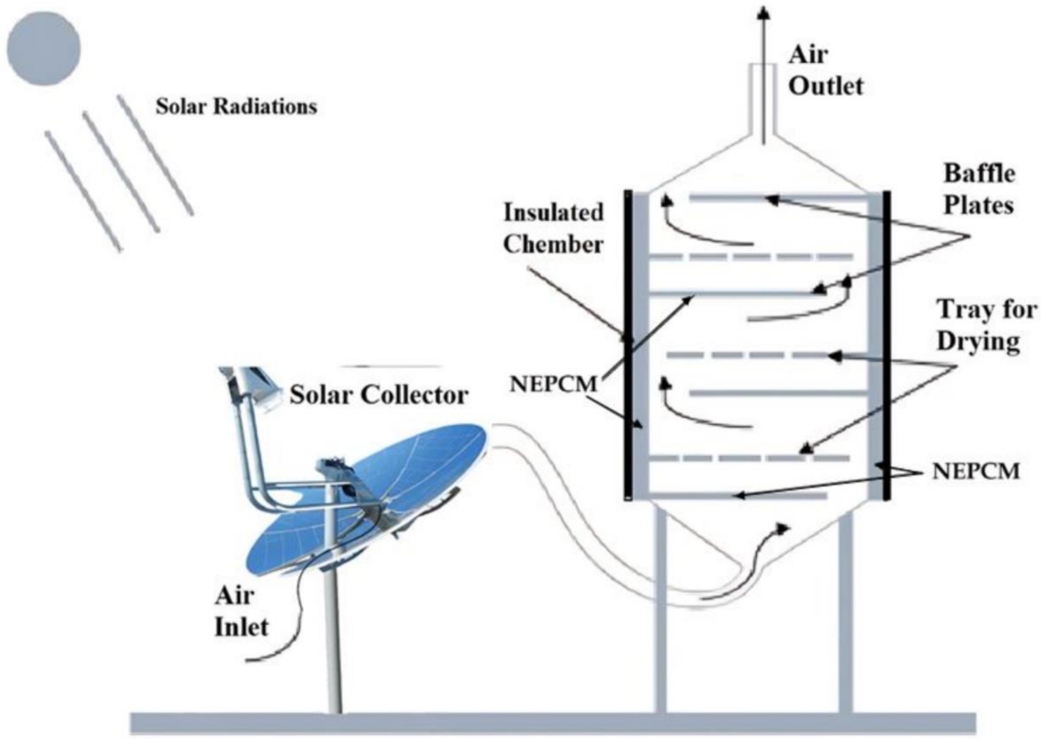

Fig 2. Block diagram representing position of NEPCM in walls and inside baffle plates of model.

For experimentation temperature data loggers (12 channel), thermoanemo meter, hygrometer, solar radiation measurement device, electric oven, weighing machine, etc were used.

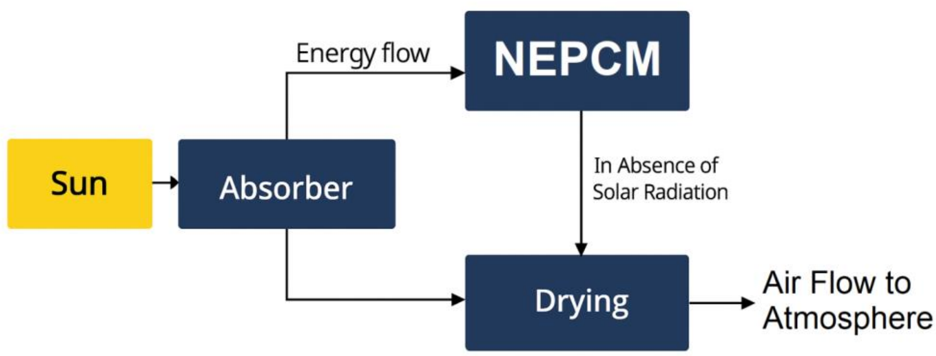

Fig 3. Energy flow diagram

Fig. 3 shows the flow of energy within the system. Solar energy is firstly focused and collected by the absorber of parabolic collector and passed to the cabinet of the solar dryer. Inside the cabinet, the energy is divided between two processes: storage in the NEPCM and drying of the product. In the absence of solar input, the stored energy in the NEPCM is utilized for drying purposes.

