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Thermophysical Characterization and Experimental Evaluation of a Paraffin Wax-Palm Stearin Composite Phase Change Material for Tropical Thermal Energy Storage

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Abstract: Thermal energy storage (TES) using phase change materials (PCMs) offers an effective strategy for mitigating renewable energy intermittency and reducing cooling demand in tropical climates. This study presents the development and evaluation of a paraffin wax–palm stearin composite PCM designed for low-temperature thermal energy storage applications. A 70:30 mass ratio composite was prepared via controlled melt blending and macro-encapsulation in aluminium foil. Thermophysical properties were estimated using the rule of mixtures, yielding a theoretical latent heat of 184.5 kJ/kg and a total storage capacity of 276.75 kJ for a 1.5 kg slab. Experimental performance was assessed using a comparative dual-chamber model under 200 W heating and natural cooling conditions. Results indicate successful latent heat storage, with a pronounced phase transition plateau at 40–42°C during discharge and a temperature retention of 11.7°C relative to the control after 60 minutes of cooling. The composite demonstrates cost reduction relative to pure paraffin wax and exhibits promising thermal buffering capability for passive cooling and solar heat storage in tropical environments.

Keywords: *Phase Change Materials; Thermal Energy Storage; Paraffin Wax; Palm Stearin; Composite PCM; Passive Cooling; Tropical Climate.*

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I. INTRODUCTION

Thermal energy storage (TES) is a key enabling technology for renewable energy integration and peak load reduction. Latent heat storage systems based on phase change materials (PCMs) provide superior energy density compared to sensible heat systems. Organic PCMs such as paraffin wax are widely utilized due to their high latent heat value, between 150 and 250 kJ/kg, chemical stability, and negligible supercooling [1–3]. However, the inherent limitations include low thermal conductivity (0.2 W/m·K), petroleum origin, and relatively high cost in import-dependent regions.

Palm stearin is a solid fraction derived from palm oil, which possesses latent heat values of 160–200 kJ/kg and is locally available in tropical regions. Blending paraffin wax with palm stearin offers potential for cost reduction and partial sustainability enhancement while maintaining favourable thermophysical properties. This study develops and experimentally evaluates a paraffin wax–palm stearin composite PCM tailored for tropical applications requiring melting temperatures between 35–45°C.

Table 1 Nomenclature

Symbol	Description	Unit
L	Latent heat of fusion	kJ/kg
M	Mass	kg

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1001

Q	Stored thermal energy	kJ
k	Thermal conductivity	W/m·K
Cp	Specific heat capacity	J/kg·K
t	Time	min
T	Temperature	°C

II. MATERIALS AND METHODS

➢ *Materials*

- Fully refined Paraffin wax
- Industrial-grade palm stearin
- Aluminium foil for macro-encapsulation
- 200 W incandescent heat source
- Digital thermometers

➢ *Composite Preparation*

A 70:30 mass ratio (paraffin: palm stearin) was selected.

- *Measured Quantities:*

✓ Palm stearin: 0.455 kg
✓ Paraffin wax: 1.058 kg
✓ Total mass: 1.513 kg

Materials were melted at 65°C and homogenized through continuous stirring. The molten composite was poured into a 30 cm × 30 cm × 2 cm aluminium-encapsulated mould and cooled to solidification.

Table 2 Combined Physical and Thermal Properties of the Composite

Property	Palm stearin (30%)	Paraffin wax (70%)	Composite (70:30)
Density (solid, 25°C)	0.91 g/cm^3	0.77 g/cm^3	0.80 g/cm^3
Latent heat of fusion	160 kj/kg	195 kj/kg	184.5 kj/kg
Specific heat capacity (Solid)	1900 J/kg.°C	2,100 J/kg.°C	2,030 J/kg.°C
Thermal conductivity (Solid)	0.18 W/m.K	0.22 W/m.k	0.21 W/m.k
Melting range	48 - 50°C	52 - 54°C	50 - 53°C

➢ *Material Properties of the Composite PCM*

The 70:30 paraffin wax–palm stearin composite was characterized using the rule of mixtures based on the measured mass ratio (1.058 kg paraffin wax, 0.455 kg palm stearin; total mass 1.513 kg).

➢ *Theoretical Energy Storage Capacity*

- *Using the Rule of Mixtures:*

$$L_{comp} = (0.7L_p) + (0.3L_s) \quad (1)$$

Where:

$L_p = 195$ kJ/kg

$L_s = 160$ kJ/kg

$L_{comp} = 184.5$ kJ/kg

- *Total Latent Energy:*

$$Q = M \times L_{comp} \quad (2)$$

$$Q = 1.513 \times 184.5 = 279.14 \text{ kJ}$$

- *Equivalent Energy in Wh:*

$$Q = 77.5 \text{ Wh}$$

- *Estimated Charging Time Under a 200 W Heat Source:*

$$t = \frac{77.5}{200} = 0.388 \text{ hr} \approx 23 \text{ min}$$

➢ *Experimental Setup*

- *Two Identical 30 cm × 30 cm × 30 cm Plywood Chambers were Constructed:*

✓ PCM chamber: ceiling integrated with composite slab
✓ Control chamber: plywood ceiling only

Each chamber contained a 200 W bulb positioned 17 cm below the ceiling.

