Characterization of Bio-based Phase Change Materials for Solar Energy Applications

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Abstract

Solar radiation is the primary energy source on Earth and plays a crucial role in decarbonizing the energy matrix, but the intermittency of this source makes energy storage indispensable, with thermal energy storage emerging as a promising technology. Among the storage types, latent thermal energy storage, employing phase-change materials, stands out due to its high energy density and nearly isothermal heat transfer, making these materials suitable for temperature management applications. Despite the predominant use of paraffins, derived from fossil fuels, bio-based phase-change materials, such as lauric acid and vegetable waxes, have emerged as sustainable alternatives. However, several compounds remain unexplored, and their thermophysical properties are still unknown. To address this gap, this study reports, for the first time, the characterization of three different compositions of commercial coconut waxes. The latent heat and phase-change temperature are determined using differential scanning calorimetry. Density and viscosity are measured as a function of temperature with specific apparatus. Lastly, the measured properties are used to comparatively asses the performance of the materials during the melting process, through the use of Rayleigh and Nusselt numbers.

Keywords: solar energy, thermal energy storage, bio-based, phase-change materials, natural waxes.

1. Introduction

Solar radiation is the primary energy source available on Earth and, except for a few forms (geothermal, nuclear, and tidal), all other types derive from it. Solar energy can be directly used as heat or transformed into electricity, playing an important role in decarbonizing the energy matrix and achieving the goal of the Paris Agreement. According to the International Energy Agency (IEA), solar photovoltaic (PV) and wind energy are expected to represent 95% of the added capacity of all renewables, up to 2030 (IEA, 2024). However, due to the intermittent nature of such sources, energy storage becomes imperative, where thermal energy storage (TES) appears as a promising technology for this transition (Rocha et al., 2023a). Among the three types of TES (sensible, latent, and thermochemical), latent thermal energy storage (LTES) stands out due to the balance between high energy density and maturity level. Moreover, in LTES systems, the charge/discharge process of thermal energy occurs at an almost constant temperature of the phase-change material (PCM). These characteristics make PCMs suitable for systems where thermal energy should be stored and (later) recovered, but also allow a wide range of applications where passive thermal management, i.e. temperature control, is required. In this context, PCMs have been used in different solar systems, including solar collectors (Bharathiraja et al., 2024), PV panels (Saeed et al., 2025), solar-assisted heat pumps (Li et al., 2025), concentrated solar power (Senthil, 2020), Trombe walls (Xiong et al., 2022), solar dryers (Lad et al., 2023), solar greenhouses (Bi et al., 2024), solar chimneys (Rashid et al., 2025), solar desalination (Kumar R et al., 2022), etc.

The traditional classification of PCMs groups them into three classes: organics, inorganics, and eutectics. For

10.18086/swc.2025.01.03 Available at http://proceedings.ises.org

low to mid-temperature (<100°C) applications, undoubtedly, paraffin is the most used type of PCM due to its high latent heat, good long-term stability and chemical compatibility. However, these materials are composed of hydrocarbons derived from fossil fuels, which hinder the full contribution of PCMs to achieve carbon neutrality. For this reason, part of the scientific community has turned its attention to the development and utilization of sustainable and renewable materials, called bio-based PCMs. These materials are mainly derived from edible oils and fats, non-edible oils, waste animal fat, waste cooking oil, and genetically modified oil (Ismail et al., 2025). From this point of view, some authors classify organic PCMs into bio-based or non-bio-based materials (Mehrizi et al., 2023).

Lauric (dodecanoic) acid, a fatty acid, is a widely investigated bio-based PCM due to its characteristics of high heat capacity and good long-term thermochemical stability, although it may suffer from low thermal conductivity, as paraffin does. In addition, its melting temperature (T_m) around 45°C and latent heat (L) of 190 kJ/kg make it suitable for a wide range of solar applications (Rocha et al., 2023b). Vegetable oils are rich sources of fatty acids; lauric acid represents about 50% of the coconut oil composition. Nevertheless, unrefined oils and waxes have also been used as PCMs, as summarized in Table 1.

