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Comparative Analysis of Phase Change Materials as Solar Thermal Energy Storage for Yogurt Incubation

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ABSTRACT

A study was conducted during October, 2022 to June, 2023 at National Dairy Research Institute, Karnal, Haryana, India to evaluate the thermal performance and melting behaviour and the effect of different container materials on energy storage efficiency of phase change materials (PCMs). Paraffin wax, Beeswax and Palm oil was selected for this study and for the container material stainless steel (SS) and polyethylene terephthalate (PET) was selected. The results indicated that PET containers, although slower to heat (100 min), provide a prolonged cooling period (240 min), making them ideal for applications that require delayed heat release. Among the PCMs, Paraffin wax, with a melting temperature of 59.3°C and a melting time of 36 min, was found to be the most suitable for solar thermal applications. Beeswax, while viable, had a higher melting temperature (68.1°C) and a longer melting time (48 min). Palm oil, with a melting temperature of 43°C, was deemed unsuitable. Image analysis confirmed these findings, showing that palm oil had the highest reduction rate in area and perimeter, while all three PCMs displayed favourable roundness values. Based on the results, Paraffin wax in PET containers was identified as the optimal combination for efficient solar energy storage.

KEYWORDS: Melting, phase change material, solar energy, thermal storage, yogurt

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1. INTRODUCTION

Phase Change Materials (PCMs) are widely recognized for their ability to store and release significant amounts of thermal energy during phase transitions, particularly between solid and liquid states. PCMs have been extensively applied in various industries, such as building energy efficiency (Wang et al., 2022), electronics cooling (Arshad et al., 2020), and cold chain logistics (Burgess et al., 2022), due to their capacity to regulate temperature fluctuations and enhance thermal management. Recently, the adoption of PCMs in solar energy storage systems has gained considerable attention, as they can effectively store excess thermal energy during peak solar radiation hours and release it when solar input is minimal, thus improving the efficiency and reliability of solar thermal applications.

PCMs, due to their ability to maintain consistent temperatures during phase transitions, offer significant potential in food applications such as yogurt incubation (Aldaw Ibrahim et al., 2019). In yogurt production, maintaining an ideal incubation temperature is crucial for the fermentation process (Arab et al., 2023; Ray et al., 2024). PCMs, such as paraffin wax or beeswax, can absorb excess heat during peak temperatures and release it slowly to sustain the required thermal environment without fluctuations. This not only ensures optimal fermentation but also reduces energy consumption by minimizing the need for active heating or cooling systems.

In solar energy storage systems, various parameters such as the melting and solidification temperatures of PCMs (Al-Yasiri and Szabó, 2021), thermal conductivity (Panchabikesan et al., 2019), and the design of the storage container (Punniakodi and Senthil, 2021) play critical roles in determining the overall efficiency of the system. Proper selection of PCMs is crucial to ensuring optimal heat absorption and delayed release. Commonly available and cost-effective PCMs like paraffin wax, palm oil, and beeswax have been identified as potential candidates for solar applications due to their favourable melting characteristics and availability. Paraffin wax, for example, has been widely used for its stable thermal properties (Bharathiraja et al., 2023), while natural alternatives like palm oil (Fabiani et al., 2020) and beeswax (Mishra et al., 2022) offer renewable and biodegradable options.

To maximize energy storage capacity, it is essential to design storage cells or containers that can enhance the heat transfer rate and improve energy retention during both the melting and solidification phases. The material and structure of the containers can significantly influence the PCM's ability to store and release energy efficiently, with materials like stainless steel (SS 304) and polyethylene terephthalate (PET) being commonly used in energy storage systems (Devanuri et al., 2020; Liu et al., 2023).

Despite the wide range of PCMs available for solar energy storage, there is a significant research gap in the comparative analysis of commonly used, low-cost PCMs like paraffin wax, palm oil, and beeswax, specifically in terms of their melting and solidification characteristics and their application in solar energy storage systems for yogurt incubation. This study aims to address this gap by performing a comprehensive comparison of these three PCMs, utilizing both thermal and image analysis to evaluate their melting behaviour, solidification rates, and overall effectiveness for energy storage in food incubation systems. Additionally, the study examines the influence of container materials, such as SS 304 and PET, on PCM performance, with the goal of identifying the most efficient combination of PCM and container for sustainable solar energy storage, particularly for maintaining optimal temperatures during yogurt incubation.

2. MATERIALS AND METHODS

This study was conducted during the year 2023 in the lab of Dairy Engineering division of National Dairy Research Institute, Karnal.

