An Experimental Investigation of a PCM-Integrated Indirect Solar Dryer for Effective Coconut and Onion Dehydration

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Abstract: The purpose of this study is to experimentally evaluate an indirect sun dryer combined with a phase change material (PCM) based on lauric acid for drying agricultural items like coconuts and onions in order to meet the rising need for sustainable and energy-efficient food preservation techniques. A medium-temperature PCM called lauric acid was added to the system to stabilise the drying temperature by storing thermal energy during periods of high solar radiation and releasing it during periods of low sunlight. By contrasting moisture reduction and specific energy consumption between PCM-integrated and traditional (non-PCM) configurations under various weather conditions, the system's performance was evaluated. According to the results, the PCM-based drier reduced the moisture content of coconuts by 71% and onions by 62%. It also reduced the specific energy consumption to 2.1 kWh/kg, which was lower than the non-PCM's 3.5 kWh/kg. These results demonstrate how well the system works to maintain steady drying efficiency in spite of variations in sun availability. Small-scale farmers and rural agro-processing facilities will especially benefit from the suggested dryer's scalable and affordable decentralised crop drying solution. This work supports wider adoption in sustainable farming practices by providing a new dual-crop case study and important experimental insights into the thermal performance and dependability of PCM-based sun drying systems.
Keywords: Food dryer; Phase change material; Thermal storage; Moisture reduction; Energy efficiency.

Introduction

Dietary requirements have increased as the world population and urbanization continue to expand. Inadequate storage and preservation facilities (for fruits and vegetables) induce spoilage, limiting food availability, and resulting in significant price increases. Fruits and vegetables must be preserved to lengthen their shelf life and to retain their quality over time. Several large-scale processing procedures, including drying, freezing, canning, and dehydration, are commonly used in poor nations (Bano, et al. 2015; Getahun, et al. 2021). Drying is one of the oldest methods for preserving and storing food, and it is frequently accomplished by exposing food directly to sunshine. Solar energy is a well-known renewable energy source that has grown in popularity in recent decades. This increase is attributable to the scarcity of fossil fuels and the environmental damage caused by their usage. Solar energy is the most abundant renewable energy source because it is free, environmentally friendly, and readily available throughout the year(Mohamed, et al. 2021). The conversion of solar energy, into heat is the most common and easiest use of this resource (El-Mesery, et al. 2022). This technique significantly decreases the product weight by lowering the moisture content, resulting in dry food that is easily packaged, stored, and transported. Water removal from vegetables and fruits using this approach allows them to be kept for longer periods of time, as water is a critical element in the physiological and.

chemical processes that cause food degradation. This ancient sun-drying method for food preservation was effective, efficient, and ecological. In a direct-type solar dryer, the dried article is directly exposed to sun radiation and

protected by a clear cover. This cover protects goods from the weather and external particles while allowing heat energy from incident solar radiation (Ameri, et al. 2018; Hussein, et al. 2024). Indirect solar dryers provide a higher thermal efficiency than direct sun dryers. These dryers circulate air via a solar air collector, which is heated by solar energy before being sent to the drying chamber(Hussein, et al. 2024). Convection heat transfer occurs in the drying chamber between the hot air and the product, finally removing moisture from the product to dry it. In addition to natural convection systems, forced convection systems for increased thermal efficiency have already been created (Moses, et al. 2013; Muthuvairavan, et al. 2023; Suraparaju, et al. 2024). Solar dryers have a big issue due to the shifting nature of solar radiation, since sunshine does not remain stable throughout the year. Reduced sunshine due to overcast or rainy weather has a major impact on solar dryer performance, resulting in low-quality goods and an increased risk of spoiling (Sarsavadia 2007; Usubiaga, et al. 2018). Other disadvantages of typical drying methods include lengthier drying duration, uneven temperature exposure, and food hardening. To minimize these challenges, the food sector is pushed to enhance existing drying processes and create new drying technologies. The next generation of dryers and drying technologies is projected to encourage more sustainable development by increasing thermal and energy efficiency, lowering operating costs, and improving product quality. As the world moves toward the adoption of green technology and sustainable practices, the use of alternative energy-efficient drying systems has become increasingly important. For these reasons, sun-drying techniques have been discovered to be the most acceptable methods for the dehydration of food items, eliminating the environmental difficulties that arise from traditional drying processes (Mehta, et al. 2022; Menon, et al. 2020). Drying is a food preservation method that involves evaporation of water from harvested items to avoid bacterial development. However, technical advancements have resulted in thermal methods being used in agricultural businesses for food processing and storage (Menon, et al. 2020; Suraparaju, et al. 2024). The inherent shortcomings of traditional energy sources, as well as the benefits of solar energy, such as cost-effectiveness and efficiency, present long-term solutions for environmental development. Solar radiation is readily accessible worldwide, replacing the customary drying method to preserve fruits and vegetables for as many days as possible(Ahmad, et al. 2022; Tyagi, et al. 2024). Food drying is also a complex process that involves variations in heat and mass transport as well as physical and chemical interactions that may degrade product quality(Chandramohan and Talukdar 2014; Selimefendigil, et al. 2022). It is a complicated process that involves both mass and heat transfer as well as physicochemical changes. Drying is an important stage in the creation of many different types of chemical products because it adjusts and controls moisture levels in solid materials(Ahmad and Prakash 2019). Because it is used in practically every plant and facility that manufactures or processes solid materials, the chemical process industries may have a considerable influence on both the quality of the finished product and the efficacy of the drying operations(Muthuvairavan, et al. 2023) (Ar and Veeramanipriya 2022). Two similar natural convection solar tunnel dryers with different heat energy storage configurations were designed, built, and experimentally tested. Four storage configurations were evaluated, and the third configuration, using a bed of paraffin-filled cans, showed the best thermal performance. At the end of the day, the temperature difference between the storage mediums of the two dryers was 26°C for the third configuration, 17°C for the fourth, 10°C for the second, and 6°C for the first (Benseddik, et al. 2023). The results demonstrate the benefits of integrating thermal energy storage in solar drying systems to improve their performance and extend the drying hours(Romero and Romero 2021). Drying solid materials, including powders and granules, is a common and major unit activity in chemical process industries. The use of phase-change materials (PCMs) in thermal energy storage systems has gained substantial attention in solar energy applications, notably within the realm of solar heat dryers. PCMs provide a considerable advantage over typical sensible heat storage materials, principally owing to their high energy density within certain temperature ranges, which makes them extremely ideal for such applications. In the design of solar heat dryers, selecting an optimal PCM is crucial for improving the system performance and efficiency. Key variables, including the melting point, latent heat of fusion, thermal conductivity, and overall thermal stability, must be carefully examined to ensure that the PCM aligns with the unique working conditions of the solar heat dryer (Dhaou, et al. 2021; Hirmiz, et al. 2018). Encapsulated high-temperature PCMs have emerged as viable alternatives to thermal storage in concentrated solar power applications (Muñoz-Sánchez, et al. 2015). These materials can be incorporated into a thermocline-based storage system in which PCM capsules are mixed with filler materials to boost the overall thermal performance. The integration of PCMs into solar heat dryers has various benefits, including prolonged heat retention, more constant drying temperatures, and less dependency on extra heating sources. However, the limited heat conductivity of certain PCMs may create a barrier that may reduce their overall efficacy. Numerous studies have been conducted on various kinds of solar energy-based dryers, and it has been shown how important they are for drying food and agricultural items all over the world. Additionally, it has been noted that adding thermal energy storage units to solar dryers improves the thermal efficiency and shortens the drying time.

