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# Characterization of Some Selected Bio-based PCMs Derived fromNatural Lipidsas Thermal Energy Storage Application

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## ABSTRACT

The increasing interest in creating thermal energy storage (TES) application is closely related to understanding the properties of the materials involved. Recently, the utilization of phase change materials (PCMs) in TES systems, which help bridge the gap between energy supply and demand, has significantly risen. Since the storage capacity in a TES system relies on the phase transitions (primarily solid to liquid) of PCM, understanding their thermal properties is crucial. In this research the thermophysical properties of hybrid PCMS: combination of Shea butter and Animal (Ram)fat as well as Animal fat (Ram) and Coconut oil were Characterized using a Differential Scanning Calorimeter (DSC). at heating rate of 10 °C/min across a temperature range of 30.03°C - 200.13°C,the results for thermal analysis show that the combination of shea butter and ram fat has latent heat of 155.33J/kg, specific heat capacity 2070 j/kg.k, thermal conductivity 0.24W/m·K, density 905kg/m³, energy storage density 140.5MJ/m³. while Ram fat and Coconut oil has a latent heat of 110.80j/k, specific heat capacity 2080j/kg.k, thermal conductivity 0,22 w/m. k, density 910kg/m$^3$, energy storage density 100.8 mj/m$^3$. From the results it was observed that shea butter-Ram fat blendreveals highest thermophysical properties of around 20% increasefor latent heat and 8% increase for thermal conductivity. The ram fat-shea butter blend demonstrated a better performance which make it a better thermal storage potential. The performance of the shea butter–Ram fat composite is attributed to its enhanced molecular structure and improved thermal stability. These findings indicate that locally sourced bio-based PCMs, particularly shea butter and ram fat, are promising candidates for thermal energy storage applications. Their integration into solar thermal systems can significantly enhance energy efficiency, extend the thermal Applications periods, and promote environmentally sustainable solutions for thermal management.

**Keywords**: Thermal storage, latent heat, Composite, thermal conductivity and energy storage density.

## I. INTRODUCTION

The global transition toward sustainable energy systems has intensified the demand for efficient Thermal Energy Storage (TES) technologies capable of bridging the temporal mismatch between energy supply and demand. Solar energy, despite its abundance and zero-emission profile, remains constrained by diurnal intermittence and weather dependency, particularly in off-grid and agricultural applications Beihropathai, V. S(2025).Phase Change Materials (PCMs) address this limitation by storing and releasing large quantities of latent heat during solid-liquid transitions at nearly constant temperatures, offering significantly higher energy density than conventional sensible heat storage Zhang, N*et al.,* (2018). In tropical regions such as Nigeria, where solar drying and low-temperature thermal processing are vital to post-harvest preservation and rural energy access, locally sourced, cost-effective PCMs present a compelling alternative to synthetic or imported materialsBarzigar, A*et al*., (2025). However,to address this, integration of PCMs into TES systems requires knowledge of the thermophysical properties of the materials. thermal storage systems are important for enhancing energy efficiency, lowering operational cost, and integrating renewable energy by bridging the gap between energy supply and demandElkhatat, A., & Al-Muhtaseb, S. A. (2023). These systems allow excess energy to be stored as heat or cold, reducing peak electricity demand, reducing carbon emissions and increasing building or industrial resiliencyRecent