2.1. Selection of phase change material

The PCM was selected after considering various factors such as latent heat, melting temperature, thermal conductivity, physical and chemical stability, cost, and availability. The following steps were followed to select a suitable PCM:

- The operating temperature range of the solar unit was determined, which will assist in selecting a PCM with a suitable melting temperature.
- The energy storage capabilities of PCMs were considered to match our requirements.
- Thermal Conductivity of PCMs was also considered.
- Chemical and Physical stability were considered so that they do not degrade over time.
- The affordability and availability of PCM were also taken into consideration.

After thoroughly comparing all the available options, paraffin wax, beeswax and palm oil were selected for further investigation.

2.2. Experimental setup

In order to analyze the melting behaviour of PCM, an old hot air oven was modified to create a simulation of the conditions present in a solar air heater. The oven was made of aluminium on the inside and cast iron on the outside, with glass wool insulation in between to avoid heat loss. The overall dimensions of the setup were 75×75×60 cm^3. Temperature sensors were connected to a temperature controller and contactor. The contactor maintained the temperature of the cabinet at a pre-set temperature i.e., when a set temperature was achieved it would cut off the power and turn off the heater and vice versa. A data logger was used to record temperature data continuously. A camera was placed outside the oven to capture images of the melting process. A glass door and mirror were used to facilitate image capturing. LED lights were installed to improve the image quality. A schematic diagram of the experimental setup is shown in Figure 1.

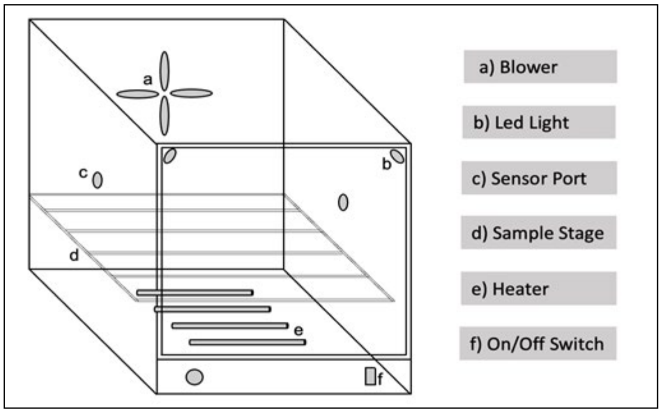


Figure 1: Schematic diagram of experimental setup

2.3. *Fabrication of test container*

A test rig was fabricated in the workshop of the Dairy Engineering Division, ICAR-National Dairy Research Institute in Karnal, Haryana (Chitranayak et al., 2022), to examine the melting properties of the selected PCMs. In order to conduct the melting trials, it was fabricated using SS304 as a base material. The conceptual Diagram of the container is shown in Figure 2. The SS pipe of desired length was taken and welded with a base plate to form a cup like container. It was fabricated in such a way that temperature sensors can be easily attached and detached from it. Three legs were also provided to ensure proper support to the container Figure 3. Moreover, it was painted black to increase its absorptivity so as to absorb maximum solar radiation coming from the sun. The technical specifications of the test rig are given in Table 1.

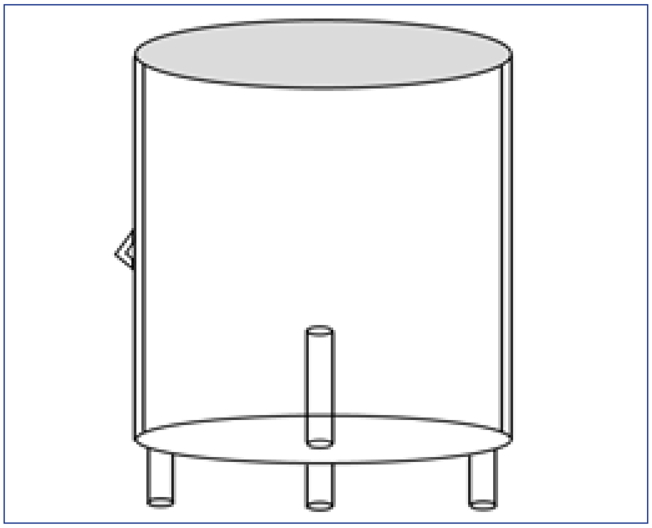


Figure 2: Conceptual diagram of test container

Figure 3: Actual representation of the test container

Table 1: Technical specification of test rig

Parameter	Value
Material	SS 304
Diameter	59 mm
Height	60 mm
Thickness	2 mm
Volume	137.70 ml
No of legs	3 (20 mm Height)

2.4. *Image capturing system*

The image capture system depicted in the figure was employed for the purpose of continuously monitoring the fermentation process.