In the present work, the efficacy of phase change materials (PCMs) as mechanisms for thermal energy storage was thoroughly studied in connection to the dehydration processes of onions and coconuts. This research tries to provide essential understandings that may guide the potential deployment of PCM-integrated systems in the drying procedures relevant to numerous agricultural commodities(Bhutto, et al.).

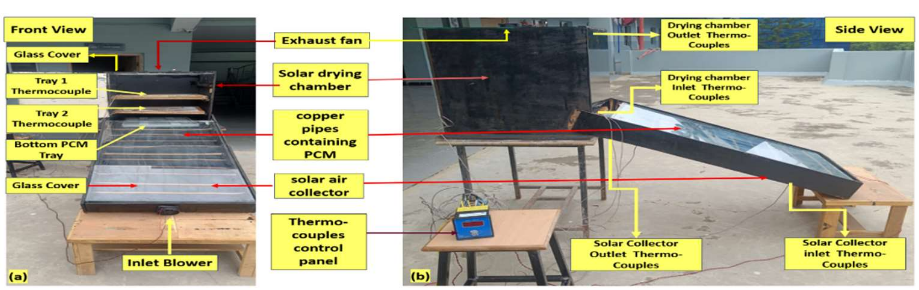
Although various studies have compared PCMs in solar drying, few consider theoretical models, a single crop, or controlled or optimal conditions. This paper presents a new, two-crop experimental assessment using lauric acid as PCM, which was selected for its appropriate melting point and stability. Notably, it demonstrates how thermal energy storage improves efficiency, uniformity of drying, and energy savings under naturally varying solar radiation. The comparison of the system performance with and without PCM, expressed as specific energy consumption, drying rate, and mass loss, offers practical insight into the use of PCMs for food preservation in rural or off-grid areas

Materials and Methods

2.1 Experimental procedure

Onions and coconuts were chosen for their economic significance and extensive culinary and industrial applications. These crops are prone to substantial post-harvest losses, but drying effectively extends their shelf life, reduces wastage, and enhances marketability. This study addresses global demands for sustainable preservation and value addition in agricultural products. Experimental solar drying system was designed and tested at Vardhaman College of Engineering, Rangareddy district. It has two major components: a solar air collector and a drying chamber. The system was tested in two configurations: with and without PCM for comparative analysis. In the PCM system, a series of sealed copper pipes containing lauric acid (the chosen PCM) were installed inside the solar air collector to increase heat storage. The copper tubes store excessive heat during intense solar radiation and release the generated heat slowly under low-intensity conditions. Further thermal buffering to level drying temperatures was achieved by a special PCM tray mounted at the bottom of the drying chamber trays. For the non-PCM system, the same experimental system was employed without the copper pipes and the PCM tray to investigate performance under natural solar conditions alone. The drying chamber is a 60 × 60 × 60 cm^3 cube, with three removable steel mesh trays (60 × 50 cm) mounted inside wooden frames. Airflow is facilitated by an air vent (7.62 × 7.62 cm^2), and the solar collector is equipped with a 3 mm transparent glass sheet (121 × 60 cm^2). Temperatures at major points attracting the collector inlet/outlet, drying chamber, and PCM tray—were measured using Omega Engineering thermocouples (±0.1°C accuracy). A control panel displayed real-time temperatures. Mass of drying samples (onions and coconuts) was measured hourly using a digital weighing machine. Ambient conditions like humidity and wind speed were recorded using a hygrometer and anemometer. To compensate for environmental fluctuations, all the measurements were normalized against solar radiation levels by the use of a lux meter (±2% accuracy). The schematic diagram of experiment solar dryer design with the components labeled, including the PCM configurations, is presented in Figure 1.

Figure 1. Experimental Set-up



Thermocouples measured the temperatures at these points in the solar dryer between 8 a.m. and 8 p.m. Readings were taken for one day. During this period, 1 kg each of onions, 1 kg Coconut were dried. The weights of these samples were measured at the end of each hour to determine the amount of moisture lost.