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studies emphasize that the performance of PCM-integrated TES systems is heavily dependent on accurate thermal property data, particularly phase change temperature, latent heat of fusion, specific heat capacity, thermal conductivity, and volumetric energy storage density (ρ·ΔH) G. Alva *et al.,* (2017). Differential Scanning Calorimetry (DSC) remains the most widely accepted technique for measuring enthalpy and transition temperatures, with standardized protocols such as ASTM E793 and the RAL-GZ 896 quality framework guiding calibration, heating/cooling rates, and data reporting S. Gschwander *et al*., (2011). However, literature reveals that DSC results are highly sensitive to sample mass, thermal history, and ramp rates, necessitating careful experimental design to avoid artificial hysteresis or peak shifting C. Barreneche *et al.,* (2018).Despite methodological advances, critical research gaps persist: Absence of PCM-specific testing standards: Existing standardsMehling, H. (2023). are adapted from petroleum or general materials testing and do not fully address phase-transition dynamics or cycling stability Fultz, B. (2020). Overreliance on manufacturer specifications: Published thermal properties frequently reflect idealized values, neglecting batch variability and application-relevant thermal histories Lou, Q (2026). Limited empirical profiling of indigenous bio-PCMs: Lipid materials such as ram fat, shea butter, and coconut oil lack comprehensive, peer-reviewed thermophysical datasets, particularly for thermal conductivity and volumetric storage capacity within the 30–45°C range Isania, F. (2026). Insufficient application-driven benchmarking: Few studies correlate experimentally derived PCM properties with system-level performance metrics for solar drying in off-grid contextsGuo, Y(2025). Researchhas indicated that shea butter and coconut oil can serve as effective bio-based phase change materials (PCMs) due to their exceptional latent heat capacities and melting ranges. Shea butter has a latent heat of fusion of about 50.3 kJ/kg and a melting range of 31–40 °C, making it suitable for applications in medium-temperature waste heat recovery Asmau, S. R. (2023) On the other hand, coconut oil has a higher latent heat, usually ranging from 74 to 115 kJ/kg (often cited as 105 ± 11 kJ/kg), and a melting point between 18–27 °C, which is beneficial for thermal regulation in buildings and thermo-regulating textiles Fabek, H et al., (2021). Although coconut oil offers better energy density and cycling stability over many freeze-melt cycles, its lower thermal conductivity typically necessitates the use of additives such as graphene or graphite nanoplatelets. In contrast, while shea butter has lower energy density, it remains a viable renewable solution for medium-temperature energy storage (Wi *et al*., 2015; Kone *et al.,* 2024). Overall, both materials are sustainable alternatives to paraffin-based PCMs, with ongoing studies aimed at developing composite formulations and assessing long-term performance. Mishra, D. K*et al*., (2022).Recent research on phase change materials (PCMs) has highlighted their vital importance in thermal energy storage (TES) for renewable energy systems. PCMs are extensively applied in solar thermal technologies, energy management in buildings, and drying systems due to their significant latent heat storage capacity, which allows for efficient thermal energy absorption and release at nearly constant temperatures Khudhair, A. M., & Farid, M. (2021). In solar applications like dryers and collectors, latent heat thermal energy storage (LHTES) systems that use PCMs offer energy storage densities that can be 5-14 times higher than those of sensible heat storage, thus improving system efficiency and minimizing energy loss Agrawal, A., & Rakshit, D. (2021). Additionally, PCMs are increasingly being utilized as thermal batteries to enhance energy conservation and bolster the reliability of intermittent renewable energy sources Nandi, A*et al*., 2025). Recent developments also emphasize nano-enhanced and encapsulated PCMs, which enhance thermal conductivity, stability, and heat transfer rates, making them more suitable for practical TES applications such as heat exchangers and solar dryers Khlissa, F*et al.,* (2023). Despite these innovations, challenges related to low thermal conductivity, phase segregation, and long-term stability continue to be significant areas of ongoing investigation in PCM-based thermal storage systems Ali, S. A*et al*., (2024).

To the best of my knowledge from the above literature review no research was conducted on PCM composite using local available material. This study experimentally evaluates the thermal behavior of selected bio-based PCM composites shea butter and ram fat, and ram fat and coconut oilto establish their viability for solar-driven thermal storage in warm-climate applications.PCMs are broadly classified into organic, inorganic, and eutectic families, with organic lipid-based materials favored for their chemical stability, non-corrosiveness, and congruent melting behavior Faraji *et al*., (2023).

## II. METHODOLOGY

The PCM samples were gathered from various locations of Bida local governments in Niger State, Nigeria. These samples (Ram Fat, Shea butter and Coconut oil), were sourced from the

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specified area and blended to form composite with 50/50 were appropriately blended to create a representative sample. To achieve this, the cone and quartering method as outlined by the American Society for Testing and Materials Mason, G. L*et al.*, (2020) was employed.Evaluating the physical properties of the PCM samples involves analyzing various characteristics such as latent heat, specific heat capacity, volumetric expansion/thermal diffusivity, mass loss, thermal conductivity, and thermal shock resistance. This assessment was carried out using the methodology established by the American Society for Testing and Materials (ASTM) device used.The sample were analysis using (DSC) and was conducted in the central laboratory of the physics department of Umaru Musa Yar Adua University Katsina State.

The mass of the sample used for this analysis for shea butter and Ram fat composite is 6.4 mg, at the heating rate of 10°C/min.while coconut oil and Ram fat composite the mass of the sample used for this analysis is 5.4 mg, at the heating rate of 10°C/min.

