
EXPERIMENTAL EVALUATION OF A SOLAR DRYER INTEGRATED WITH A CARBON DOT-ENHANCED SHEA BUTTER PHASE CHANGE MATERIAL (PCM).

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ABSTRACT

The increasing demand for sustainable and renewable energy solutions has stimulated significant research into technologies that enhance agricultural productivity and reduce post-harvest losses. Among these technologies, solar drying has emerged as an environmentally friendly, cost-effective method for preserving agricultural products by reducing moisture content and extending shelf life. Its relevance is particularly pronounced in developing countries such as Nigeria. Phase change materials (PCMs) are needed to enhance the performance of solar dryers, especially after sunshine hours. In this study, two solar dryers, with and without PCM, each with a capacity of 2 kg, were constructed and tested alongside open sun drying under an average ambient temperature of 28.6 °C and average solar irradiance of about 876 W/m². The PCM-integrated dryer achieved a drying heat load of 835.81 MJ and an outlet air temperature of 51.6 °C, removing 0.68 kg of moisture with an average drying rate of 0.20 kg/h reaching a final moisture content of about 9% which was 4% short of reaching the target final moisture of the study of 5%. The required PCM mass was 3.924 kg (0.0042 m³), providing a thermal energy storage capacity of 489,853 J and enabling extended drying for up to 5 hours beyond sunshine hours. The PCM-integrated solar dryer achieved a drying efficiency of 85%. While the non-PCM dryer and open sun drying achieved drying efficiencies of 77% and 40%, respectively. This demonstrates the superior drying efficiency of the PCM-integrated dryer over the other drying methods.

Keywords: Phase change material; Drying rate; Moisture removal; and Thermal efficiency

1. INTRODUCTION

In recent years, integrating thermal energy storage into solar dryers has gained attention as a solution to intermittent solar radiation Dhass *et al.* (2025). Phase change materials (PCMs) are widely studied due to their capacity to absorb, store, and release latent heat, enabling stable drying temperatures and improved system efficiency. However, conventional PCMs, particularly organic types, suffer from low thermal conductivity, limiting heat transfer during charging and discharging cycles Zhang *et al.* (2018). To address this limitation, nano-enhanced phase change materials (NEPCMs) have been developed by incorporating nanoparticles into base PCMs. Among these, carbon dots have emerged as promising additives because of their high surface area, good thermal conductivity, and enhanced photothermal conversion Li *et al.* (2021). When combined with natural PCMs such as shea butter, which is biodegradable, locally available, and has a suitable melting range, overall thermal performance can be significantly improved. This combination is especially relevant for drying perishable agricultural products like okra, where maintaining quality and reducing spoilage are critical. Integrating PCM-based storage into solar dryers ensures continuous drying even without sunlight. Experimental evaluation of such systems typically examines temperature distribution, drying rate, moisture removal, and efficiency, contributing to the development of sustainable, low-cost drying technologies. Agbetiloye *et al.* (2022) developed a mixed-mode solar dryer using shea butter with 3% aluminium powder as PCM for ginger rhizomes. The PCM achieved 164.53 kJ/kg latent heat and improved thermal performance, reaching 77% collector efficiency. Moisture content decreased from 71% to 13%, while drying efficiency remained 30% during operation. Li *et al.* (2021) developed a shape-stabilised PCM by integrating polyethylene glycol (PEG) into carbonised wood with carbon dots, improving thermal

conductivity (0.449 W/m.K) and photothermal efficiency (84.4%). The composite showed good stability and reliability, but reduced latent heat (112.4 J/g) due to limited PEG loading, indicating a need for further optimisation. Salisu et al. (2022) developed encapsulated shea butter as a bio-based PCM for thermal storage, with a melting peak of 37.5°C, latent heat of 50.34 kJ/kg, and thermal conductivity of 0.26 W/m.K. Experimental and CFD results demonstrated efficient thermal storage and improved overall system performance.

2. METHODOLOGY

2.1 Materials

The carbon precursors used in the hydrothermal synthesis of carbon dots were p-phenylenediamine and folic acid; ethanol was obtained from Haddis Chemical, Samaru, Zaria. Deionized water was obtained from the Ahmadu Bello University Multiuser Laboratory, and food-grade shea butter was purchased from the open market.

