
DEVELOPMENT AND CHARACTERIZATION OF CARBON DOT (CD)-ENHANCED SHEA BUTTER AS A PHASE CHANGE MATERIAL FOR THERMAL ENERGY STORAGE

Yotolmbaye Sylvain^{1,*}, T.o. Ahmadu¹, F.o. Anafi¹, L.o.yusuf¹

¹Ahmadu Bello University

Email: yotolmbayes@gmail.com*, talibahmadu@gmail.com, Fataianafi@yahoo.com,
queenteeafah95@gmail.com

*Corresponding author: Yotolmbaye Sylvain

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

The rapid evolution of thermal energy storage technologies has positioned phase change materials (PCMs) as a cornerstone for advanced heat management and energy conservation systems. The PCMs are distinguished by their ability to absorb, store and release large quantities of latent heat during phase transitions. Organic phase change materials such as shea butter exhibit low thermal conductivity and latent heat of fusion, hence the need to enhance these properties with suitable additives. In this study, carbon dots (CDs) were synthesized hydrothermally with a yield of 40.3% and particle sizes predominantly below 20 nm, before being integrated into pure shea butter. Pure shea butter exhibited low thermal conductivity (0.222577 W/mK), heat transfer coefficient (37.09621 W/m²·K), latent heat of fusion of 50.50 kJ/kg and specific heat capacity of 0.021054 J/kgK. Addition of 3wt% CDs to pure shea butter increased thermal conductivity to 0.341 W/m·K, heat transfer coefficient to 56.9 W/m²·K, latent heat of fusion to 163.03 kJ/kg and specific heat capacity to 0.062023 J/kgK. Overall, the composite PCM indicated potential for enhanced thermal storage capacity and heat transfer efficiency, indicating its suitability as a sustainable and cost-effective material for thermal energy storage applications.

Keywords: Phase change materials; Carbon dots; Shea butter; and hydrothermal synthesis

1.0 INTRODUCTION

The growing demand for reliable and efficient thermal energy management has drawn considerable research attention to phase change materials (PCMs) for latent heat storage. PCMs absorb, store, and release large quantities of thermal energy during solid–liquid phase transitions while maintaining a nearly constant temperature (Yang et al., 2021), making them attractive for building thermal regulation, waste heat recovery, and solar energy applications such as solar drying (Pandey et al., 2024).

Organic PCMs, including paraffins and fatty compounds such as shea butter, are valued for their chemical stability, high latent heat per unit mass, non-corrosive nature, and minimal supercooling (Faraj et al., 2020). However, their inherently low thermal conductivity limits the rate of heat absorption and release, reducing efficiency in time-sensitive applications such as solar drying (Agbetiloye et al., 2022). Shea butter a low-cost, renewable fat extracted from the shea tree (*Vitellaria paradoxa*), is a promising bio-based organic PCM but shares this conductivity limitation.

Considerable research has focused on improving the thermal conductivity of shea butter and similar organic PCMs using high-conductivity additives such as metallic powders, carbon nanotubes, graphene, and expanded graphite, without significantly compromising latent heat storage (Tariq et al., 2020). Agbetiloye et al. (2022) achieved a thermal conductivity of 0.0538 W/m·K and latent heat of 164.53 kJ/kg using 3 wt% aluminium powder in shea butter for a ginger solar dryer. Stonehouse and Abeykoon (2022) compared several carbon nanomaterials in PCM matrices and reported large conductivity enhancements but at high material cost. Yadav et al. (2021) reviewed carbon-based nanomaterials as conductivity enhancers, reporting improvements of up to 2700% but flagging nanoparticle agglomeration, elevated cost, and reduced latent heat as recurring drawbacks, while Radomska et al. (2020) similarly identified a persistent trade-off between conductivity gain and latent heat retention across enhancer materials. Collectively, these studies confirm the effectiveness of carbon-

based nanomaterials but highlight their high cost as a barrier to economically viable composite PCMs, and underline the need for more affordable enhancers.

This study addresses this gap by investigating carbon dots synthesized from p-phenylenediamine and folic acid as a low-cost additive for shea butter, with the aim of developing a cost-effective composite PCM for thermal energy storage.

2.0 MATERIALS AND METHODS

2.1 Materials

The carbon precursors p-phenylenediamine and folic acid (99% purity) and ethanol (95%, CAS 64-17-15) were purchased from Haddis Chemical, Samaru, Zaria. Deionised water was obtained from the Ahmadu Bello University Multiuser Laboratory, and food-grade shea butter was procured from the open market.