2.2 Selection of Phase Change Material

The PCM for this research employed was lauric acid because of its positive attributes that match the operating requirements of the solar drying system(Geete and Singh 2023). It has a melting point of 43.8°C, which is suitable for the drying of agricultural products like onions and coconuts. In addition, lauric acid has a high latent heat (187 kJ/kg), which makes it a favourable substance for thermal energy storage and utilization. Lauric acid also offers improved chemical stability and reduced supercooling over paraffin wax and stearic acid, which are critical for applications involving multiple thermal cycles(He, et al. 2022; Kalidasan and Pandey 2024). Paraffin wax has a similar energy density but a lower thermal conductivity, which could lead to the overall heat transfer efficiency being reduced. Stearic acid, though proven efficient, has a higher melting point (69°C, 156°F), causing heat membrane and risking the product integrity. When combined with cost-effectiveness and accessibility, these aspects make lauric acid an ideal choice for this application(Fan, et al. 2022). The PCM characteristics are listed in Table 1. According to the box made for PCM storage, a 1.5 kg PCM, which covers 80% of the volume of the PCM, was employed in this experimentation.

Table 1: Properties of Lauric acid

PCM	Melting Point(°C)	Thermal Conductivity (W/m.K)	Boiling Point(°C)	Density (g/cm^3)
Lauric acid	43.8	0.442	297.9	1.007

2.3 Analytical performance factors

The following method was used to determine the amount of heat required to dry the material:

$$Q_m = c_p m_i (Tm_f - Tm_i) \quad (1)$$

The initial and final values are denoted by subscripts i and f, respectively. The quantity of heat required to remove moisture from the material is

$$Q_e = H(m_i - m_f) \quad (2)$$

In this equation, H represents the latent heat of vaporization measured in kJ/kg. The total heat required for the drying process is

$$Q_t = Q_m + Q_e \quad (3)$$

2.3.1 Heat available from Solar Air Collector

The amount of heat released by solar air collector (SAC) (or) the heat accessible for drying can be expressed as

$$Q_a = c_{pa} m_a (T_{out} - T_i) \quad (4)$$

In the given context, the subscript 'a' denotes air and T_{out} refers to the SAC outlet. Multiple factors influence the effectiveness of SAC, including geographic location, ambient air speed, temperature, and moisture content. The SAC efficiency can be calculated using the following formula:

$$\eta_c = \frac{Q_a}{I} = (\dot{m}_a c_{Pa} (T_{out} - T_i))/A_C I_C \quad (5)$$

where A_c is the area of the collector and I_c is the solar intensity (W/m^2).

2.3.2 Drying characteristics

Initial MC in wet basis (wb) and dry basis (db), respectively, is estimated by,

$$MC_i = \frac{m_i - m_d}{m_i} \quad (6)$$

$$MC_i = \frac{m_i - m_d}{m_d} \quad (7)$$

where mi and md represent the initial and final dried masses of the product, respectively. The drying rate (DR) of the material in indirect type solar dryer (ITSD) is calculated using moisture content (MC) at two successive time points divided by the difference in time (dt) and is expressed as,

$$DR = \frac{dM}{dt} = \frac{M_{t+dt} - M_t}{dt} \quad (8)$$

The calculation of ITSD's thermal efficiency (η_d) of the ITSD involves the following:

$$\eta_d = \frac{(m_i - m_f)(\gamma + m_i(T_{do} - T_a))}{Q_a} \times 100\% \quad (9)$$

The subscript a denotes water, while do indicates the drying chamber's outlet

2.5 Uncertainty Analysis

The analysis was conducted according to the standard root-sum-square (RSS) error propagation method. The process addresses uncertainties of major variables within collector efficiency, dryer efficiency, and mass loss calculations. Equipment used in the present study included thermocouples with ±0.1 °C accuracy to record temperature, a lux meter with ±2% uncertainty for measuring solar radiation, and a digital balance with ±1 g accuracy to record mass loss. Table 2 shows the measurement uncertainty of instruments used in the current study. An anemometer and hygrometer were also used to measure wind speed and relative humidity, with accuracies of ±0.5 m/s and ±3% RH, respectively. Taking into account compounding uncertainty in measured parameters, the overall uncertainty in collector and dryer efficiency was found to be within ±5.2%, and that of mass loss measurements within ±2%. These ranges of uncertainty provide the validity and reliability of the experimental results and justify the performance comparison drawn between the PCM and non-PCM designs.

Table 2: Measurement Uncertainty of Instruments Used

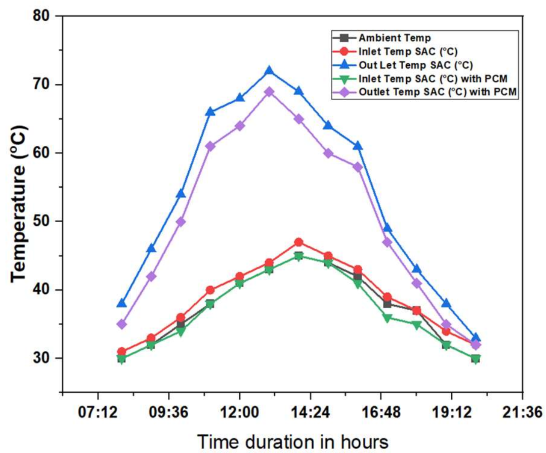
Parameter	Instrument Used	Accuracy / Uncertainty
Temperature	Thermocouples (Omega)	±0.1 °C
Solar radiation	Lux meter	±2%
Mass measurement	Digital balance	±1 g
Time	Stopwatch	±1 s
Wind speed	Anemometer	±0.5 m/s
Relative Humidity	Digital hygrometer	±3% RH

Results and Discussions

3.1 Solar Drying of Onion Without PCM

3.1.1 Temperature Profiles and Solar Intensity

An investigation of the onion drying process without PCM indicated a different temperature trend throughout the drying period (08:00 to 20:00 Hrs). The solar air collector (SAC) input temperature starts at 31°C in the morning and rapidly rises, reaching a maximum of 47°C at approximately noon (14:00). The SAC output temperature displayed a parallel pattern, commencing at 38°C at 08:00, rising at 72°C at 13:00, and then gradually dropping to 32°C by the end of the day. This continuous increase in outlet temperature closely coincides with the growing sun intensity, which begins at 225 W/m² and reaches its peak of 1200 W/m² by 13:00. The different temperature trends throughout the drying period are illustrated in **figure 2 a.** where as figure 2 b illustrate the full drying condition of onion.