Table 2. Thermal and Physical Property Comparison

Property	**Pure Paraffin Wax**	**0.1% FMWCNT**	**0.5% FMWCNT**	**1.0% FMWCNT**
Thermal conductivity (W/mK)	~0.25	↑ (10–15% increase)	↑↑ (40–45% increase)	↑↑↑ but with drawbacks
Stability / Dispersion	Excellent	Good	Stable	Poor (agglomeration observed)
Cost-effectiveness	High	Moderate	Optimal	Low (increased cost)
Practical application	Baseline	Viable	Most effective	Not preferred (inefficiency due to agglomeration)

3. PERFORMANCE EVALUATION

3.1 Evaluation of Solar Dryer Performance

To evaluate the efficiency of the solar dryer system integrated with Nano-Enhanced Phase Change Material (NEPCM), a series of experiments were carried out using mushrooms as the target drying material. The mushrooms were prepared and arranged in thin, uniform layers on the trays inside the cabinet dryer. The study included both no-load and full-load testing conditions to comprehensively assess thermal behavior and drying effectiveness.

3.2 No-Load Testing of the NEPCM-Integrated Solar Dryer

During no-load testing, the dryer was operated without any material inside, primarily to monitor baseline thermal performance. Measurements of internal temperature, relative humidity, and air velocity were recorded throughout the day and compared with ambient environmental conditions. These tests were conducted during the summer season from 8:00 AM to 5:00 PM to capture variations in solar radiation and assess the thermal storage response of the NEPCM embedded in the chamber walls and baffle plates.

3.3 Full-Load Testing with Mushroom Samples

For full-load testing, mushrooms were evenly distributed over perforated aluminum trays inside the dryer. The trials were conducted under natural sunlight during the summer. Initial sample weights were noted before drying, and weight measurements were taken hourly throughout the day, alongside temperature, humidity, solar radiation, and air velocity readings. The drying continued daily from 8:00 AM to 5:00 PM until the mushrooms reached their equilibrium moisture content (EMC), indicating completion of the drying process. This setup helped evaluate how effectively the NEPCM contributed to thermal stability and enhanced drying efficiency under actual load conditions.

3.4 Study of drying characteristics

In drying characteristics following parameters were determined as

3.4.1 Moisture content

The calculations of the moisture present (Ndukwu et al., 2023) in the product can be calculated by using equation below.

$$M.C.(wb)\% = \frac{(w_a - w_b)}{w_a} \times 100 \tag{1}$$

$$M.C.(db)\% = \frac{(w_a - w_b)}{w_a} \times 100 \tag{2}$$

Where,

W_a – initial weight of product, g
W_b- final weight of dry product, g

3.4.2 Ratio of Moisture

The calculations of the Moisture ratio (Rouzegar et al. 2023) of the product can be calculated by using equation below.

$$MoistureRatio = \frac{(M - M_1)}{(M_2 - M_1)} \tag{3}$$

Where,

M – total Moisture (db), %
M_1 – moisture content after equilibrium, (db), %
M_2 – Moisture present in product initially, (db), %

3.4.3 Efficiency of drying (η)

The drying ability or efficiency of solar dryers (Singh et al. 2016) was calculated by following formula.

$$\eta = \frac{m_l \times C_a \times (T - T_{out})}{I_t \times A_c} \times 100 \tag{4}$$

Where,

M_l - amount of water evaporated, kg/hr
C_a - Specific heat of air, kJ/kg^{0}C
I_t - insolation on collector surface, kJ/m^{2}hr
T - Average temperature inside the solar cabinet dryer, ^{0}C
T_{out} - chimney exhaust temperature,
A_c - Collector Area m^2

3.4.4 Rate of Drying

The rate of reduction of moisture i.e drying ratio (Bala et al. 2003) of the product dried can calculated by using formula mentioned below:

$$\text{Rate of Drying } (D_r) = \frac{\Delta W}{\Delta t} \tag{5}$$

Where, ΔW = reduced weight in every one hour (g $100g^{-1}$of bdm)
Δt = Difference in time reading (h)

4 RESULTS AND DISCUSSION

The data presented in Fig. 4 illustrate the temperature distribution inside the solar dryer integrated with NEPCM, along with ambient temperature, relative humidity, and solar radiation during a no-load test conducted in March. The temperatures inside the dryer were recorded at the lower, middle, and upper trays of the drying chamber throughout the daytime.