## III. Results and Discussions

The Differential Scanning Calorimetry (DSC) analysis of the two binary PCM composites reveals significant insights into their thermal energy storage potential. Both blends exhibit melting transitions within the 31–39°C range, which aligns optimally with tropical solar drying operational temperatures (30-45°C) and ambient conditions in Niger State, Nigeria Shazad, A et al., (2024).

Figure 2.1:Shea butter and Ram fat, sample mass is 5.4 mg, at the heating rate of 10°C/min. the minimum point of heat flow was observed at -6mW with corresponding temperature of 36 °C and maximum at -10mW with temperature of 190°C, the onset temperature 31.69 °C and end set 39.26 °C. the latent heat of the sample is155.33 J/g , specific heat capacity 2070 j/k , thermal conductivity 0.24W/m.k, density905kg/$m^3$ and energy storage density 140.5MJ/$m^3$as shown in figure 2.1figure 2.1

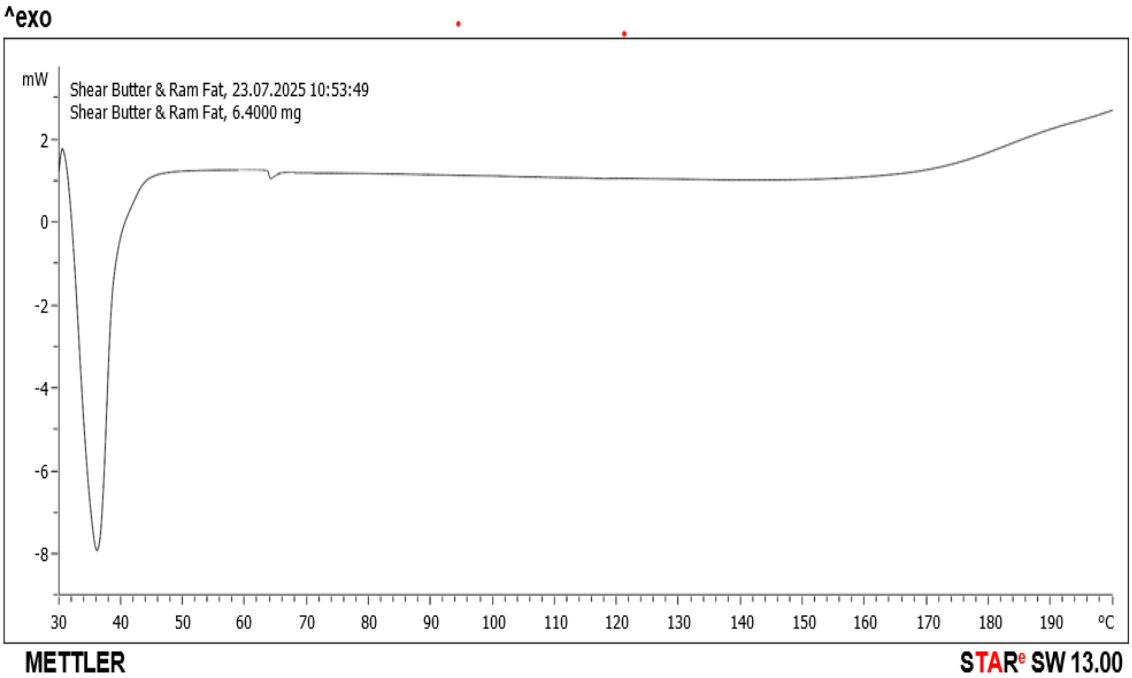


**Figure 2.1:** Thermogram of Shea butter and Ram fat composite

**Table 1: shows the thermophysical properties of shea butter and Ram fat composite**

| Composite Blend | ΔH (J/g) | $C_p$ (J/kg·K) | k (W/m·K) | ρ (kg/m³) | ρ·ΔH (MJ/m³) |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Shea butter + Ram fat | 155.33 | 2070 | 0.24 | 905 | 140.5 |