Tab. 1: Summary of investigations employing bio-based PCMs in low-mid temperature applications.

Ref.	PCM	T_m [°C] / L [kJ/kg]	Application	Remarks
(Faraj et al., 2021)	Coconut oil	25 / 103	Underfloor heating, building walls, and roof	Annual cost savings were achieved by shifting the heating system operation from on-peak to off-peak periods.
(Gunawan et al., 2023)	Soy wax Palm wax	44 / 117.6 57 / 149.2	Solar dryer	Energy efficiency during discharging (nighttime – 6 PM to 6 AM) for the solar dryer: • With soy wax: 29.4%; • With palm wax: 27.8%; • Without PCM: 0;
(Bartali et al., 2023)	Carnauba wax	83 / 192-206	Evacuated-tube collector	9 kg of PCM stabilized the outlet water temperature at 65°C for 30 min, under shading conditions.
(Balasundaram et al., 2023)	Different PCMs, including fatty acids and natural waxes	40-80 / 106-211	Solar dryer	The three best candidates indicated by the multicriteria algorithm were: stearic acid, palmitic acid, beeswax. The algorithm considered thermophysical properties and cost as input parameters.
(Rudra Murthy et al., 2022)	Shellac wax	79.5 / 148	Thermal energy storage	The authors indicated the PCM as a good option for medium temperature applications (60-80°C), presenting comparable efficiency to paraffin.

As noted in Table 1, bio-based PCMs can be employed in TES applications or used to improve the efficiency of solar/heating systems. Nevertheless, other materials, such as coconut wax, can also be considered potential PCMs, but investigations are not yet available for such materials, to the best of the author's knowledge. Such waxes could be a cheaper option compared to processed substances (e.g. lauric acid), and, hence, could make the utilization of PCMs even more valuable. Therefore, to address this gap, this work characterizes the thermophysical properties of three commercial coconut waxes, as well as lauric acid, considered a reference PCM. The dynamic viscosity and density are obtained as a function of temperature, while the latent heat of fusion and the phase change temperature are measured by differential scanning calorimetry (DSC). Lastly, a comparison of the heat transfer characteristics during the melting process is carried out with the aid of Rayleigh and Nusselt numbers.

2. PCM characterization

Several bio-based waxes, alternatives to oil-based paraffins, are available on the Brazilian market, but are usually commercialized for candle production. To verify the suitability of using some of them as PCMs, three commercial-grade coconut waxes were characterized. The first is a 100% pure coconut wax, from now on referred to as coconut wax. The second is a mixture of coconut, rice, palm, and soy waxes, named hard coconut wax, while the third is a mixture of coconut, rice, and palm waxes, named T02 coconut wax. Lauric acid, 99% purity, was also selected to be the reference PCM due to its widespread utilization and known properties. Figure 1 illustrates the PCMs under investigation.

Figure 1: PCMs under investigation. From top to bottom: lauric acid, coconut wax, hard coconut wax, T02 coconut wax.

Differential scanning calorimetry (DSC) was employed to measure the latent heat and phase change temperature. The equipment is a Shimadzu DSC-60, with uncertainties of 0.1°C and 1% of the reading, for temperature and heat flux, respectively. All tests were conducted with a nitrogen flow of 100 ml/min and a heating rate of 5°C/min, from ambient temperature to 100°C. An analytical balance from Shimadzu, with a resolution of 0.01 mg, was used to weigh the PCM sample for DSC measurements. A Python script was written to perform the data reduction. The phase change region was delimited by tangent lines at the most inclined points, at the beginning and at the end of the phase change, while the onset and offset temperatures were obtained by intercepting these tangents with the baseline, as illustrated in Figure 2. The latent heat of fusion was calculated by the numerical integration of the DSC signal, using Simpson's 1/3 rule.