The temperature in the dryer integrated with NEPCM ranged from 35.6 to 59.0 °C at the lower tray, 34.6 to 57.4 °C at the middle tray, and 33.6 to 54.9 °C at the upper tray. Correspondingly, the ambient temperature, relative humidity, and solar radiation varied between 27.1 to 36 °C, 23% to 46%, and 53.1 to 847.8 W/m², respectively.

The airflow rate at ambient conditions and at the exhaust chimney was observed in the range of 0.0 to 2.55 m/s and 0.1 to 0.4 m/s, respectively. The average temperatures in the dryer integrated with NEPCM were 49.17 °C, 47.50 °C, and 45.76 °C at the lower, middle, and upper trays, respectively. Meanwhile, Sundari, (2013) has the average ambient temperature, relative humidity, and solar radiation were recorded as 32.28 °C, 34%, and 559.79 W/m², respectively.

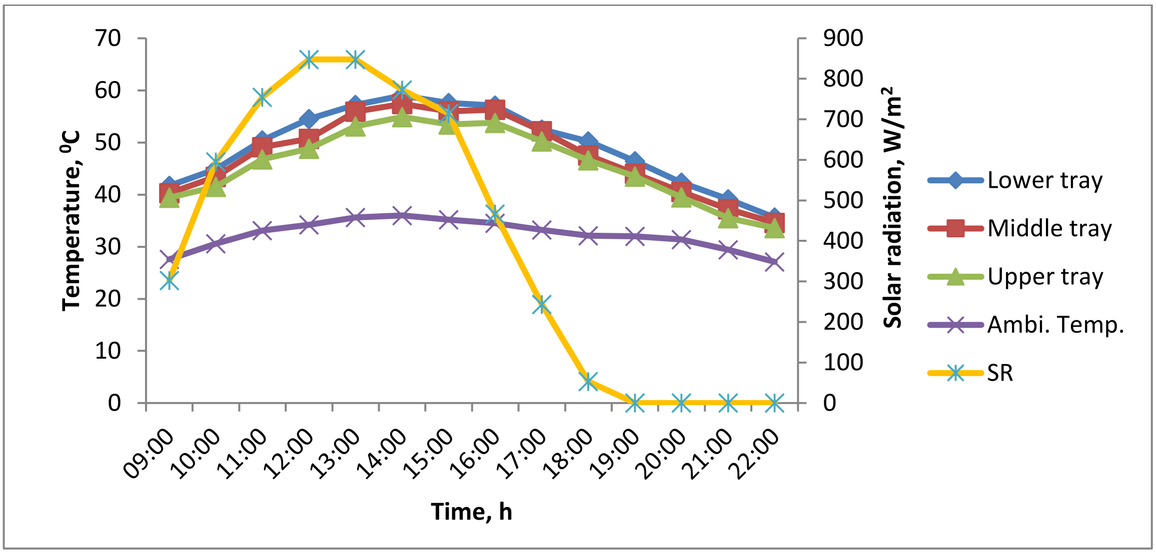

Fig 4. Temperature profile of dryer integrated with NEPCM for no load test.

Figure 5 illustrates the temperature variations inside the dryer integrated with NEPCM, along with ambient temperature and solar radiation during the full-load test. A minimum temperature of 34.4°C inside the NEPCM-integrated dryer was recorded at 9:00 a.m., corresponding to an ambient temperature of 30.5°C. The temperature conditions were found on peak around 1:00 p.m., reaching 59.1°C on the lower tray, followed by 58.4°C on the upper tray and 57.2°C on the middle tray. These values corresponded to an ambient temperature of 37.5°C, solar intensity of 562.4 W/m², and ambient relative humidity of 15%.