A webcam was installed in the experimental setup to achieve uninterrupted image capture of the melting process of PCM. The webcam was positioned outside the setup, with a mirror installed inside to facilitate the image capture process (Figure 4). The captured images were sent to a desktop computer that used an Auto Mouse Clicker application to capture images of the PCM at one-minute intervals.

Figure 4: Image capturing system

2.5. *Temperature control and data acquisition*

During the experiment, the PID controller TC513 was used to keep the temperature at a specific fixed point. The temperature fluctuated by 2°C in relation to the fixed temperature. A temperature data logger was used for temperature monitoring by autonomously recording temperature over a defined period of time (Sinha et al., 2017). The digital data can be retrieved, viewed, and evaluated after it has been recorded. The data logger from Countronics (8 Channel) was used. The RTD PT-100 sensors were used to record the temperature (Sinha et al., 2021). Contactors are electrically operated switches that are used to switch loads and control electrical circuits. When the system temperature reached the preset degree, the automatic contactor stopped power and turned off the heater. When the system temperature falls below a certain threshold, the heater is activated automatically (Sinha et al., 2017).

2.6. Study of melting characteristics

The melting characteristics of PCM are important because they determine the amount of energy that can be stored and released during these phase changes. The melting properties can vary depending on the specific material used. These characteristics play a vital role in determining the effectiveness and efficiency of these materials in thermal energy storage applications (Chitranayak et al., 2021). A study of the melting characteristics of the three selected PCM was carried out Figure 5.

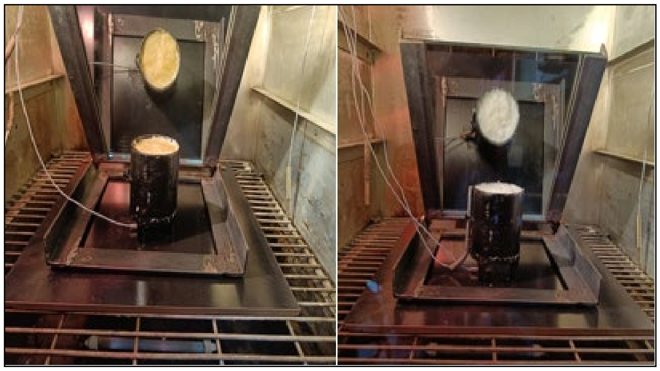


Figure 5: Melting of different phase change material

2.6.1. Procedure for melting study

- Melting study of PCM was conducted by taking the known quantity (110 g) of sample in the test cup and placing it inside the experimental cabinet.
- The heating element and blower fan were turned on.
- The camera was placed outside the cabinet, and the light inside the cabinet was switched on to get better image quality.
- The image was captured with the help of the Auto Mouse Clicker application.
- PT-100 sensors were placed to record the temperature of ambient air, container surface and center point of the PCM container.
- These sensors were then attached to the data logger to record the temperature at regular intervals (1 min)
- The process is continued till complete melting, then the heater is switched OFF and a sample is allowed to solidify.
- After complete solidification, the process is stopped.
- Captured images and temperature recorded by the data logger are further analysed.

2.7. Analysis of captured images

The analysis of captured images can involve several steps depending on the specific application and the type of information that needs to be extracted from the images. Here the main purpose of image analysis was to the melting characteristics of PCM. These images assisted in determining the melting temperature, melting time, and solidification time. Image analysis software was used to determine to area, diameter, and perimeter reduction of the melting surface.

2.7.1. Image analysis procedure

ImageJ is used to analyse the captured images (Figure 6). ImageJ is a widely used open-source software program designed to analyse, process, and visualize images. The following steps were followed in order to analyse the melting images (Figure 7):