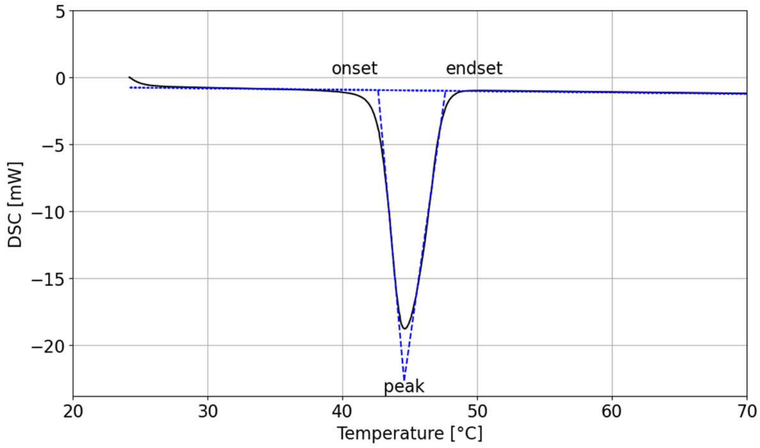

Figure 2: Example of DSC graph indicating the onset, peak, and endset temperatures of phase-change.

The density was calculated through mass and volume measurements, with a maximum uncertainty of 8.2% and 5.8% of the reading for the liquid and solid phases, respectively. After obtaining the density–temperature curve, the coefficient of thermal expansion was calculated with Eq. 1.

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T} \quad \text{(eq. 1)}$$

The dynamic viscosity was measured with a digital rotary viscometer, manufactured by Marte, model MVD-5, with a low viscosity spindle (rotor #0). The accuracy is 1% of the full scale, which depends on the spindle rotation, corresponding to ±0.1 mPa.s, for readings up to 9 mPa.s, and ±0.2 mPa.s, between 9 and 19 mPa.s. A constant temperature water bath was used to vary the temperature during the density and viscosity tests, while a PT-100, with an accuracy of 0.3°C, was used for temperature measurements. Although the viscosity and the coefficient of thermal expansion are not used to directly evaluate PCMs, they may influence the heat transfer characteristics of the phase change process. It is widely recognized that melting is governed by natural convection, which in turn, is related to the Rayleigh (Ra) number, given by Eq. (2). To compare the performance of these PCMs during the charging (melting) process, it was assumed that the thermal diffusivity is the same for all of them, making Ra solely a function of β and ν. Subsequently, lauric acid received a unitary value for Ra, while Ra for the other materials was normalized on a unitary basis. Lastly, the Nusselt number (Nu) was estimated considering Eq. (3) and a unitary value was assigned to lauric acid. Similarly, Nu for the other materials was normalized.

$$\mathrm{Ra} = \frac{g\beta\left(T_{\mathrm{wall}} - T_{\mathrm{melting}}\right)X^3}{\alpha\nu} \quad \text{(eq. 2)}$$

$$\mathrm{Nu} = C\mathrm{Ra}^{0.25} \quad \text{(eq. 3)}$$

where g is the gravitational acceleration, X is the characteristic length, α is the thermal diffusivity, and ν is the kinematic viscosity.

3. Results and discussions

The DSC curves for lauric acid and the three coconut waxes can be seen in Figure 3. As can be seen, the coconut wax curve shows a sharp and narrow transition, similar to refined or eutectic substances, which is desired when used for thermal management purposes. However, it is clear that its phase change temperature is higher than that of lauric acid. The curves of the hard and T02 coconut waxes display a greater phase change (mushy) region, due to the mixture of several compounds. Table 2 summarizes the phase change temperatures, latent heat, and price in the Brazilian market for these materials.