(a)

(b)

Figure 2: (a) Temperature trend throughout the drying time (b) Onion sample after full drying condition

The inlet and outlet temperatures of the drying chamber showed a similar increase, as illustrated in **figure 3**, with the outlet reaching 72°C at approximately 13:00, matching the SAC outlet temperature. Throughout the day, the mass flow rate remained constant at 0.047 kg/s. During peak sunlight hours, the elevated temperatures suggest that the system efficiently captures and uses solar energy to dry onion slices. Nevertheless, the temperature variations, especially in the afternoon, underscore the system's lack of temperature control, which is a drawback of this setup without a phase change material to help regulate the temperatures. The drying chamber's inability to maintain a consistent temperature throughout the day is a limitation that could impact the quality and efficiency of the drying process. **Figure 4** illustrates the temperature variation across various trays in the drying chamber. This temperature variation across the drying trays is a significant discussion point, as it suggests the system

may not provide uniform drying conditions, which could adversely affect the quality and consistency of the final dried product (Aghbashlo, et al. 2015) (Mari, et al. 2024) . Uneven temperature distribution in the drying chamber can lead to non-uniform moisture content in the dried onion slices, resulting in variations in texture, color, and nutritional content (Mari, et al. 2024). The temperature variation observed in this study highlights the need for further optimization of the drying chamber design to ensure more uniform drying conditions.

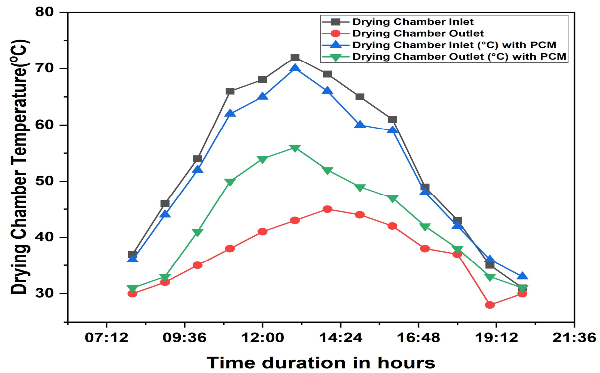


Figure 3: Illustrates the Inlet and outlet temperatures of the drying chamber with and without PCM.

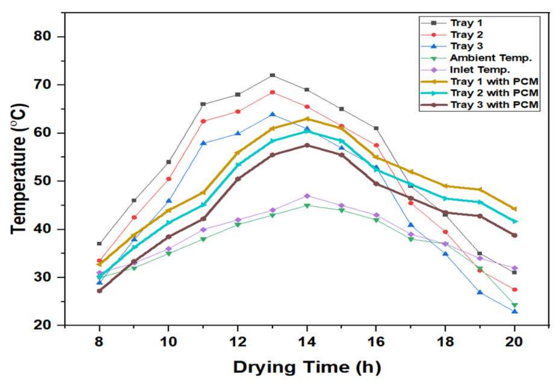


Figure 4: Illustrates the temperature variation across various trays in the drying chamber with and without PCM.

The system's tendency to overheat the product during peak daylight hours is demonstrated by the very high temperature observed at the drying chamber exit around midday. This intense heat can perhaps affect the dried onions' quality, diminishing their texture and taste. A parallel experiment by (Rahman 2020) demonstrated similar temperature fluctuations, revealing that onion drying efficiency was considerably influenced by solar intensity, with optimal drying occurred at same temperatures. Their findings also suggest that overheating has a negative effect on product quality, which is consistent with the conclusions of the current experiment.

Mass Loss and Heat Supplied Without PCM for onions

As anticipated, the amount of heat provided to the system is precisely proportional to the sun intensity illustrated in **figure 5**. The amount of heat supplied was calculated from equation 4. It begins at 330.65 W in the morning, reaching its maximum of 1885.38 W by 13:00, and thereafter declines to 35.18 W by 20:00 as sun intensity diminishes. This relationship underscores the strong dependency of the drying process on the availability of solar energy throughout the day. The change in onion mass during the drying process provides an indicator of the pace at which moisture is being eliminated. Initial measurements at 8:00 AM revealed a mass differential of 0.05 kg, which rose to 0.20 kg by afternoon. This shows a considerable acceleration in moisture evaporation during moments of peak sunlight intensity illustrated in **figure 6**. However, the rate of mass loss stabilizes during the late afternoon and evening, corresponding to a fall in solar intensity and, consequently, a slower drying rate. The experimental results demonstrate that solar energy can be effectively harnessed to dry onion slices, as evidenced by the significant moisture loss over the course of the day the same analysis reported by Coelhe et al., (Coelho, et al. 2013). The experimental results indicate that the system can effectively utilize solar energy to drive the drying process, resulting in significant moisture loss over the course of the day.