2.2 Synthesis of Carbon Dots

Carbon dots (CDs) were synthesized hydrothermally following the method of He et al. (2024). P-Phenylenediamine (30 g) was dissolved in 1 L of ethanol to form solution A, while folic acid (5 g) was dissolved separately in 500 mL of deionized water to form solution B. Solutions A and B were combined under magnetic stirring to obtain a homogeneous mixture, which was then transferred into a Teflon-lined autoclave reactor and heated at 180 °C for 12 hours. After natural cooling to room temperature, the crude product exhibited characteristic red fluorescence under ultraviolet light, indicating successful carbon dot formation. The product was purified by silica gel column chromatography using methanol as the eluent, followed by rotary evaporation and freeze-drying under vacuum. The final carbon dots were obtained with a synthesis yield of 40.3%.

2.3 Preparation of Carbon Dot-Shea Butter Blend

This was done according to the method of (Agbetiloye *et al.*, 2022). 10 mL of shea butter was poured into a clean beaker, and it was heated gently to the desired mixture temperature (40 °C, 50 °C, & 60 °C) Priyadarshi & Paul (2019) until it was completely melted. The appropriate proportion of carbon dots (1%, 2%, & 3% by weight) were measured based on the experimental run. The carbon dots were gradually added into the molten shea butter while stirred to avoid agglomeration. The magnetic stirrer was Placed in side beaker and maintained continuous stirring at the selected temperature. The blending process was allowed to proceed for the specified mixing time (10, 20, & 30 minutes) for each run to ensure uniform dispersion of the carbon dots within the shea butter to achieve homogeneity. The mixture was then removed from the heat source and allowed to cool under ambient conditions.

2.4 Performance evaluation of the PCM in solar dryer

The performance of the PCM for solar drying was evaluated by incorporating it into a solar dryer and carrying out experimental tests to dry okra. A solar dryer of the same capacity (without PCM) and open sun drying were also tested simultaneously, and performances were compared. The temperature and humidity were measured using ATO Bluetooth Temperature and Relative Humidity Logger model ATO-TDL-BT06, made in China. The air flow rate on the other hand was measured using Bluetooth anemometer model AZ/AERMANDA AZ89171, made in China.

2.5 Okra Samples Preparation

The okra was then sliced into 7 mm thick pieces using a kitchen knife. A total of 2 kg of these slices was evenly spread on trays to ensure maximum surface area exposure to incoming hot air during the drying process. The initial moisture content of the okra was about 45% and the target final moisture content after drying was 5%.

2.6 Instrumentation of solar dryer experiment

A thermocouple was used as a temperature sensor for both measurement and control purposes. In this context, thermocouples were employed to measure the inlet and outlet temperatures of a solar dryer, the temperature of the absorber plate with and without phase change material (PCM), as well as the ambient and tray temperatures. A data logger was additionally used to record solar radiation over a four-day period, during which all temperature parameters were monitored. A Camry weighing scale was utilised to determine weight. Specifically, it was used to measure the mass of moisture loss from okra slices, recorded in kilograms.

Experimental procedure



Plate I. The constructed solar dryers.

Plate I shows the solar dryer as constructed. The experimental solar dryer was designed as a compact, portable unit with an overall drying chamber of approximately 360 mm × 340 mm in plan dimensions and 500 mm in height. The solar collector measured approximately 708.9 mm in length and 150 mm in width, while the upper air outlet/chimney section had a height of approximately 500 mm and an internal diameter of 190 mm. The dryer was fabricated primarily from mild-steel shells to provide the structural enclosure and mechanical support, with a wooden table/support frame provided beneath the drying tray to accommodate and stabilize the drying chamber. Aluminium sheet was employed as the glazing/covering material for the solar collector to provide a lightweight and durable enclosure for solar-energy capture. The resulting configuration provides a relatively lightweight and compact experimental platform suitable for controlled investigation of drying characteristics under solar radiation

The experiment was conducted in October, during which two solar dryers and open sun drying processes were operated simultaneously to compare their performance. Additional experimental trials were carried out on the 17th, 18th, 19th, and 20th of October 2025 under the prevailing weather conditions in Zaria, Nigeria.

The evaluation focused on moisture removal and thermal performance parameters, including system drying efficiency, collector efficiency, and drying rate for each drying method, alongside the corresponding moisture content at specific time intervals.