2.2 Synthesis of Carbon Dots

Carbon dots (CDs) were synthesized hydrothermally following the method of He et al. (2024). P-phenylenediamine (30 g) was dissolved in 1 L of ethanol (solution A), while folic acid (5 g) was dissolved in 500 mL of deionised water (solution B). The solutions were combined under magnetic stirring, transferred into a Teflon-lined autoclave, and heated at 180 °C for 12 hours. After natural cooling, the product exhibited characteristic red fluorescence under UV light, confirming CD formation. The product was purified by silica gel column chromatography (methanol eluent), followed by rotary evaporation and freeze-drying, giving a synthesis yield of 40.3%.

2.3 Preparation of Carbon Dot–Shea Butter Blend

Following the method of Agbetiloye et al. (2022), 10 mL of shea butter was heated to a set mixture temperature (40, 50, or 60 °C; Priyadarshi & Paul, 2019) until fully melted. Carbon dots (1, 2, or 3 wt%) were gradually added under continuous magnetic stirring to avoid agglomeration, and the blend was stirred for a specified mixture time (10, 20, or 30 minutes) to achieve homogeneous dispersion. The mixture was then cooled under ambient conditions and stored in airtight containers for further analysis.

2.4 Characterization

Thermal conductivity was measured using a Searle's apparatus, and specific heat capacity using a radial heat conduction apparatus (Armfield HT12), applied to both pure and CD-blended shea butter.

2.4.1 Thermal Conductivity

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

The thermal conductivity was computed using equation 2.1.

$$k = \frac{mC(\theta_2 - \theta_1)L}{A(T_1 - T_2)} \quad (2.1)$$

where; k = Thermal conductivity of sample (W/mK), m = Mass of water collected per second (kg/s), C = Specific heat capacity (J/kg.K), A = Area of the cross-sectional area of the bar (m^2)

θ_1 = Inlet water temperature (K), θ_2 = Outlet water temperature (K), L = Distance between the 2-thermometer point (m), T_1 = Temperature of hot end of the bar (K)

T_2 = Temperature of cold end of the bar (K)

2.4.2 Specific heat capacity

The specific heat capacity was computed using equation 2.2

$$C = \frac{Q}{m\Delta T} \quad 2.2$$

Where: C = Specific heat capacity (J/kg.K), m = Specific heat capacity of water (kg), Q = change in energy (J), and ΔT is Temperature change ($^{\circ}\text{C}$).

2.4.3 Latent heat of fusion

An experimental method involving water in calorimeter with stirrer was used to measure the latent heat. In order to account for heat loss that may occur, the following measures were taken:

The PCM was properly sealed.

The hot medium (water) temperature of 90°C is far above the melting temperature of shea butter.

Full melting/solidification was allowed for throughout the experiment.

The latent heat was computed using equation 2.3 and 2.4.

$$mL + ms_2(\theta_2 - 0) = (m_2s_2 + m_1s_1)(\theta_1 - \theta_2) \quad (2.3)$$

$$L = [(m_2s_2 + m_1s_1)(\theta_1 - \theta_2) - s_2(\theta_2 - 0)]/m \quad (2.4)$$

Where: m_1 = Mass of Copper Calorimeter and Stirrer, m_2 = Mass of Water, s_1 = Specific Heat Capacity of Water, s_2 = Specific Heat Capacity of Copper, θ_1 = Initial Temperature of Warm Water

θ_2 = Final Temperature of Mixture, m = Mass of Sample, L = Specific Latent Heat of Fusion of Sample

2.5 Determination of the optimum blend of carbon dots & shea butter using Taguchi design of experiment.

Taguchi design of experiment was employed in Minitab statistical 22 software (2022 version) to determine the optimum blend. Three factors with 3 levels each, were used in an L9 orthogonal array (which has 9 experimental runs). The three factors were optimize using Carbon dots (CDs) concentration (1%, 2% and 3%), The mixture temperature of (40°C , 50°C and 60°C) and the mixture times (10 min, 20 min and 30 min). The response variables were thermal conductivity, latent heat of fusion and specific heat as seen in Table 1.