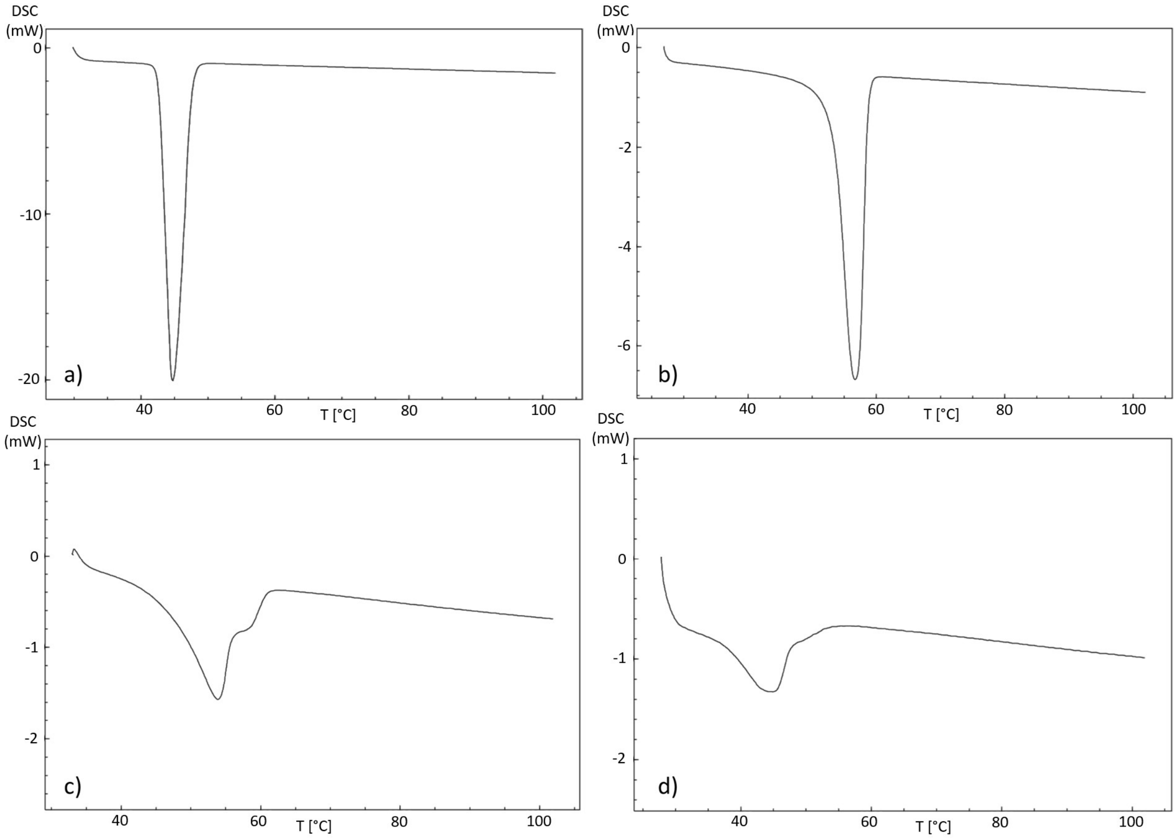

Figure 3: DSC curves for: a) lauric acid; b) coconut wax; c) hard coconut wax; d) T02 coconut wax.

Tab. 2: Latent heat, phase-change temperature, and price for lauric acid and coconut waxes.

PCM	Onset [°]	Peak [°]	Endset [°]	Latent heat [kJ/kg]	Price [R$/kg]	Price [USD/kg]*
Lauric acid	42.7	44.7	47.7	191.87	168	31.6
Coconut wax	53.2	56.3	58.67	174.29	45	8.5
Hard coconut wax	46.7	53.9	56.6	99.22	42	7.9
T02 coconut wax	35.1	44	46.7	85.67	47	8.8

*Based on an exchange rate of 1 USD = R$ 5.32 on set 9, 2025.

From Table 2, one can note the relatively high latent heat of coconut wax, comparable to lauric acid and to some paraffins, which qualifies it as a potential PCM. In contrast, hard and T02 coconut waxes exhibited a lower latent heat, but one comparable to other bio-based PCMs, such as coconut oil (103 kJ/kg – Faraj et al., 2021). When analyzing the economic aspect, all three waxes have comparable prices, which are 3.6 times lower than that of lauric acid. Once again, this aspect favors these materials as potential PCMs, especially coconut wax.

The results for density are presented in Figure 4. A linear regression was performed for the density in the liquid state of each material, yielding Eq. (4) for lauric acid and Eqs. (5) to (7) for coconut, hard coconut, and T02 coconut waxes, respectively. By multiplying the latent heat with the liquid density near the phase change temperature, energetic densities of 170.2, 146.5, 80.6, and 73.2 MJ/m³ are obtained for lauric acid, coconut, hard coconut, and T02 coconut waxes, respectively. The coefficient of thermal expansion (β) for each material, calculated with the liquid density near the phase change, is indicated in Table 3.