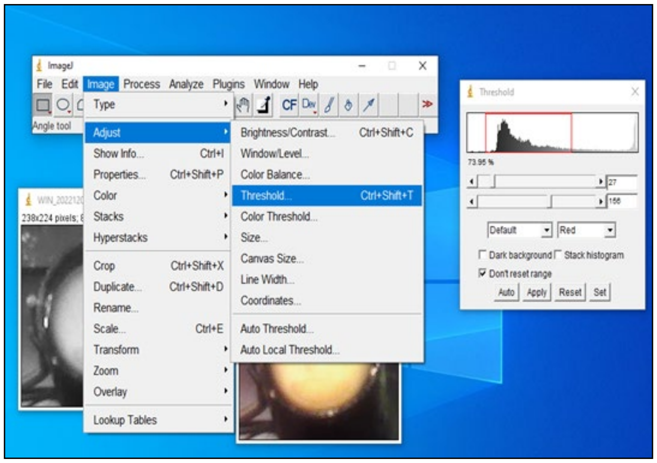


Figure 6: Images user interface

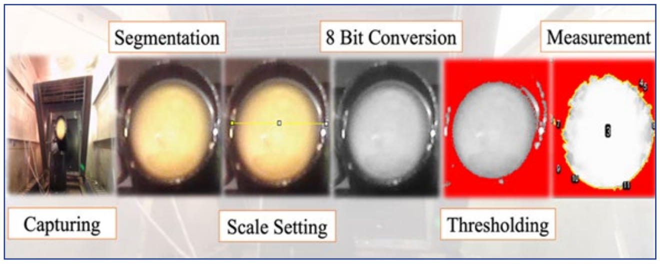


Figure 7: Image analysis steps

- Image Capturing: Images were captured after an interval of 1 min with the help of a web cam.
- Segmentation: The area of interest was selected for further analysis. Segmentation is important for extracting relevant information for the images.

- Scale setting: The scale was set by measuring a known distance like diameter with the help of software.
- 8 Bit conversion: Images were converted to 8 Bit binary images for further analysis.
- Thresholding: It is the process of converting an image into a binary image, where all pixels above a certain intensity level are set to one value (usually white), and all pixels below that intensity level are assigned to another value (typically black).
- Measurement: Parameters like area, diameter, perimeter, roundness, etc are measured by using the Analyse option.

2.7.2. Study of melting characteristics of pcms

The study of the melting characteristics of PCMs was done with an objective of finding properties like their melting temperature, melting range, melting time and solidification time. The experimental setup for the study involved various components such as a heater assembly, an image-capturing system, a data logger, Pt 100 sensors, a contactor, and a test rig. Trails were taken with three selected PCMs i.e. Paraffin wax, Beeswax and Palm oil, in order to estimate their melting properties.

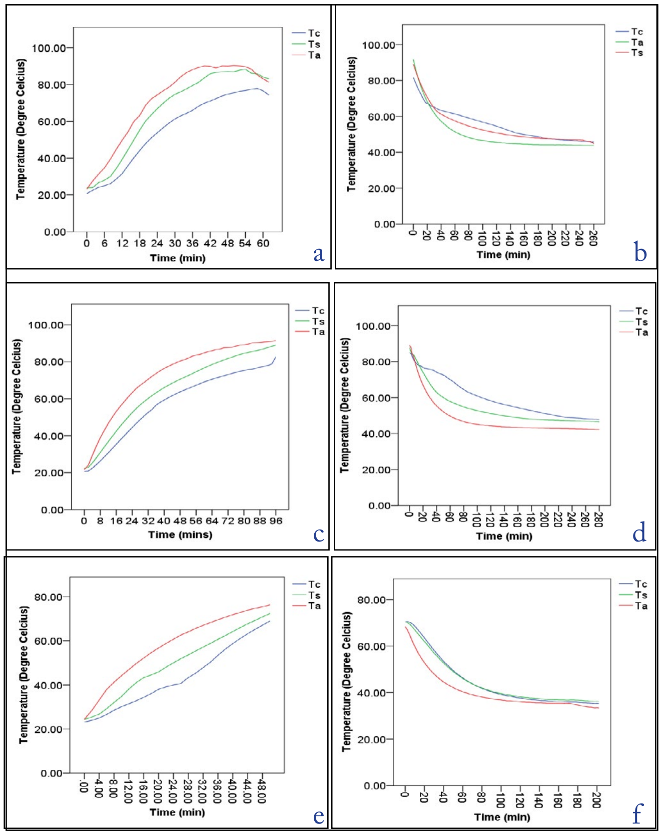
3. RESULTS AND DISCUSSION

3.1. Temperature profile during melting and solidification of paraffin wax

The paraffin wax was initially in a solid state at room temperature. An electrical heater was used to apply heat to the wax and initiate the melting process. As the temperature increased, the wax gradually reached its melting point. The solid wax began to soften and transition into a liquid form at this stage. Figure 8a displayed the temperature profile during the melting process, depicting the ambient air temperature (Ta), outer surface temperature (Ts), and center point temperature (Tc). During the melting phase, the temperature profile followed a nearly linear trend until the melting temperature was reached. As the PCM neared its melting point, the temperature rise slowed down due to the heat being utilized for the material's phase change. It took approximately 60 minutes for the paraffin wax to heat from 20°C to 78°C. The center point temperature increased slower than the ambient air temperature due to the low thermal conductivity of paraffin wax. The heater was switched off once the wax had melted entirely, and solidification began. Figure 8b illustrated the temperature profile during the solidification of the paraffin wax. The solidification process followed an exponential decrease in wax temperature over time. The paraffin wax took around 240 minutes to cool from 81°C to 50°C.