Table 1: Factors and level chosen for experiment design

Factors	Symbol	Units	1	2	3
Carbon dots	CDs	%	1	2	3
Mixture temperature	MT	$^{\circ}\text{C}$	40	50	60
Mixture time	Mt	Min	10	20	30

3.0 RESULTS AND DISCUSSION

3.1 Results from characterization of carbon dots/shea butter blends and pure shea butter

Result from characterization are presented in Table 2 and 3

Table 2: Thermophysical properties of carbon-dot /Shea butter PCM samples

S/N	ID	Thermal conductivity (W/mK)	heat transfer coefficient (W/m ² . K)	specific heat capacity (J/kgK)	Latent heat of fusion (kJ/kg)
1	A1	0.24188415	40.31402504	0.044471	85.198
2	A2	0.276439029	46.07317147	0.050761	91.23
3	A3	0.252400852	42.06680873	0.046357	104.834
4	B1	0.24188415	40.31402504	0.044129	117.275
5	B2	0.24188415	40.31402504	0.046027	130.17
6	B3	0.232208784	38.70146404	0.042601	137.075
7	C1	0.276439029	46.07317147	0.049495	152.689
8	C2	0.341483506	56.9139177	0.062023	163.033
9	C3	0.263873618	43.9789364	0.048464	173.437

Table 2 presents the thermophysical properties of the nine carbon dot-shea butter (CDs-SB) composites (A1-C3) prepared under the Taguchi L9 design across varying CD concentration, mixing temperature, and mixing time. Thermal conductivity ranged from 0.232–0.341 W/m·K, comparable to Asmau et al. (2022), while convective heat transfer coefficients ranged from 38.7–56.9 W/m²·K. Sample C2 recorded the highest heat transfer coefficient, consistent with its higher thermal conductivity (Shende et al., 2018), although the relationship was not strictly linear across all samples.

Specific heat capacity (0.0426–0.0620 J/kgK) correlated positively with thermal conductivity: sample B3 recorded the lowest values of both properties (0.232 W/mK; 0.0426 J/kgK), while C2 recorded the highest (0.341 W/mK; 0.0620 J/kgK).

Latent heat of fusion increased progressively with CD loading from approximately 85–104 kJ/kg at 1 wt%, to 117–137 kJ/kg at 2 wt%, and 152–163 kJ/kg at 3 wt%, with an overall maximum of 173.437 kJ/kg at 3 wt% CDs, 60 °C, and 30 minutes. This trend suggests that CDs enhance both conductivity and energy storage capacity, most likely through nanoparticle-induced heterogeneous nucleation, increased interaction sites between the carbon dot surfaces and the PCM matrix, and strengthened intermolecular forces that raise the energy required for phase transition. Overall, sample C2 (3 wt% CDs, 50 °C, 20 min) gave the best combined performance in thermal conductivity, heat transfer coefficient, and specific heat capacity, while C3 recorded the highest latent heat of fusion.

Table 3: Thermophysical properties of pure shea butter & carbon-dots/shear butter PCM

Thermophysical properties	Thermal conductivity (W/m·K)	heat transfer coefficient (W/(m ² ·K)	specific heat capacity (J/kg·°C)	Latent heat of fusion (kJ/kg)
Pure shea butter	0.222577	37.09621	0.021054	50.5
Blended carbon dots with shea butter	0.341483506	56.9139177	0.062023	163.033

Table 3 compares pure shea butter to the CD-blended shea butter PCM. It can be seen that the thermal conductivity of shea butter increased from (0.22577 to 0.341484 W/m.K) which gives an increase percentage of 53%. An increase in heat transfer coefficient of shea butter from 37.096 to 56.914 W/(m²·K), specific heat capacity from 0.021054 to 0.062023 J/kgK with the addition of carbon dots was also observed. There was also an increase in latent heat from 50.5 to 163.033 kJ/kg indicating an increase of over 200%. This shows that the addition of carbon dots greatly improved the shea butter thermal conductivity, heat transfer coefficient and specific heat capacity.

3.2 The cost analysis phase change material.

Table 4: Cost analysis of the PCM (Shea butter and carbon dots)

S/N	Materials	Unit Cost (N)	Total Cost
1	Shea Butter 4.53kg	₦ 2400	₦ 12000
2	<i>P</i> -phenylenediamine 40 g	₦ 200	₦ 8000
3	Ethanol 1 liter	₦ 8000	₦ 8000
4	Methanol 1 liter	₦ 8000	₦ 8000
5	Folic acid 7 g	₦ 1000	₦ 7000
6	Deionized water 2 liters	₦ 500	₦ 1000
7	Transport and labour	₦ 3000	₦ 2000
8	Total		₦ 47000

Carbon dots cost approximately ₦695.65 per gram, considerably cheaper than multi-walled carbon nanotubes (MWCNTs, US\$10 / ₦15,000 per gram) and graphene nanoplatelets (GNPs, up to US\$50 / ₦75,000 per gram) at current market prices representing cost savings of 95.3% and 99%, respectively. This confirms carbon dots as a more cost-effective alternative to conventional carbon-based conductivity enhancers.