The experiment aimed to test the developed PCM and evaluate the performance of the solar crop dryer by analysing moisture loss, drying efficiency, and drying rate of sliced okra. In terms of procedure, the solar dryer, integrated with phase change material (PCM), was loaded with sliced okra of average thickness between 5 and 7 mm and then exposed to solar radiation. Hourly measurements were recorded for temperatures at various locations, including the collector inlet, absorber plate, chimney, ambient air, and drying tray. These measurements were taken from 08:00 to 20:00 on 17 October 2025, from 08:00 to 20:00 on 18 October, from 06:00 to 20:00 on 19 October, and from 06:00 to 20:00 on 20 October 2025.

Each solar crop dryer was loaded with 2 kg of sliced okra. On the first day, the weight of the samples was measured every two hours, while on subsequent days, measurements were taken hourly. During daylight hours, airflow was naturally established over the absorber plate as the air became less dense upon heating. Solar radiation was also directly incident on the top glazing, enabling both heated air and direct radiation to enhance the drying of the sliced okra while simultaneously charging the PCM within the rectangular absorber plate in the collector and the cylindrical PCM container in the drying chamber.

The heat energy stored within both the rectangular and cylindrical PCM units was released during periods of low solar radiation, thereby sustaining the drying process and extending it beyond sunshine hours. The air mass flow rate into the collector was determined from the product of the measured wind speed (using an anemometer), the collector cross-sectional area, and the air density. The weight of the okra slices on each tray was recorded at the beginning of the drying process and subsequently at two-hour intervals on the first day and at one-hour intervals on the remaining days. The overall procedure followed standard methods recommended in related studies for evaluating solar dryer performance.

2.7 Characterization of carbon dots and blends of carbon dots with shea butter.

2.7.1 Thermal conductivity

Thermal conductivity test was done on the pure shea butter and the modified shea butter (PCM). The Searles apparatus was used in Equation 1

$$\lambda = \frac{Q \cdot X}{A(T_2 - T_1)} \quad (1)$$

where;

λ ; Thermal conductivity of sample [W/mK]

Q; generated heat per unit length of sample/time [W/m²]

Sample diameter = 0.0018 and length = 0.0043 [m]

X; Thickness of sample [m]

A; Area [m²]

T₁ and T₂; Temperature at t₁ and t₂ [K]

t₁ and t₂; measured time length [seconds, s]

2.7.2 Specific heat capacity

$$\text{Specific heat capacity (c)} = \frac{Q}{m \Delta T} \quad (2)$$

Unit of C is J/kg*°C, M is the Mass (kg), Q is the change in energy (J), and ΔT is the temperature change (°C)

2.7.3 Thermal Diffusivity

$$\alpha \text{ (m}^2\text{/s)} = \frac{\lambda}{\rho c p}$$

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Where:

ρ is the density of the material and

C_p is the specific heat capacity (J/gK)

The same apparatus (Armfield equipment model HT12) with a heat transfer service unit (Armfield equipment model HT10XC) was used in this thermal diffusivity calculation.

2.7.1 Latent heat of fusion.

Apparatus:

Ice, blotting paper, copper calorimeter and stirrer, insulating jacket, heater, beaker, thermometer and balance.

Procedure:

The water was gently warmed in a beaker until it reached approximately 32 °C. The calorimeter and stirrer were weighed, after which the calorimeter was filled to about one-third of its capacity with the warm water and reweighed. The calorimeter was then kept within its enclosure, and the initial temperature of the water was observed until it was about 32 °C above room temperature. Small pieces of the sample, previously dried using blotting paper, were added until the temperature fell to around 20 °C below room temperature. The mixture was stirred continuously, ensuring that each portion of the sample had completely melted before additional pieces were introduced. Finally, the calorimeter and its contents were reweighed, and the value of the latent heat of fusion (L) was calculated using the appropriate equation.

Theory:

The specific latent heat of fusion of a solid is the heat required to convert unit mass of it at its melting point into liquid at the same temperature.