3.2. Temperature profile during melting and solidification of beeswax

Beeswax, an organic phase change material, is readily available and had a lower cost per unit than traditional PCMs (Souissi et al., 2023). Figure 8c depicted the temperature profile during the melting of beeswax. It was worth noting that beeswax had a higher melting point compared to paraffin wax, typically ranging between 62°C and 64°C (Rathore et al., 2023). The heating pattern of beeswax followed a similar trend to that of paraffin wax, but due to its higher melting temperature, the time required for beeswax to reach 80°C was significantly longer than that of paraffin wax. Figure 8d illustrated the temperature profile during the solidification of beeswax. As the temperature gradually decreased, beeswax reached its solidification temperature, typically below its melting point. Once the beeswax had completely solidified, the temperature stabilized at the solidification temperature. Similar to paraffin wax, beeswax exhibited a delayed heat release during solidification. The solidification time of beeswax was approximately 280 minutes, which was longer than that of paraffin wax. This prolonged solidification time could be attributed to the lower thermal conductivity of beeswax compared to paraffin wax. The lower thermal conductivity of beeswax necessitated more time for heat to dissipate through the material (Sinaringati et al., 2016).



Figur 8: Temperature profile of different PCM's melting and solidification (a: Paraffin wax melting, b: Paraffin wax solidification, c: Beeswax melting, d: Beeswax solidification, e: Palm oil melting, f: Palm oil solidification)

3.3. Temperature profile during melting and solidification of palm oil

Palm oil recently emerged as a potential PCM and had been the subject of investigation. In a recent study, palm oil was used as a PCM and compared to paraffin. Surprisingly, palm oil exhibited higher mean efficiency than paraffin, despite not having been previously considered a solar thermal storage medium in the literature (Ojike and Okonkwo, 2019). Figure 8e and 8f in the study depicted the temperature profiles during the melting and solidification of palm oil, respectively. The temperature trends observed in the case of palm oil were similar to those of paraffin and beeswax. However, palm oil exhibited faster heating and cooling rates compared to the other two materials. Notably, palm oil demonstrated faster heat release, taking only 200 minutes to cool from 71°C to 38°C, which could limit its effectiveness in maintaining a sustained and extended release of stored thermal energy.

3.4. Centre point temperature analysis of the pcms

Figure 9a and Figure 9b illustrated the variation in center point temperature during the melting and solidification processes of different PCMs. During the initial melting phase, the temperature rose linearly for all three PCMs. However, a sudden temperature spike occurred due to the superheating of the liquid PCM. After complete melting, the temperature dropped for paraffin and palm oil, as these PCMs had faster melting rates compared to beeswax. Figure 9a also provided insights into the heating rates of the different PCMs, revealing that paraffin exhibited the highest heating rate among the three. Regarding solidification, palm oil demonstrated an exponential decrease in temperature, whereas paraffin and beeswax displayed a linear trend. Furthermore, paraffin and beeswax exhibited delayed heat release during solidification, a characteristic desirable for thermal energy storage applications. These observations highlighted the diverse thermal behaviors of various PCMs, underlining their potential for tailored applications in specific contexts.

3.5. Temperature difference between hot air and centre point of test rig of the pcms

The temperature difference served as the driving force for heat transfer between the hot air and the PCM within the test rig. Figure 9c and Figure 9d showed the temperature difference between the hot air and the center point of the rig during the melting and solidification processes. During the initial stages of melting, the temperature difference between the hot air and the PCM increased for all three PCMs. This was attributed to the faster heating rate of the air compared to the PCM. However, as the system reached equilibrium and complete melting was achieved, the temperature difference tended to decrease. In the case of solidification, two peaks were observed for paraffin and beeswax. The first peak corresponded to the temperature difference when the hot air temperature was higher than the center point temperature at the beginning of the solidification stage. The second peak occurred when the hot air temperature fell below the center point temperature towards the end of the solidification stage. It was important to note that the modulus values of the temperature difference were plotted, leading to the observation of these two peaks.

Figure 9e. and Figure 9f. present the temperature difference between the test rig's outer surface and centre point during the melting and solidification processes. Although the temperature difference between the outer surface and the centre point was smaller compared to the temperature difference between the hot air and the centre point, the overall trend remained similar.