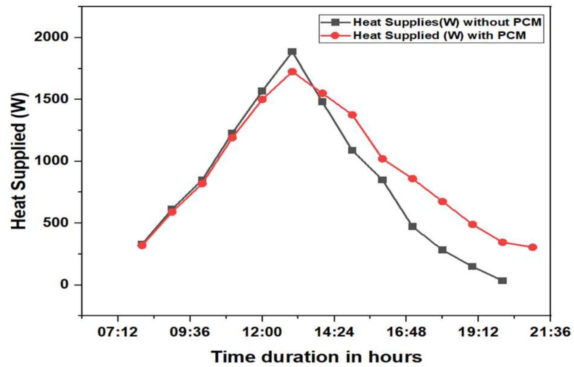


Figure 5: Heat supplied to drying chamber in a day

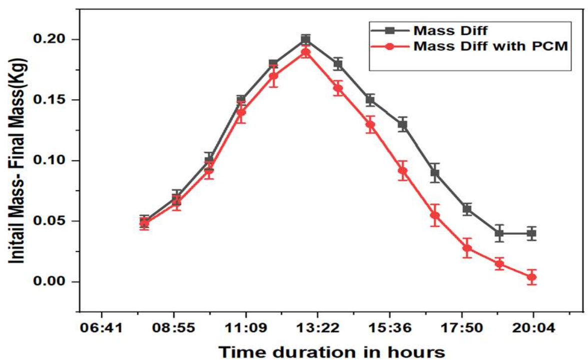


Figure 6: Mass loss of onion in the drying process

3.1.3 Efficiency of collector without PCM for Onions drying

Without PCM, the solar air collector's efficiency during the drying of onions starts at 48.98% in the morning and varies throughout the day, peaking at noon at 43.33% and 54.15%. The collector efficiency was calculated from equation 5, and the dryer efficiency was calculated using equation 9. According to this pattern, the solar air collector works best when the sun is at its Peak, efficiently absorbing and distributing solar energy to the air that moves through the system. Later in the day, as the solar intensity decreases, the collector's efficiency naturally declines as well illustrated in **figure 7**.

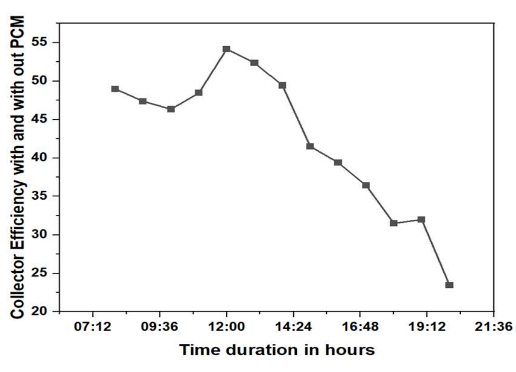


Figure 7: Illustrates Collector Efficiency in both the cases with and without PCM

3.2. Solar Drying of Onion With PCM

3.2.1 Temperature Profiles and Solar Intensity

When lauric acid is incorporated into the solar dryer system, the temperature patterns show significant moderation. The SAC inlet temperature was slightly reduced in the initial hours, starting at 30°C and peaking at 45°C at 14:00. The SAC outlet temperature reached a maximum of 69°C, which was lower than the 72°C observed without the PCM. The PCM helps stabilize the temperature variations, preventing the outlet temperature from exceeding a critical limit, thus helping to maintain the quality of the dried onions. With the PCM, the outlet temperature of the drying chamber exhibits more consistent curves, reaching a maximum of 44°C at noon, in contrast to 46°C without the PCM. The capacity of the PCM to act as a thermal buffer, which retains surplus heat during times of high solar intensity and releases it when the evening solar radiation decreases, is responsible for this drop in output temperature. This technique reduces the possibility of overheating and produces a more controlled drying environment, both of which are critical for maintaining the product quality. As reported by Shalaby and Bek, the incorporation of the PCM, specifically lauric acid, into the solar dryer system has demonstrated its ability to moderate the temperature patterns and provide a more stable drying environment (Shalaby and Bek 2014). The phase change material (PCM) regulates heat by absorbing excess thermal energy when the temperature rises and releasing it when the temperature drops. This dynamic heat management helps maintain a stable outlet temperature in the drying chamber, ensuring it does not exceed critical thresholds that could compromise the drying process. By maintaining optimal conditions, the PCM preserves the texture, flavor, and overall quality of the dried onions. The similar approach by Djaeni And Hidalgo highlights the potential benefits of integrating phase change materials into solar-powered drying systems to improve the overall efficiency and consistency of the drying process (Djaeni, et al. 2021; Hidalgo, et al. 2021).

3.2.2 Mass Loss and Heat Supplied with PCM for Onions

The incorporation of phase change materials (PCM) within solar drying systems markedly improves both the efficiency of drying processes and the utilization of energy resources. The observed reduction in mass of onions subjected to drying via a PCM system was found to be analogous to those subjected to drying without the application of PCM. Nonetheless, the PCM system exhibited a marginal decrease in the rate of mass loss during the afternoon hours, signifying a more regulated and stable drying environment. By 13:00, the disparity in mass within the PCM system was quantified at 0.19 kg, which is slightly inferior to the 0.20 kg recorded in the non-PCM system. Additionally, the PCM system achieved a peak heat output of 1825.40 W, which was less than the 1885.38 W measured in the alternative configuration, indicating a potential for enhanced energy efficiency. The augmented drying efficiency associated with PCM systems can be ascribed to their capacity to absorb thermal energy during periods of maximal solar irradiation and subsequently release it during intervals of diminished sunlight, thus facilitating the maintenance of stable drying temperatures. Similar observations made by rehman et al., (Rehman, et al. 2023). Salve and Fulambarkar studied similar system equipped with PCM achieved a drying efficiency rate of 30.84%, in contrast to the 28.76% efficiency observed in systems lacking PCM (Salve and Fulambarkar). Moreover, the PCM system significantly curtailed energy consumption, resulting in substantial savings in electrical energy and a reduction in CO_2 emissions (Divyangkumar, et al. 2022). Mandal et al., studied PCM architectural design permits extended functionality beyond daylight hours, thereby optimizing the drying potential (Mandal, et al. 2020).