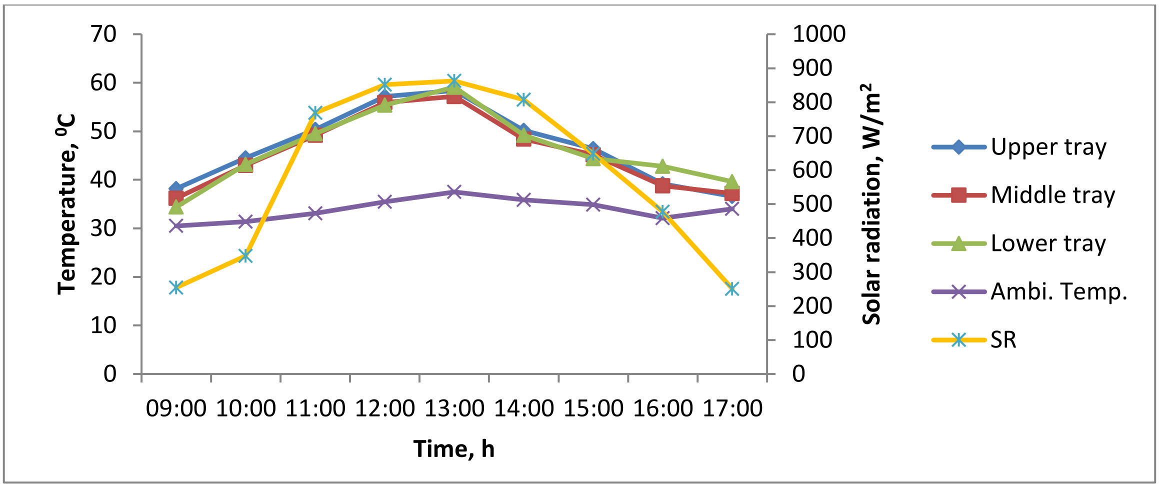

Fig 5. Temperature profile of dryer integrated with NEPCM for full load test.

4.1 Energy efficiency of NEPCM Solar Dryer

The main factors considered for the energy analysis of NEPCM Solar Dryer (Tosun et al. 2022) are the actual absorbed heat (QA) from sun and the available heat obtained by the collector of dryer (Qu). These values were determined for three different NEPCM during fruit drying tests. The fluctuation of these values over time is shown in Figure 6.

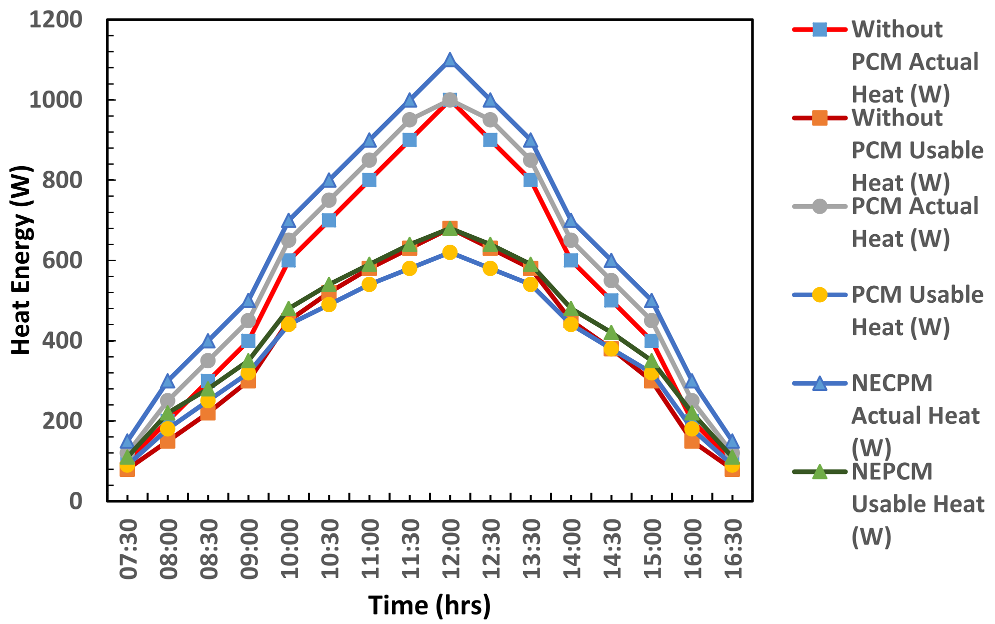

Fig 6. The energy efficiency of Solar Dryer collectors with respect to time for without PCM, PCM and NEPCM.

The fig 7 shows collectors' energy efficiency ranges from 51.02% to 67.45% for without PCM, from 53.02% to 85.09% for PCM, and from 58.77% to 77.52 % for NEPCM. The collector's efficiency improved after 2:30 PM as a result of the utilization of TES in Nano-Enhanced phase change material, which helped maintain consistent temperatures between the input and output air. As a consequence, the collector's beneficial heat energy surpassed the heat energy received by the NEPCM Solar Dryer collector. The current analysis by Wakerley et al. (2017) has determined that the NEPCM Solar Dryer collector efficiency aligns well with previous studies. The energy efficiency of the collector changed in the range 52.46% to 93.94% for forced convection and from 41.75% to 76.65% for natural convection, as reported in reference.