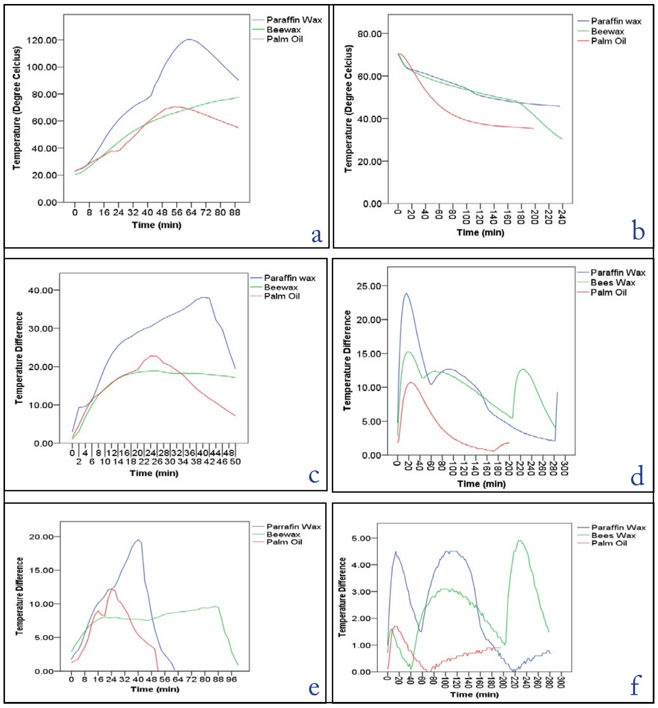


Figure 9: Centre point temperature variation during melting and solidifications of the PCMs (a: Paraffin wax melting, b: Paraffin wax solidification, c: Beeswax melting, d: Beeswax solidification, e: Palm oil melting, f: Palm oil solidification)

3.6. Melting time analysis of the PCMs

The melting time of PCMs refers to the duration required for a PCM to transition from its solid to liquid state when exposed to a heat source. The melting times of various PCMs are depicted in Figure 10a. The data revealed that beeswax had the longest melting time of 48 minutes, followed by paraffin wax with a melting time of 35 minutes. In contrast, palm oil exhibited the shortest melting time, requiring only 20 minutes to transition into a liquid state. The melting time of a PCM is influenced by multiple factors, including the specific PCM material, its thermal properties, the initial temperature of the PCM, and the applied heat flux or temperature difference. Researchers have investigated the melting and solidification behavior of PCMs, and their findings indicated that melting time decreases as the heating fluid temperature increases (Akgün et al., 2007; Kant et al., 2018). Understanding the melting time of PCMs is essential for designing and optimizing thermal energy storage systems.

3.7. Melting temperature analysis of the PCMs

The melting temperature of a PCM refers to the specific temperature at which the PCM undergoes a phase transition from solid to liquid. Selecting a PCM with an appropriate melting temperature is crucial for ensuring its suitability for a given application. Figure 10b displays the melting temperatures of various PCMs, as determined through a melting study. Among the tested materials, beeswax exhibited the highest melting temperature at 68.1°C, followed by paraffin wax at 59.3°C and palm oil at 43°C. In a recent comparative study on PCMs with different melting temperatures, researchers reported that a PCM with a higher melting temperature could help smooth out high-temperature peaks (Colarossi et al., 2022). Conversely, a PCM with a lower melting temperature ensures a higher and more stable temperature at night due to the release of latent heat, making it valuable in applications where a constant outlet fluid temperature is required. Similar findings were reported by other researchers, who concluded that using PCMs with higher melting temperatures could be impractical, as such PCMs may not melt significantly during the day (Badiei et al., 2020).