3.2.3 Dryer Efficiency Analysis with and without PCM for Onions

The efficiency of drying the onions was tested under two configurations: with and without Phase Change Material. **Figure 8** presents temporal variations in dryer efficiency, along with corresponding uncertainty error bars based on instrumentation and measurement accuracy. Both configurations initially recorded high values of dryer efficiency, which reached a peak around 35.8% (with PCM) and 34.6% (without PCM) at about 07:12 hrs. This early peak can be explained as due to the lower ambient temperature and higher availability of solar resources, thereby providing conducive thermal conditions for evaporation. But a dramatic decline in efficiency is noted soon after, reflecting a phase of transition in which the increasing ambient temperatures started to deplete the thermal gradient and air circulation efficiency. Towards the latter part of the day, a fairly distinct delineation of the two configurations became apparent. The system with PCM uniformly outperformed the non-PCM configuration in performance between 10:00 and 19:00 hrs. Interestingly, the PCM system recorded a relatively steady efficiency of between 28 -31%, which can be explained as due to the thermal buffering effect of lauric acid. While soaking up excess heat during peak solar radiation inputs and dumping it during declining solar inputs, the PCM permitted a uniform drying medium, minimizing thermal losses and ensuring drying effectiveness. The non-PCM system, on the other hand, continuously declined in efficiency, reaching a low of 21% at 19:12 hrs and further declining to below 19% at 21:36 hrs. This decline reflects poor heat retention as solar intensity went down, resulting in a less effective drying operation during late afternoon and evening hours. The addition of error bars further confirms the validity of the results and reflects consistent accuracy in measurement. Although there are some local overlapping uncertainty intervals for certain intervals, the overall pattern shows a statistically significant rise in the efficiency of dryers with the addition of phase change materials. The results concur with earlier research that shows enhanced thermal performance and drying uniformity when PCM is used

(Ramirez, et al. 2020) (El Khadraoui, et al. 2017; Manirathnam, et al.) (Rosenthal, et al.).

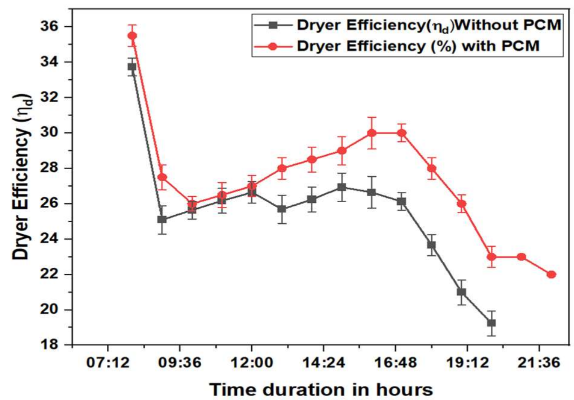


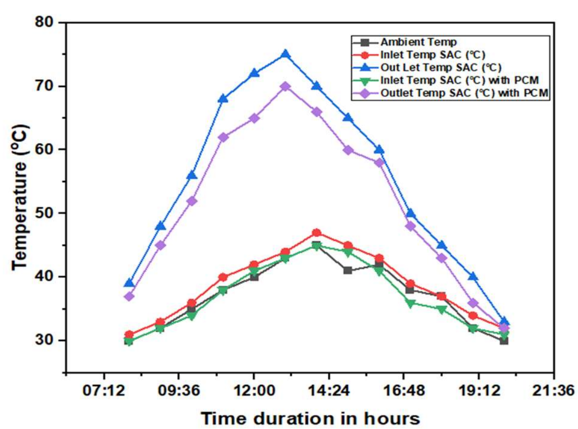
Figure 8: Drying Efficiency Analysis of onion with and without PCM

The higher dryer efficiency with the PCM can be ascribed to its heat storage and release properties, which assist in maintaining a consistent temperature in the drying chamber despite changes in sun intensity.

3.3 Solar Drying of Coconut Without PCM

3.3.1 Temperature Profiles and Solar Intensity

The solar drying process of coconut without the use of phase change materials (PCM) demonstrated significant temperature variations essential for effective moisture removal. **Figure 9** (a) demonstrates temperature profiles of solar air collector of coconut without PCM. The inlet temperature of the SAC began at 31°C and peaked at 47°C by 14:00, while the outlet temperature reached a maximum of 75°C at 13:00. These values were notably higher than those recorded during onion drying, reflecting the greater energy demand for thicker coconut slices similar analysis were reported elsewhere (Diez, et al.). Additionally, the drying chamber temperature rose to 64°C around midday, highlighting efficient heat retention and moisture extraction during peak sunlight hours, the same observation made by Kulanthaisami et al (Kulanthaisami, et al. 2009). Coconut drying required higher energy input compared to other agricultural products due to the elevated temperatures necessary to reduce the moisture content from 50–55% to approximately 6% this observation made by sahari et al and also, similar kind of observations were made in this work (Sahari et al., 2023). While these higher temperatures facilitate faster moisture removal, they pose potential risks to product quality. As noted by Muthuvairavan (Muthuvairavan, et al. 2023), prolonged exposure to high temperatures may compromise the quality of dried coconut, emphasizing the importance of precise temperature control. These findings indicate that while solar drying systems enhance drying efficiency through elevated temperatures, achieving a balance between temperature control and product quality remains a critical challenge in optimizing drying performance. The full drying condition of coconut is illustrate in figure 9 (b).



(a)

(b)

Figure 9: (a)Temperature Profiles of Solar air collector of Coconut Without PCM (b) full drying condition of coconut

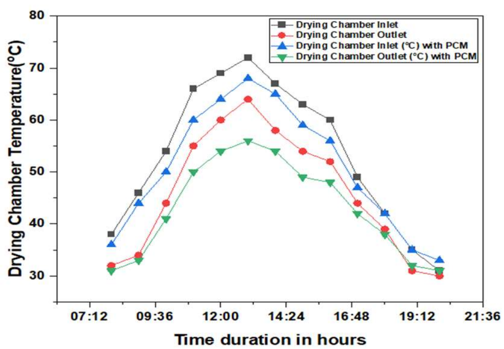


Figure 10: Temperature Profiles of Solar dryer of Coconut with and Without PCM.