Heat gained by shea butter + Heat gained by water = Heat lost by water and calorimeter

Equations:

$$mL + ms_2(\theta_2 - 0) = (m_2s_2 + m_1s_1)(\theta_1 - \theta_2) \quad (4)$$

$$L = [(m_2s_2 + m_1s_1)(\theta_1 - \theta_2) - s_2(\theta_2 - 0)] / m \quad (5)$$

Where:

m_1 =Mass of Copper Calorimeter and Stirrer

m_2 =Mass of Water

S_1 =Specific Heat Capacity of Water

S_2 = Specific Heat Capacity of Copper

θ_1 = Initial Temperature of Warm Water

θ_2 =Final Temperature of Mixture

m =Mass of Sample

L =Specific Latent Heat of Fusion of Sample



Plate II. controlled heat transfer -HT12XC

3. RESULTS AND DISCUSSION

3.1 The dried okra obtained from the experiment



(a)



(b)



(c)

Plate III: Sample dried okra from (a) open sun drying, (b) dried without PCM, and (c) dried with PCM.

3.2 Solar Dryer Testing and Evaluation

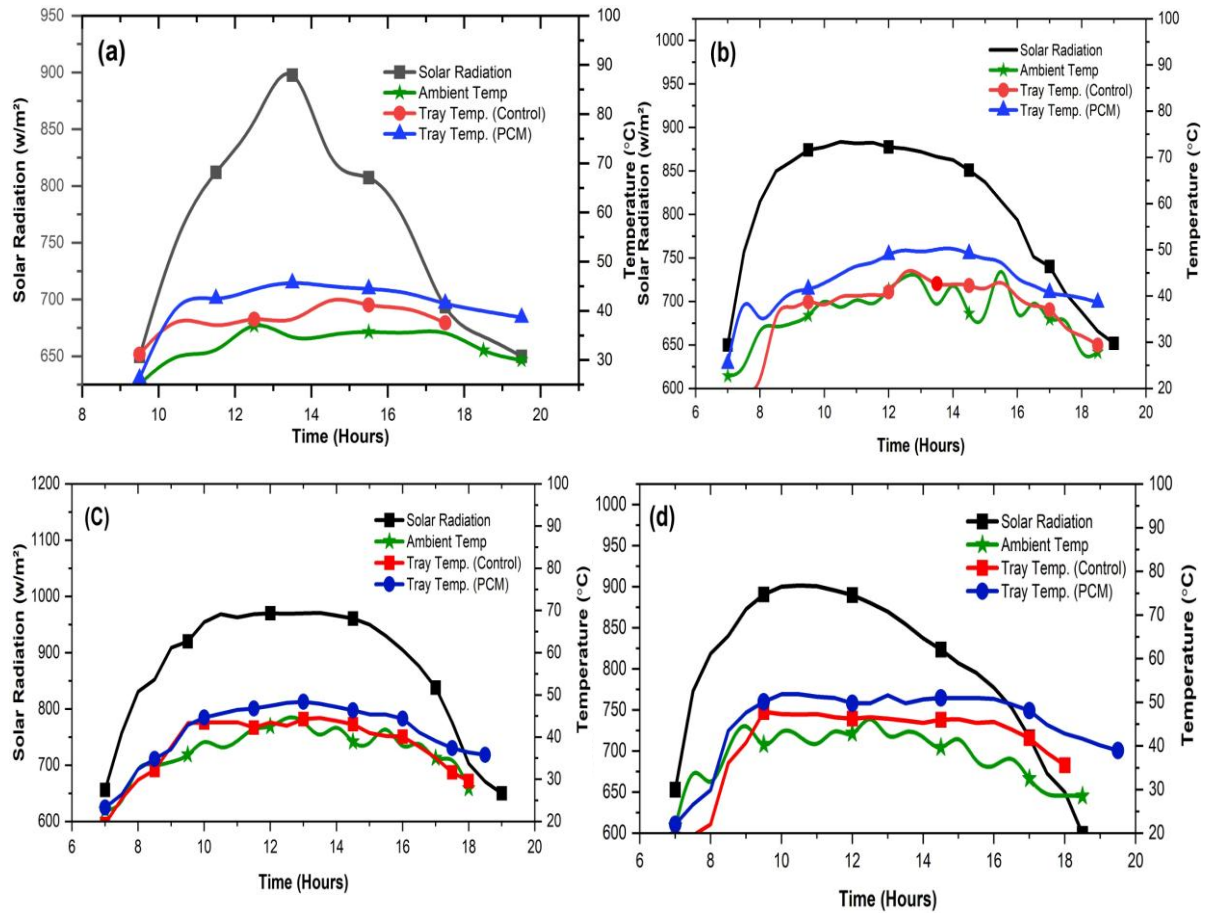


Figure 1: Solar radiation and temperature profiles for (a) day 1, (b) day 2, (c) day 3, and (d) day 4 of the experiments