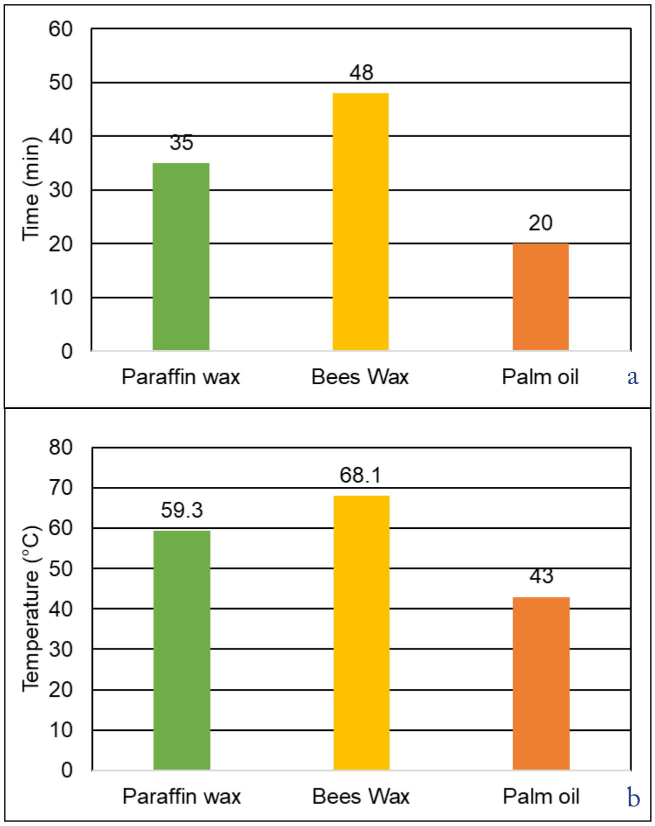


Figure 10: Melting characteristics for different PCMs (a: Melting Time, b: Melting temperature)

3.8. Image analysis technique for characterization of melting behaviour

To characterize the melting behavior of different PCMs, an image analysis technique was employed to analyze the images captured during the melting and solidification processes. Figure 11 shows the melting images of various PCMs at different time intervals. ImageJ software was utilized for analyzing these images, and parameters such as area, perimeter, diameter, and roundness were calculated. As depicted in the figure, the different PCMs exhibit varying melting rates. Palm oil, with a melting time of 20 minutes, melts faster than paraffin wax (35 minutes) and beeswax (49 minutes). These differences in melting time can be attributed to the varying melting temperatures and thermal properties of the PCMs.

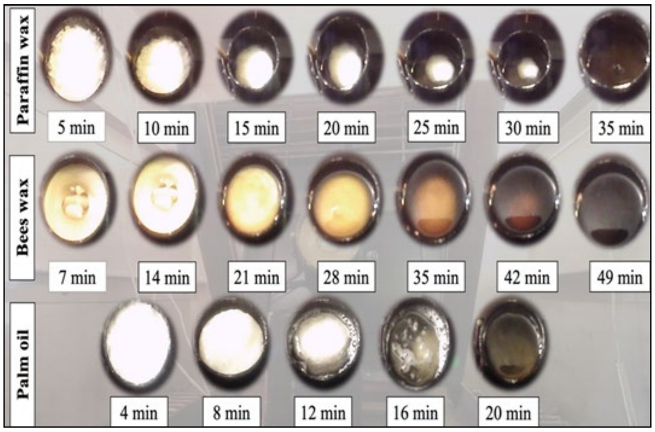


Figure 11: Melting images of different PCMs

3.9. Melting parameters analysis of the PCMs

During the melting process, the solid phase reduces in spatial extent while the liquid phase expands to occupy the space previously held by the solid. Figure 12a illustrates the melting front progression of various PCMs in terms of area. Palm oil exhibited the fastest area reduction rate, with an average reduction of 105.45 mm^2/min. This was followed by paraffin wax and beeswax, with rates of 60.25 mm^2/min and 43.93 mm^2/min, respectively.

Figure 12b presents the melting front progression in terms of perimeter, which followed a trend similar to area reduction. Palm oil showed the highest perimeter reduction rate at 8.63 mm/min, followed by paraffin wax at 4.93 mm/min and beeswax at 3.59 mm/min. These metrics provided insights into the progression rate of the melting front and the shape changes of the PCMs during melting.

The reduction in diameter during melting offers insights into the kinetics and efficiency of the phase change process. Figure 12c illustrates the melting front progression of various PCMs in terms of diameter. The calculated average diameters showed that paraffin wax had the largest average diameter at 41.11 mm, followed by palm oil at 40.57 mm, and beeswax at 38.62 mm. These measurements highlight the initial size and the reduction in diameter as the melting process advanced.

The roundness of the melting profile has implications for heat transfer efficiency and overall melting behavior. Spherical or well-rounded melting shapes yield a larger surface area-to-volume ratio, enabling more efficient heat transfer. Conversely, irregularly shaped PCMs may experience slower melting rates due to uneven heat flow. Figure 12d illustrates the roundness of the melting front for the different PCMs. Palm oil, paraffin wax, and beeswax exhibited good roundness values during melting, with averages of 0.81, 0.80, and 0.78, respectively. These results suggest that the materials maintained smooth and uniform melting profiles, facilitating effective heat transfer and consistent melting behavior.