3.3.2. Mass Loss and Heat Supplied Without PCM for Coconuts

The desiccation process of coconuts exhibited considerable mass reduction and thermal energy requirements, particularly during intervals of maximal solar radiation (**figure 11**). The peak observed mass variance was 0.20 kg by 13:00, signifying effective moisture extraction and proficient drying efficacy. This operation successfully diminished the moisture content of coconuts from roughly 55% to 7% (wet basis), demonstrating comparable efficiency to the dehydration of other agricultural commodities such as onions (Sahari, et al. 2023) (Ayyappan, et al. 2021). The findings underscore the necessity for meticulous temperature and energy regulation to attain uniform drying results for thicker coconut slices. The energy requirements associated with coconut desiccation were apparent, with a maximum thermal input of 1820 W necessitated during the procedure. This highlights the energy-demanding character of coconut drying in contrast to onions, which employ hybrid drying systems. Such systems, integrating solar and biogas energy, have been evidenced to decrease onion moisture content from 80.06% to 9.88% within a span of 12 hours, presenting potential benefits in terms of energy efficiency and sustainability (Rupnar, et al. 2020). These results indicate that while coconut drying is efficacious, alternative or hybrid methodologies could augment energy efficiency for other crops, thereby facilitating the advancement of more sustainable drying technologies.

Solar Drying of Coconut With PCM

4.1 Temperature Profiles and Solar Intensity

The use of phase change materials (PCMs) in solar drying systems markedly increases heat control and overall drying performance, as seen in Figures 9 and 10. This phenomenon is most pronounced in coconut drying, where PCM systems sustain a consistent output temperature of 70°C, in contrast to the 75°C recorded in non-PCM systems, hence offering a more regulated drying environment. This exact thermal management mitigates the possibility of overheating, ensuring uniform drying performance and enhancing product quality(Rehman, et al. 2023; Rulazi, et al. 2023). Phase Change Materials (PCMs) are essential for regulating temperatures in solar dryers, efficiently preventing excessive heat that may damage product quality. Phase Change Materials (PCMs) reduce the likelihood of overheating and thermal damage by sustaining lower peak temperatures compared to traditional systems. This stabilisation is especially advantageous for temperature-sensitive items, facilitating consistent drying and yielding improved outcomes(Diez, et al.). Empirical research indicates that PCM systems significantly decrease total drying times, enhancing efficiency and economic feasibility(Kavya and Ramana 2024; Rehman, et al. 2023). In the work of Baibhaw Kumar et al.,(Kumar, et al. 2024) studied on similar kind and observed the use of phase-change materials (PCMs) in hybrid solar drying systems greatly enhances wood fuel drying by improving thermal efficiency and sustainability. The system, employing coconut oil as a PCM, provides longer heat retention, excellent thermal and exergy efficiency, and cost-effective operation, with minimum environmental impact. that Moreover, PCMs are critical in maintaining constant temperature profiles, which is especially significant for temperature-sensitive items like coconuts. Controlled drying conditions supplied by PCMs decrease thermal deterioration, enabling high-quality dried goods(Rulazi, et al. 2023).

4.2 Mass Loss and Heat Supplied Without PCM for coconut drying

Figure 11 displays the prominent advances in both mass loss management and thermal performance observed when integrating phase change materials (PCMs) into the drying processes of coconut. The mass loss of coconuts dried using PCM systems was comparatively less at 0.19 kg by 13:00 against 0.20 kg by 13:00 in non-PCM systems. The decrease demonstrates the capacity of PCMs for generating stable temperature and optimal drying conditions, resulting in an efficient drying process in controlled drying conditions. For thermal efficiency, at 13:00, the required thermal supply for the PCM system was 1800 W which was much lower than the energy requirements of a non-PCM framework. The reason for the lower thermal input is that PCMs can store and release thermal energy for a longer time and, as a result, allow for energy optimization. PCM systems not only enhance drying performance in terms of efficiency but also establish the model for a more environmentally beneficial energy regimen by reducing peak power requirements and preserving steady-state temperatures for drying. Besides energy efficiency, this use of PCMs in drying systems allows to take advantage of other useful features as presented in the following sections. This reduction in mass loss highlights the ability of PCMs to stabilize temperature, thus creating optimal drying conditions. Previous studies, such as those by Mandal et al (Mandal, et al. 2020) have underscored the role of PCMs in mitigating temperature fluctuations, but they did not offer quantitative comparisons of mass loss, making this study a novel contribution in this area. PCMs have been demonstrated to improve product quality by alleviating temperature shocks that can otherwise result in non-uniform drying and quality degradation (Sharma, et al. 2021). Temperature stabilization, for example, reduces the danger of over-drying or under-drying, preserving the organoleptic and nutritional properties of the dried coconuts. In addition, the controlled drying environment minimizes the chance of microbial growth, thus producing safe product with a longer shelf life (Alp and Bulantekin 2021).