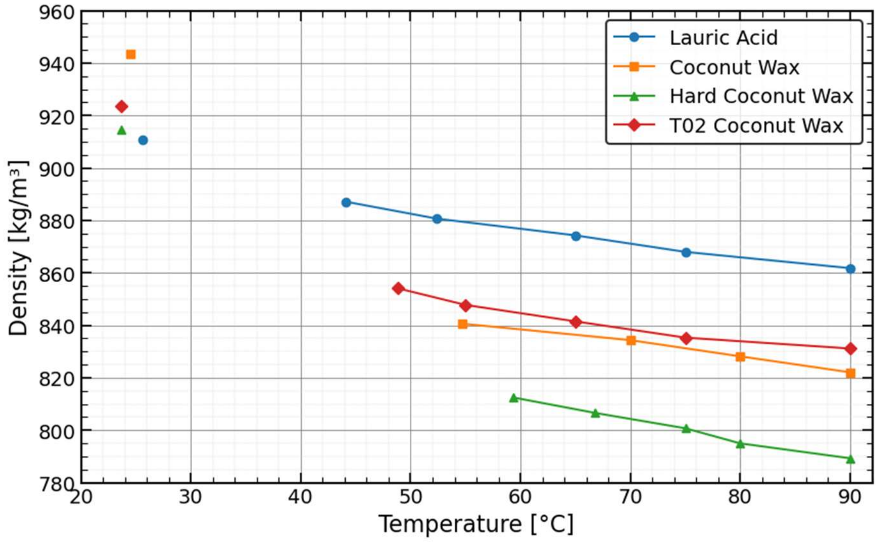

Figure 4: Density as function of temperature for lauric acid and coconut waxes.

$$\rho_{\text{liquid,lauric acid}} = 910.20 - 0.5487\,T \quad \text{(eq. 4)}$$

$$\rho_{\text{liquid,coconut wax}} = 870.11 - 0.5270\,T \quad \text{(eq. 5)}$$

$$\rho_{\text{liquid,hard coconut wax}} = 858.11 - 0.7720\,T \quad \text{(eq. 6)}$$

$$\rho_{\text{liquid,T02 coconut wax}} = 878.85 - 0.5525\,T \quad \text{(eq. 7)}$$

where T is in °C.

Tab. 3: Coefficient of thermal expansion (β) for lauric acid and coconut waxes.

PCM	Lauric acid	Coconut wax	Hard coconut wax	T02 coconut wax
β [1/K]	0.000618	0.000626	0.000950	0.000642

The viscosity of the evaluated materials can be seen in Figure 5. A power-law regression was performed, yielding Eq. (8) for lauric acid and Eqs. (9) to (11) for coconut, hard coconut, and T02 coconut waxes, respectively.

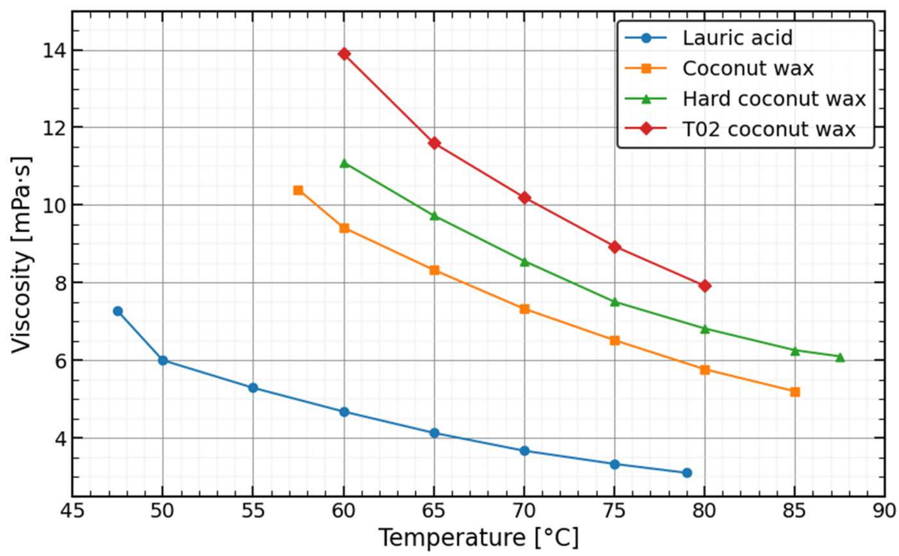

Figure 5: Viscosity as function of temperature for lauric acid and coconut waxes.