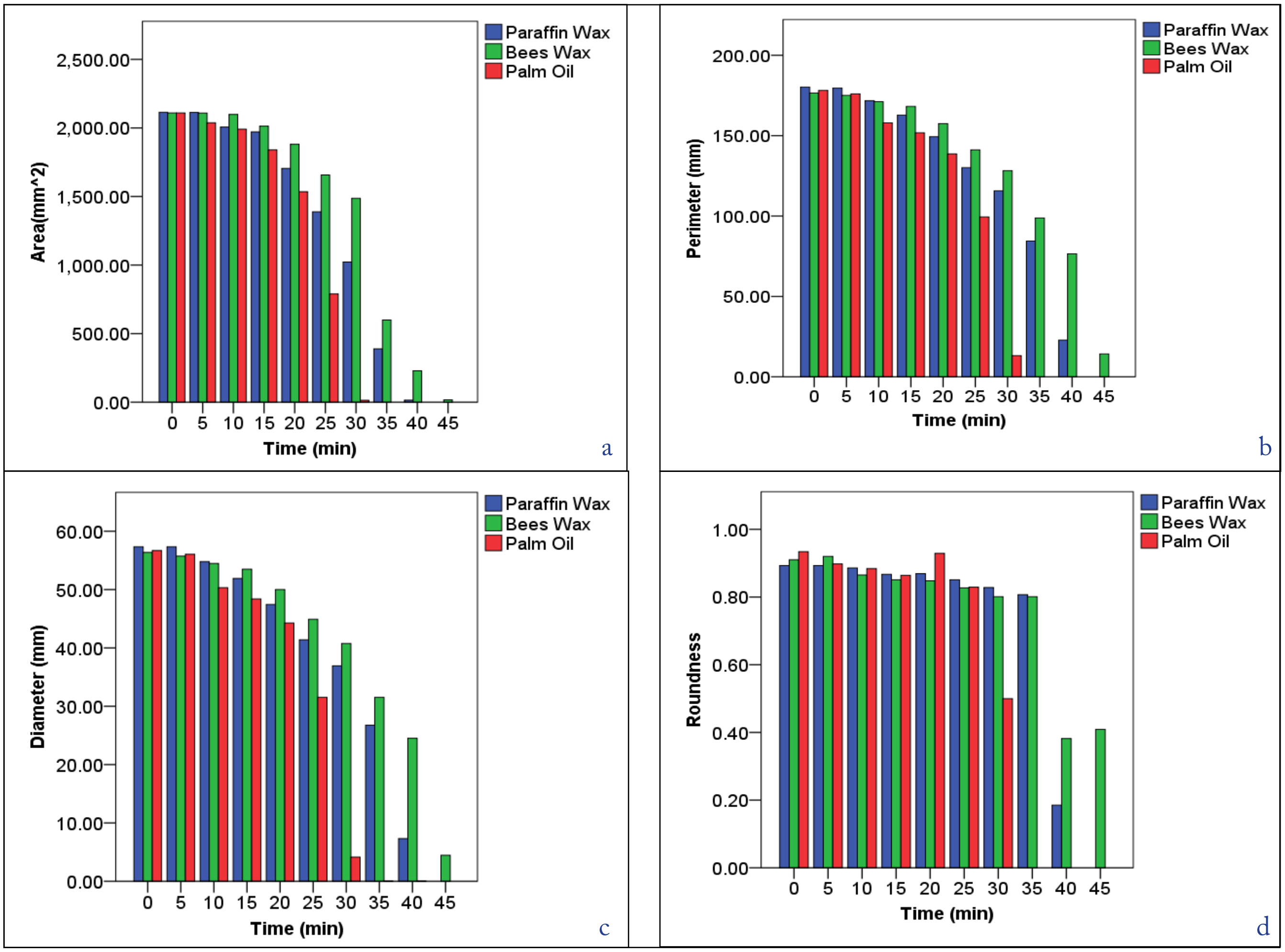


Figure 12: Melting parameters of the various PCMs (a: Area, b: Perimeter, c: Diameter, d: Roundness)

4. CONCLUSION

The comparative analysis revealed that PET containers, exhibited a prolonged cooling period. In terms of PCM melting characteristics, Paraffin wax was identified as the most suitable material, providing optimal thermal stability for the solar unit's operating conditions. Image analysis further corroborated these findings. Overall, Paraffin wax in PET containers emerged as the most appropriate PCM for the solar energy storage unit due to its balanced melting characteristics, stability, and thermal performance above the designated operating temperature range.

5. ACKNOWLEDGEMENT

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