Figure 1 for (a) day 1, (b) day 2, (c) day 3, and (d) day 4. The chamber of the PCM system exhibited higher peak temperatures, reduced temperature fluctuations, and a delayed cooling profile compared to the control system. This behaviour is attributed to the latent heat storage capability of the PCM and enhanced thermal conductivity provided by carbon dots. Between 10:00 and 14:00, temperatures rise slowly but reach higher values for the PCM system, showing that the PCM absorbs and stores heat. Even when the solar radiation dropped after 14.00, the PCM system chamber temperature remained higher than the control tray. PCM absorbs heat during peak solar radiation and releases it during off-peak periods, stabilising temperature (Han et al., 2022). Percentage temperature difference between the drying chamber temperature and the ambient temperature for all the days were calculated as $\% \text{ difference} = (T_{\text{PCM}} - T_{\text{ambient}}) / T_{\text{ambient}} \times 100$.

A peak temperature of 45.7°C was observed for the PCM-based dryer system on Day 1 at 1:30 pm, and up to a 34% increase in the system temperature compared to the ambient temperature was observed at around 2.30 pm, where the PCM-based chamber was at 45°C while the ambient temperature was 34°C. On the second day, a peak temperature of up to 50.2°C was recorded for the PCM-based dryer system. Also, up to about a 53% difference in the PCM-dryer system temperature compared to the ambient temperature was observed at around 7.30 pm where the PCM-based chamber was at 38°C while the ambient temperature was 25°C. This high early difference could be attributed to the stored heat in the PCM on the first day. A peak temperature of 52°C was recorded on the 3rd day for the PCM-based dryer system at around 10:00 am, and up to a 40% difference between this system's temperature and the ambient temperature was observed, where the PCM-based chamber was at 50°C while the ambient temperature was 36°C. This gradual daily improvement is attributable to the good storage capacity of the PCM enhanced with carbon-dot nanoparticles.

On the fourth day, a peak temperature of about 48.4°C was observed in the drying chamber of the PCM-based dryer system at 1:00 pm. Up to about a 30% increase in the PCM-system temperature was recorded compared to the ambient temperature 5.30 pm, where the PCM-based chamber was at 37°C while the ambient temperature was 29°C. When a PCM is integrated into a solar dryer, it absorbs excess thermal energy during peak solar irradiance and releases it during periods of lower insolation or at night, effectively smoothing thermal fluctuations and maintaining a more consistently elevated temperature within the drying chamber. (Fu *et al.*, 2024; Krishna *et al.*, 2025). The observed thermal lag and sustained elevated temperatures during low solar radiation periods confirm effective energy storage and release, leading to extended drying duration and improved system efficiency. These findings are consistent with established literature on nano-enhanced phase change materials in solar thermal applications. The mean solar irradiance was calculated for the more useful sunlight period of between 10.00 am and 3.00 pm based on the hourly measurement values. The calculated means for the four days were 810, 867, 961 and 867 w/m², respectively which gives a mean of 876 w/m² across the four days. The mean ambient temperature across the four days was also calculated based on hour measurement values taken giving about 28.6 °C.