A Differential Scanning Calorimetry (DSC) analysis was performed on a shea butter-Ram fat composite, using a sample weight of 5.4 mg and a heating rate of 10 °C/min. The thermogram indicated a minimum heat flow of -6 mW at around 30 °C and a maximum of -10 mW at 190 °C, indicating significant thermal activity within the examined temperature range. The phase transition was defined by onset and endpoint temperatures of 31.69 °C and 39.26 °C, respectively, which bring into line with the ideal temperature range for low-temperature thermal energy storage applications like solar drying Patel, V. D. (2024). The melting range of about 7.6 °C suggesting a quasi-isothermal phase transition, a valuable trait for efficient phase change materials (PCMs) as it allows heat absorption and release at virtually constant temperatures. This characteristic is common among organic lipid-based PCMs, which display similar melting and limited phase separation, thereby improving thermal stability during frequent thermal cycles Wijanarko, N. P*et al*., (2025)The latent heat of fusion for the composite is 155.33 J/g, which is relatively high compared to many bio-based PCMs and signifies animportant energy storage capacity during phase transitions. This figure aligns with latent heat values for fatty acid-based and animal fat composites, where the intermolecular interactions between triglycerides enhance crystallinity and energy storage Duquesne, M*et al*., (2021). Consequently, the composite features a significant volumetric energy storage density of 140.5 MJ/m³, beneficial for designing compact thermal energy storage systems. With a specific heat capacity of 2070 J/kg·K, this material can also store large sensible heat in addition to latent heat. This combination of sensible and latent heat storage enhances the overall thermal performance of the PCM system, especially for applications that require slow temperature changes Ahmed, N*et al*., (2020).Although the thermal conductivity of 0.24 W/m·K is relatively low, it is consistent with typical values for organic PCMs. Low thermal conductivity limits the speed of heat transfer during charging and discharging, but it also extends the duration of heat release, aiding in temperature stability for solar drying applications Talukdar, Set al., (2019). Toadvance system performance, integrating conductivity enhancement methods like metallic fins or nanoparticles may be beneficial Waqas, H*et al*., (2025). The composite's density of 905 kg/m³ significantly donates to its high energy storage density. A higher density allows for more energy storage per unit volume, which is vibrant for the development of efficient and compact thermal energy storage systems Sarbu, I., &Sebarchievici, C. (2018).the thermophysical properties of the shea butter-Ram fat composite climaxes its effectiveness as a PCM for low-temperature thermal energy storage. Its raised latent heat, suitable phase transition temperature range, and stable melting behavior make it particularly well-suited for solar drying applications in tropical environments, where maintaining temperatures between 30 and 40 °C is central for effective moisture removal and the preservation of product quality Barzigar, A*et al*., (2025).

The examination of Ram fat and coconut oil,sample mass is 5.4 mg, at the heating rate of 10°C/min. the minimum point of heat flow was detected at -6mW with corresponding temperature of 30 °C and maximum at +2mW with temperature of 190°C, the onset temperature 31.69 °C and end set 39.26 °C. the latent heat of the sample is 110.80 J/g, specific heat capacity 2080 j/kg.k, thermal conductivity 0.22 W/m.K , density 910kg/$m^3$ and energy storage density 100.8 MJ/$m^3$ as shown in figure 2.2.

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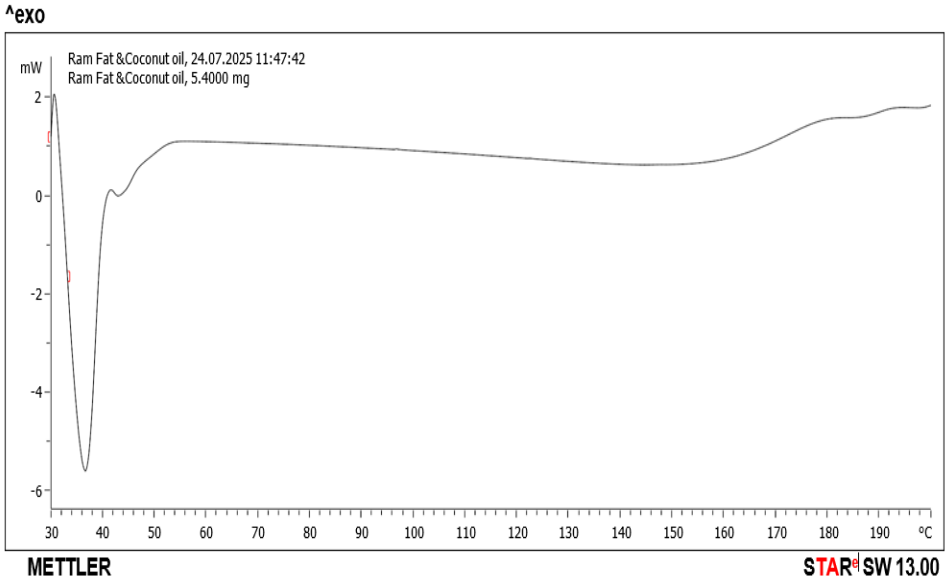