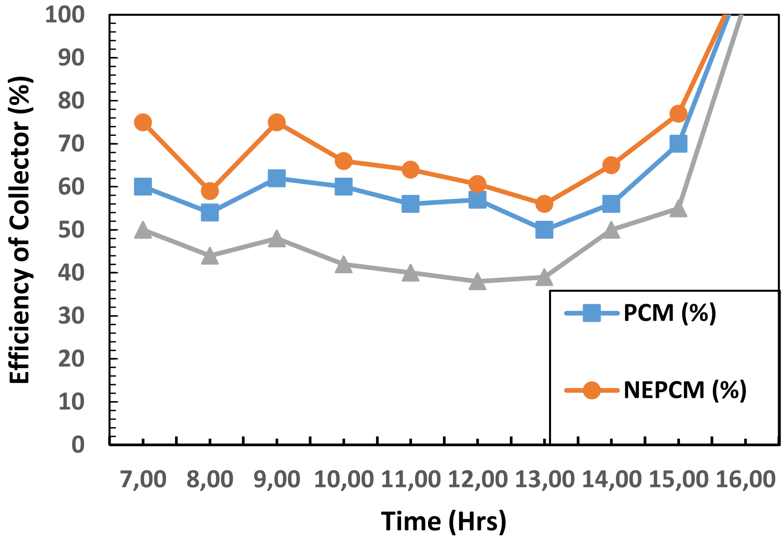

Fig 7. The energy efficiency of the dryer for without PCM, PCM and NEPCM.

The energy efficiency of the NEPCM Solar Dryer drying chamber is 6.61% for without PCM, 6.85% PCM., and 7.40% for NEPCM. The dryer's energy efficiency progressively grew as the moisture removal rate increased, starting from the commencement of the drying process until 9:30 AM. The energy efficiency of the dryer varies between 09:30 AM and 4:00 PM due to ongoing moisture removal and complete melting of the NEPCM. As a result of the heat generated by the NEPCM during the discharge period, the energy efficiency of the dryer experiences a significant boost after 4:00 PM for 2 to 3 hours.

Considering Performance Impacts in Solar Dryer, Thermal Storage & Retention. 0.5% FMWCNT-enhanced PCM could store ~2.87 kW of heat during the day and release it steadily for 2–3 hours post sunshine, offering consistent drying temperatures even in late afternoons or cloudy conditions. 0.1% enhancement helped, but not significantly better than 0.5%. 1% showed marginal thermal gain but increased losses due to poor dispersion.Dryer Temperature Profile, Max recorded dryer temp with 0.5% NEPCM is ~59.1°C, even during declining solar radiation. Pure paraffin couldn't maintain temperatures beyond sunshine hours.

Table 3. Energy Efficiency Comparison

Material	Collector Efficiency (%)	Dryer Chamber Efficiency (%)
Without PCM	51.02–67.45	6.61
With PCM	53.02–85.09	6.85
With NEPCM (0.5%)	58.77–77.52	7.40

5. CONCLUSION

The efficiency of the solar drier was assessed under both no-load and full-load conditions through the drying of mushrooms. The amount of the product loaded and its moisture content were measured both initially and during the drying process. During the test runs, key parameters such as drying time, internal dryer temperature, solar radiation intensity, product moisture content, ambient temperature, and relative humidity were carefully monitored and recorded. The drying properties of mushrooms in a dryer integrated with NEPCM were examined. The varying drying features of moisture content, drying rate, and moisture ratio were examined. The energy efficiency of the collector ranges from 50.02% to 66.45% for without PCM, from 53.02% to 85.09% for PCM, and from 58.77% to 78.21% for NEPCM. The energy efficiency of the dryer is 6.61%, 6.84%, and 7.40% for without PCM, PCM, and NEPCM respectively.

The combination of a parabolic collector, NEPCM, and dryer assembly demonstrates a positive impact on fruit drying performance. The potential of the parabolic collector can be harnessed to achieve higher temperature ranges, allowing for a more compact solar dryer design. Future studies can explore the possibility of mounting the parabolic concentrator above the solar dryer cabinet to optimize space utilization, as in most cases, the collector occupies more space than the drying chamber itself.

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