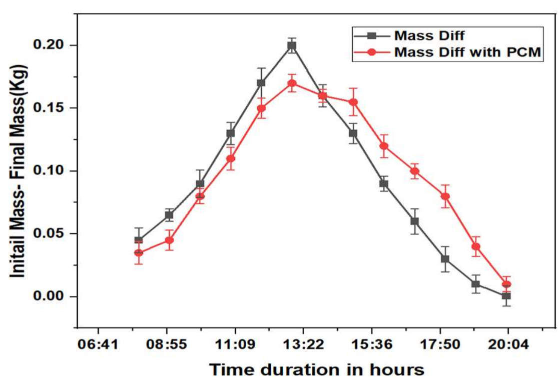


Figure 11: Mass loss of Coconut in the drying process

Another considerable benefit of PCM-based drying systems is scalability. Scale-up of drying using conventional methods is often difficult due to the lack of uniformity and efficiency; however, PCM acts as a thermal buffer and therefore is an attractive option. It is essential for industrial applications where process stability and energy reduction are both important(Ben-Abdallah, et al. 2019). Moreover, the use of PCM technology conforms to global sustainability objectives, as it minimizes carbon footprints caused by energy-demanding drying systems (Salve and Fulambarkar). These results highlight the importance of using PCMs for improving the efficiency and sustainability of dryers. These results are consistent with prior literature that has shown PCM-based systems to have improved thermal regulation (Mugi and Chandramohan 2022), energy efficiency (Arul, et al. 2022), and product quality (Sharma, et al. 2022) . These developments create the foundation for large-scale adoption of PCM technology in drying processes and can have transformative effects, particularly for energy-efficient practices in the agriculture and food sectors.

4.3 Efficiency Analysis With and without PCM

In the context of coconut drying without the inclusion of phase change materials (PCM), the collector efficiency ranges from 47.12% to 52.08%, which is slightly inferior to the efficiency observed in the drying of onions. **Figure 12** elucidates the comparative efficiency analysis of the dryer with and without the incorporation of PCM. This marginal decrease in efficiency may be attributed to the heightened energy demands associated with the drying process of coconuts. The efficiency of the dryer for coconuts devoid of PCM displays a trend analogous to that of onions, commencing at 34.5% in the morning and progressively diminishing to 24.5% by 13:00. This anticipated reduction in efficiency is a consequence of the elevated temperatures within the drying chamber, which lead to increased energy dissipation. Conversely, the utilization of PCM tends to sustain a relatively stable collector efficiency within the range of 48.10% to 54.20%, paralleling that observed in the onion drying process. The efficiency of the dryer experiences a notable enhancement when PCM is employed, initiating at 35.5% in the morning and maintaining a commendably stable output throughout the day, ultimately achieving 32.0% at 15:00, in contrast to 31.0% when PCM is absent. This augmentation in dryer efficiency can be ascribed to the inherent capacity of PCM to capture surplus thermal energy during periods of peak solar irradiation and subsequently release it during intervals of diminished solar intensity. In addition to energy savings, the controlled drying environment facilitated by PCMs was found to preserve the nutritional and organoleptic properties of the dried coconuts. The prevention of temperature shocks ensured uniform drying and reduced the risks of microbial contamination, resulting in a safer product with extended shelf life. Kumar et al. (Kumar, et al. 2024) emphasized the microbial safety benefits of controlled drying, but the correlation with PCM-based drying systems was not explicitly addressed in their work. This study bridges that gap by demonstrating how PCMs contribute to both product safety and quality. Furthermore, Patil et al. (Patil, et al.) discussed scalability and Sharma (Salhi, et al. 2024; Sharma, et al. 2009) explored energy efficiency improvements, neither study addressed these aspects in a unified manner. This research advances the field by providing a comprehensive framework that integrates energy efficiency, sustainability, and scalability. Specific energy consumption (SEC) was calculated as the ratio of total energy input to the mass of water removed. The dryer's energy efficiency was also assessed as the ratio of useful energy utilized for drying to the total energy supplied. For the PCM-integrated system, SEC was 2.1 kWh/kg compared to 3.5 kWh/kg for the non-PCM setup, underscoring the enhanced efficiency achieved by thermal energy storage.

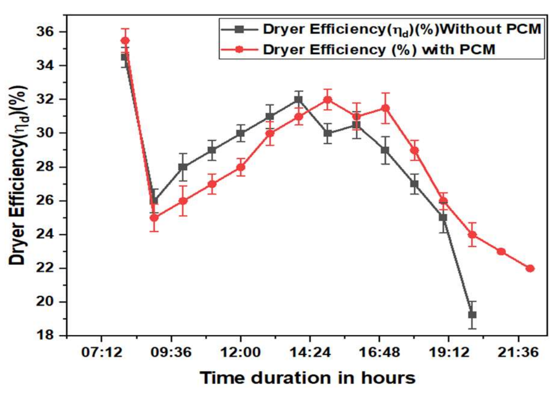


Figure 12 Dryer Efficiency Analysis With and without PCM.

The efficiency of coconut drying without phase change materials (PCM) is notably lower than that of onion drying. This decrease is primarily due to the higher energy demands of coconut drying, which leads to increased energy dissipation in the drying chamber (Ayyappan, et al. 2021). In contrast, the use of PCM enhances efficiency, stabilizing it between 48.10% and 54.20%, and maintaining a higher output throughout the day (Ayyappan, et al. 2021) (Muthuvairavan, et al. 2023). PCM captures excess thermal energy during peak solar irradiation and releases it during low intensity periods, thus improving overall efficiency. While PCM significantly enhances drying efficiency, it is essential to consider the potential trade-offs, such as increased initial costs and complexity in dryer design, which may deter some users from adopting this technology.

Conclusion

The huge advantages of introducing Phase Change Material (PCM) into sun drying systems are illustrated by the solar drying tests done on onions and coconuts, both with and without PCM. Adding PCM minimises the likelihood of overheating, enhances dryer performance, and helps stabilise temperature fluctuations, particularly in times of high solar radiation. The dryer efficiency improves significantly during the later hours of the day when solar intensity declined, although the collector efficiency generally held consistent with PCM. These results are in accordance with prior research that demonstrate PCM increases the quality of dried products and solar drying efficiency by keeping the drying chamber's conditions more constant. Onions, and coconuts were successfully dried using a drier, losing 62, and 71% of their moisture content, respectively. This system enables the drying of various agricultural products cost-effectively. The usage of alternative PCM components and the manner in which PCM effects the nutritional content and shelf life of dry foods may be the focus of future study.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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Not applicable

Consent to Participate

Not applicable

Consent to Publish

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