**Figure 2.2:** Thermogram of Ram Fat and Coconut Oil Composite

**Table 2: Thermal Properties of Ram fat and Coconut oil Composite**

| Composite Blend | ΔH (J/g) | $C_p$ (J/kg·K) | k (W/m·K) | ρ (kg/m³) | ρ·ΔH (MJ/m³) |
|---|---|---|---|---|---|
| Ram fat + Coconut oil | 110.80 | 2080 | 0.22 | 910 | 100.8 |

The Differential Scanning Calorimetry (DSC) analysis of the ram fat-coconut oil composite was conducted using a sample mass of 5.4 mg at a controlled heat The thermogram shows a minimum heat flow of -6 mW around 30 °C and a maximum of +2 mW at 190 °C, indicating significant change in thermal behavior within this temperature range. This transition from negative to positive heat flow suggests changes in melting and crystallization properties due to the addition of coconut oil, which is branded by its greater fluidity and lower melting fractions Saleel, C. A. (2022). The phase transition interval is marked by onset and endset temperatures of 31.69 °C and 39.26 °C, respectively, fitting well within the supreme temperature range for low-temperature thermal energy storage applications like solar drying. This range facilitates efficient heat absorption and release under the judicious conditions typical for solar thermal systems Zhu, L*et al*., (2023).The latent heat of fusion (110.80 J/g) is less than that of the shea butter-Ram fat composite, signifying lower energy storage capacity. This decrease is attributed to the presence of coconut oil, which has a higher concentration of medium-chain triglycerides that have lower crystallization enthalpy, thus reducing the overall latent heat of the mixture Esperanca, E*et al*., (2022). As a result, the composite offers a moderate energy storage density of 100.8 MJ/m³, making it more suitable for short-duration thermal storage rather than long-term heat retention.

With a specific heat capacity of 2080 J/kg·K, which line up with typical values for organic phase change materials (PCMs), the composite is capable of storing a significant amount of sensible heat outside of the phase transition range. This quality aids in thermal buffering and facilitates gradual temperature changes during heating and cooling cycles Liang, C*et al*., (2024). The thermal conductivity, measured at 0.22 W/m·K,to some extent lower than that of lipid-based composites, reflecting the insulating properties of coconut oil. Although this low thermal conductivity may slow heat transfer rates during charging and discharging, it can also prolong heat release, which helps maintain stable temperatures for shorter periods Yuan, K*et al*., (2020). This restriction highlights the need for methods to enhance thermal conductivity, such as using metallic fins or nanoparticles, to improve complete system efficiency u Mekrisuh, K*et al*., (2021). The density of 910 kg/m³ positively affects the volumetric energy storage capacity of the composite. Higher density values enable more thermal energy to be stored per unit volume, advancing the design of compact thermal energy storage systems Elkhatat, A., & Al-Muhtaseb, S. A.

(2023). Thethermophysical properties of the ram fat-coconut oil composite indicates its viability as a PCM for low-temperature thermal energy storage applications. However, its performance is somewhat substandard to that of the shea butter-Ram fat blend due to its lower latent heat and energy storage density. Nonetheless, its faster thermal response and enhanced fluidity make it applicable for scenarios needing fast heat absorption and release, such as short-term thermal buffering in solar drying systems Madhu, B. (2025).

## IV. Conclusions

The thermophysical analysis of the two PCM composites tells that the blend of shea butter and ram fat beats the other due to its higher latent heat (155.33 J/g) and energy storage density, making it more suitable for long-term thermal energy storage. Conversely, the ram fat and coconut oil composite has a more moderate storage capacity with a lower latent heat (110.80 J/g) but profits from a quicker thermal response due to the presence of coconut oil. Both materials fall within the required phase change temperature range (31–39 °C), signifying their suitability for lower-temperature applications like solar drying. However, the relatively low thermal conductivity of both composites may delay heat transfer efficiency, necessitating improvement strategies. Overall, while both blends are effective bio-based PCMs, the shea butter and ram fat composite is the more efficient excellent for extended thermal energy storage in solar thermal systems.

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