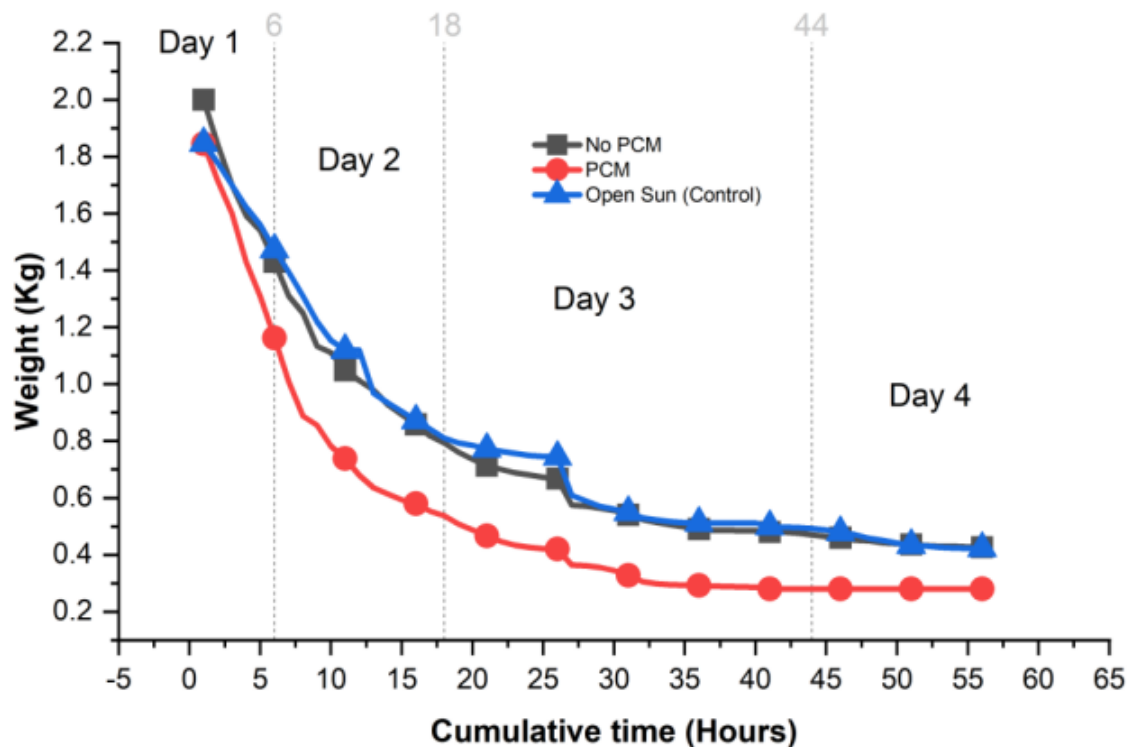


Figure 2: Drying performance recorded for open drying, a dryer with PCM, and a dryer without PCM.

Figure 2 compares drying profiles over 60 hours for open-sun drying (control), a non-PCM dryer, and a PCM-assisted dryer. All curves show the typical exponential mass decline, reflecting an initial constant-rate period followed by a prolonged falling-rate period. The PCM system consistently maintains the lowest residual mass, indicating superior drying efficiency. In the first 6 hours (Day 1), all methods show rapid weight loss from surface moisture evaporation. Still, the PCM dryer declines fastest because it absorbs excess solar heat and releases it gradually, stabilising temperatures. Accord to Azzouz *et al.* (2018) confirm that latent heat storage materials improve heat retention and reduce temperature fluctuations, thereby accelerating early-stage drying kinetics. By 18 hours (Day 2), the performance gap widens: the PCM system continues faster moisture removal while the others slow, corresponding to the shift toward internal moisture diffusion. PCM's sustained thermal input enhances this diffusion. Similar findings were reported by Mohammed *et al.* (2025) By 44 hours (Day 3), drying rates decrease as bound moisture dominates, yet the PCM dryer reaches 0.3 kg versus 0.5kg for non-pcm and 0.6 kg for the open sun. In the final stage, all systems approach equilibrium moisture content

with minimal further loss, but the PCM unit achieves the lowest final mass and greatest drying completeness. Without thermal storage, the non-PCM and open-sun methods remain more dependent on ambient conditions and diurnal temperature drops. Recent work by Kumar *et al.* (2021) highlights that PCM integration is particularly beneficial during the falling-rate period, where consistent thermal gradients are crucial for moisture diffusion from the interior.