4.0 CONCLUSION

A composite PCM was developed from shea butter and carbon dots derived from *p*-phenylenediamine and folic acid. The optimum blend, C2, showed clear improvement in thermophysical properties relative to pure shea butter: thermal conductivity increased from 0.222577 to 0.341484 W/m·K, specific heat capacity from 0.021054 to 0.062023 J/kgK, heat transfer coefficient from 37.09621 to 56.91392 W/m²·K, and latent heat of fusion from 50.5 to 163.03 kJ/kg. These results show that the developed composite PCM is suitable for thermal energy storage applications, with an effective cost saving of 95.3% relative to carbon nanotubes and 99% relative to graphene nanoplatelets.

5.0 REFERENCES

- Agbetiloye, L. A., Anafi, F. O., & Omisanya, N. O. (2022). Design, Construction and Performance Evaluation of Ginger Mixed Mode Solar Dryer Integrated with Latent Heat Storage. *Fuoye Journal of Engineering and Technology*, 7(2), 210-216. doi:10.46792/fuoyejet.v7i2.759
- Asmau, S. R. Experimental And Numerical Analysis Of Encapsulated Shea Butter Fatty as A Phase Change Material For Thermal Storage Application (2022): *International Journal of Advanced Engineering Research*. DOI:10.22161/ijners.912.322
- Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2020). A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. *Journal of Energy Storage*, (September), 101913. https://doi.org/10.1016/j.est.2020.101913
- He, P., Bai, J., Qin, F., Wang, X., Yu, X., Yao, Y., & Ren, L. (2024). Catalyst-regulated conversion of *p*-phenylenediamine-based carbon dots from red to deep-blue emission. *Materials Today Chemistry*, 38, 102082.
- Li, J., Long, Y., Cao, X., Sun, H., Jiao, R., Zhu, Z., Liang, W., & Li, a. (2024). Recent Advances and Perspectives in Solar Photothermal Conversion and Storage Systems: a Review. *Advances in Colloid and Interface Science*, 325, 103118. doi:10.1016/j.cis.2024.103118
- Pandey, S., Kumar, A., & Sharma, A. (2024). Sustainable Solar Drying: Recent Advances in Materials, Innovative Designs, Mathematical Modeling, and Energy Storage Solutions. *Energy*, 132725.
- Priyadarshi, D., & Paul, K. K. (2019). Optimisation of biodiesel production using Taguchi model. *Waste and Biomass Valorization*, 10(6), 1547-1559.
- Radomska, E., Mika, L., & Sztékler, K. (2020). The Impact of Additives on the Main Properties of Phase Change Materials. *Energies*, 13(12), 3064. doi:10.3390/en13123064

- Shende, T., Bhanvase, B., Rathod, A., Pinjari, D., & Sonawane, S. (2018). Sonochemical synthesis of Graphene-Ce-TiO₂ and Graphene-Fe-TiO₂ ternary hybrid photocatalyst nanocomposite and its application in degradation of crystal violet dye. *Ultrasonics sonochemistry*, 41, 582-589.
- Stonehouse, A., & Abeykoon, C. (2022). Thermal Properties of Phase Change Materials Reinforced with Multi-dimensional Carbon Nanomaterials. *International Journal of Heat and Mass Transfer*, 183, 122166.
- Tariq, S. L., Ali, H. M., Akram, M. A., Janjua, M. M., & Ahmadlouydarab, M. (2020). Nanoparticles Enhanced Phase Change Materials (nePCMs) - a Recent Review. *Applied Thermal Engineering*, 176, 115305.
- Yadav, A., Verma, A., Kumar, A., Dashmana, H., Kumar, A., Bhatnagar, P., & Jain, V. (2021). Recent Advances on Enhanced Thermal Conduction in Phase Change Materials Using Carbon Nanomaterials. *Journal of Energy Storage*, 43, 103173.
- Yang, L., Jin, X., Zhang, Y., & Du, K. (2021). Recent Development on Heat Transfer and Various Applications of Phase-change Materials. *Journal of Cleaner Production*, 287, 124432.