$$\mu_{\text{liquid,lauric acid}} = 3064.3\, T^{-1.582} \quad \text{(eq. 8)}$$

$$\mu_{\text{liquid,coconut wax}} = 12106\, T^{-1.745} \quad \text{(eq. 9)}$$

$$\mu_{\text{liquid,hard coconut wax}} = 8440.6\, T^{-1.622} \quad \text{(eq. 10)}$$

$$\mu_{\text{liquid,T02 coconut wax}} = 37277\, T^{-1.931} \quad \text{(eq. 11)}$$

where T is given in °C. Although the viscosity of T02 coconut wax is almost three times that of lauric acid (at 60°C), it is still less than half of the paraffin wax used by Parsa et al. (2024) (0.03 Pa.s). The normalized Ra and Nu are indicated in Table 4 for all the investigated PCMs and for the commercial paraffin wax.

Tab. 4: Normalized Ra, Nu, and Nu reduction for lauric acid and coconut waxes.

PCM	Ra	Nu	Nu reduction [%]
Lauric acid	1	1	-
Coconut wax	0.67	0.91	9.5
Hard coconut wax	0.92	0.98	2.0
T02 coconut wax	0.52	0.85	15.0
Paraffin wax (Parsa et al., 2024)	0.07	0.51	48.8

Based on the results in Table 4, the normalized Ra and Nu reveal that all bio-PCMs exhibit enhanced convective heat transfer relative to paraffin. Compared to lauric acid, hard coconut wax showd minimal Nu reduction, while paraffin wax exhibits the lowest Ra and Nu, with almost 50% reduction in the convective coefficient. Therefore, the analyzed bio-based materials demonstrate superior performance during the charging process, compared to the reference paraffin wax.

4. Conclusions

This work experimentally characterized the thermophysical properties of lauric acid and different compositions of coconut waxes as potential bio-based PCMs. The density and viscosity as a function of temperature, as well as the coefficient of thermal expansion, latent heat, and melting temperature were measured. Among the materials, (pure) coconut wax stands out due to its latent heat of fusion of 172.29 kJ/kg, comparable to 191.87 kJ/kg for lauric acid. Besides, it exhibits a narrow phase change range, from 53.2–56.3°C, almost identical to the 5 K range of lauric acid (42.7–47.7°C), which makes this material suitable for applications involving thermal management. In contrast, the T02 coconut wax shows the lowest latent heat, with 85.67 kJ/kg. Concerning the viscosity, although the value for T02 coconut wax is nearly three times that of lauric acid, it remains significantly lower than that of paraffin (0.03 Pa·s), which favors natural convection. These findings highlight the potential of bio-based materials as efficient and more sustainable alternatives for thermal energy storage applications. Future investigations include the characterization of other bio-based materials and the determination of their long-term thermal stability.

5. Acknowledgments

The authors are grateful for the financial support from Pró-Reitoria de Pesquisa da Universidade Federal de Minas Gerais (PRPq-UFMG), grant number 30563*187, FAPEMIG, CNPq, and CAPES. Acknowledgments also to Núcleo de Extensão e Prestação de Serviços (NEPS) do Departamento de Química da UFMG, for performing the DSC measurements. The second author thanks the Associação Brasileira de Engenharia e Ciências Mecânicas (ABCM) for the scholarship provided trough grant PABIC 2025.

6. Legal approvals

This research was registered in the National System for the Management of Genetic Heritage and Associated Traditional Knowledge (SISGEN) platform, with the access registration number A774B61.

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