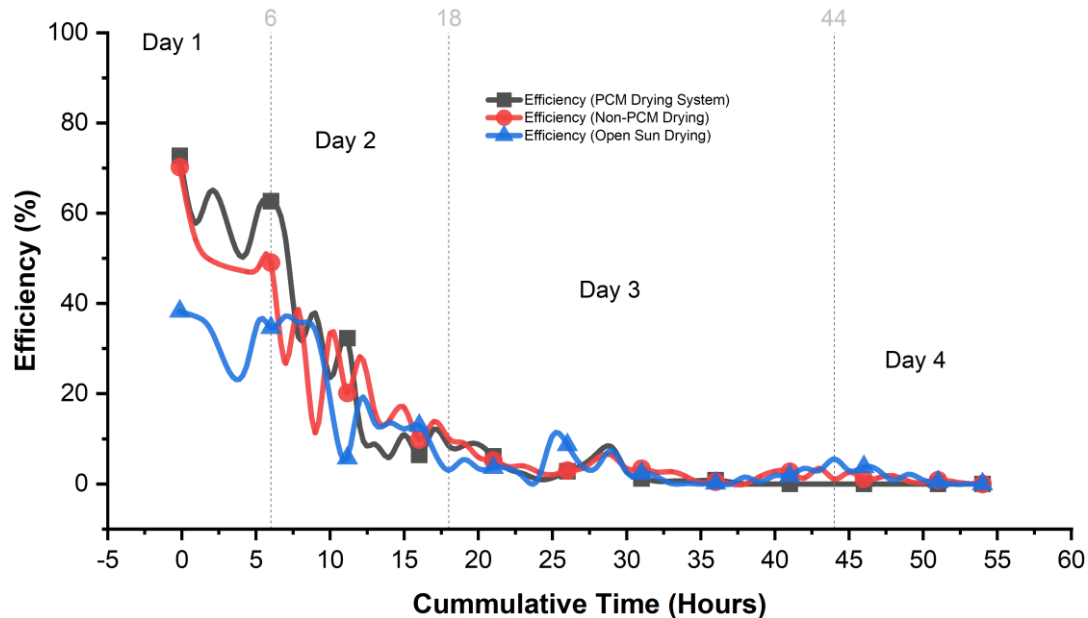


Figure 3: Variation of drying efficiencies with time for the 3 cases

Figure 3 compares the drying efficiencies of PCM, non-PCM, and open-sun systems over approximately 60 cumulative hours. On Day 1, the PCM and non-PCM system recorded similar initial efficiency of about 75%, while open-sun drying began at 40%. During the first 10 hours, however, PCM drying maintained relatively high and stable efficiency between 50% and 70%, whereas non-PCM efficiency declined sharply from to between 30% and <50%. Open-sun drying remained lower, fluctuating between 20% and 40%. By 18 hours, efficiencies declined across all systems because of reduced moisture content and the transition to the falling-rate drying period. However, the PCM system maintained smoother performance, generally achieving 20-40% efficiency, owing to latent heat storage and release during low solar irradiance. Recent studies corroborate this behavior, showing that PCM integration reduces thermal intermittency and improves energy utilization efficiency. (Rakshamuthu *et al.*, 2021) From 30 hours onward, efficiencies approached near-zero values, with all systems falling below 2% by 55-60 hours. Overall, PCM integration provided superior early-stage performance, improved thermal regulation, and sustained moisture removal compared with non-PCM and open-sun drying under variable operating conditions.

4. CONCLUSION

The experimental evaluation of a carbon dot-enhanced shea butter phase change material (PCM) integrated into a solar dryer demonstrated a significant improvement in the drying performance of okra. Under an average ambient temperature of 28.6 °C and solar irradiance of 995.5 W/m², the PCM-integrated dryer achieved an outlet air temperature of 51.6 °C and removed 0.68 kg of moisture from an initial 2 kg okra sample. The PCM-enhanced dryer recorded a peak drying efficiency of 85%, compared with 77% for the non-PCM dryer and approximately 40% for open-sun drying. The incorporation of 3.924 kg of PCM, with an energy storage capacity of 489,853 J, extended the drying period by 5 hours beyond sunshine hours. Consequently, the PCM system achieved the highest drying

rate of 0.20 kg/h, compared with 0.1425 kg/h for the non-PCM dryer and 0.1317 kg/h for open-sun drying. These results demonstrate that carbon dot-enhanced shea butter PCM can improve thermal energy storage, extend drying operations, and accelerate moisture removal. The limitations of these findings is the fact that only one crop (okra) was experimented and the testing was not extended across different seasons, and therefore multiple climatic and weather conditions. Evaluation of the dryer was done only for four days with 2 kg okra samples. Further characterisation using Differential Scanning Calorimetry (DSC) is recommended for more accurate thermal property measurements, while seasonal experiments are suggested to evaluate performance under varying weather conditions and assess the system's reliability and suitability for practical agricultural drying applications of different categories of crops, testing should also be extended for more number of days and hours per day to reduce the margin of error and get more reliable data. This study is an exemplary contribution towards sustainable resource utilization considering the fact the it was focused on the use of shea butter which is a renewable resources that has no competitive usage as food resource for humans and animals making the study directly relevant to the ICESID 2026 sub-theme of sustainable resource utilization/materials synthesis.

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