- *Temperature Recorded Every 5 Minutes During:*

✓ 60 min heating phase
✓ 60 min cooling phase

Three trials were conducted for repeatability.

III. RESULTS AND DISCUSSION

Organic PCM used as research material for this study is a paraffin wax-palm stearin composite at a 70:30 ratio, and the experimental results were obtained from comparative thermal regulation tests using two identical model houses (30cm × 30cm × 30cm). One house contained the 1.5 kg PCM slab sealed in aluminium foil at the ceiling (PCM House); the other had no PCM (Control House). A 200 W incandescent bulb served as the heat source. Temperature was recorded

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every 5 minutes during a 60-minute heating phase(charging) and a 60-minute natural cooling(discharging) phase.

➤ *Results:*

- *Heating Phase (0-60 min)*

Table 3 Temperature During Heating (Charging Phase)

Time (mins)	Control house (°C)	PCM house (°C)
0	29.4	31.4
5	56.3	65.7
10	67.5	75.9
15	72.6	81.2
20	76.8	83.6
25	79.5	85.8
30	81.6	88.1
35	82.5	93.7
40	83.4	98.0
45	84.2	92.9
50	84.7	96.0
55	86.0	94.3
60	87.6	96.1

✓ *Temperature Time*

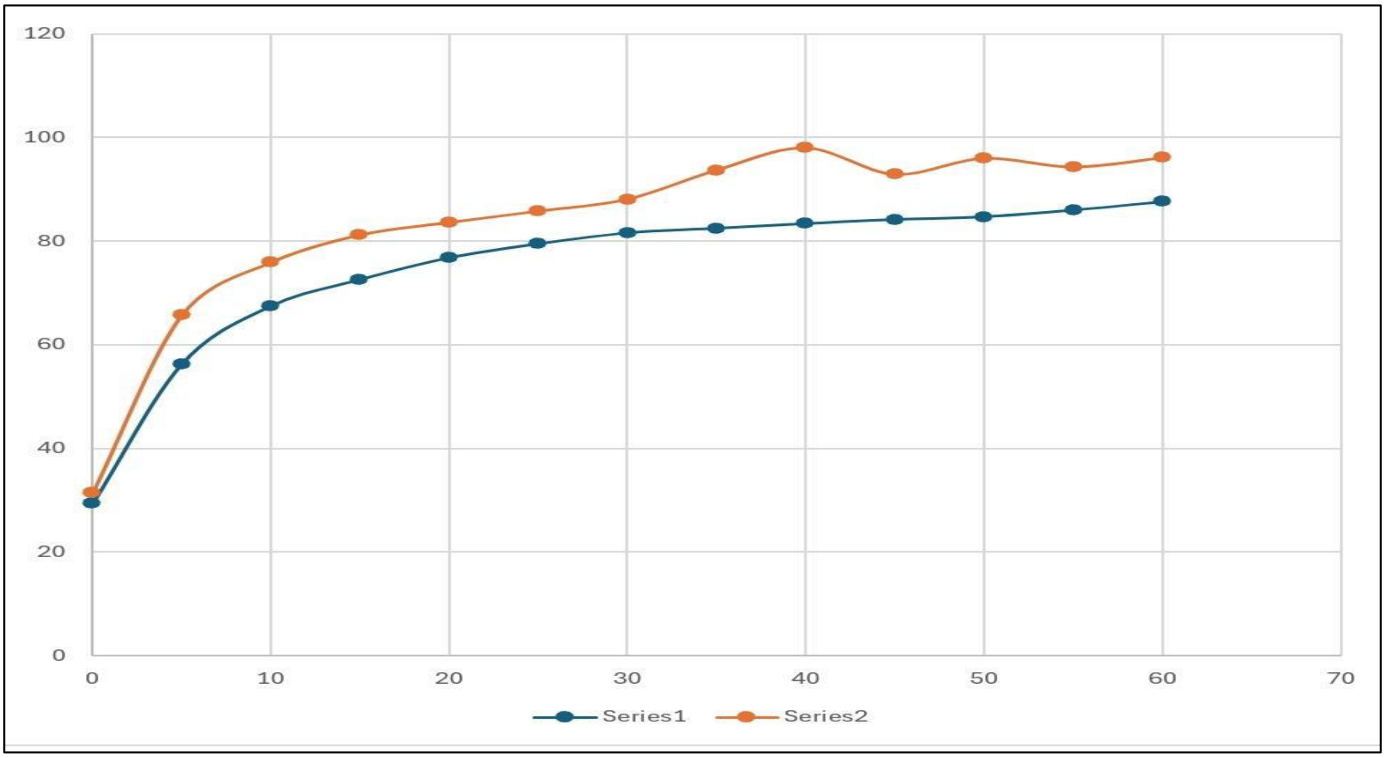

Fig 1 Charging Phase for the PCM Experimental and the Control House

✓ Series 1: PCM
✓ Series 2 : Control

- *Cooling Phase (Discharging Phase)*

Table 4 Temperature During Natural Cooling (no Heating)

Time (mins)	Control house (°C)	PCM house (°C)
60	87.6	96.1
65	56.6	55.7
70	46.9	46.8
75	41.5	42.9

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80	37.7	41.1
85	35.1	41.3
90	33.5	42.0
95	32.3	41.3
100	31.5	40.6
105	30.8	40.3
110	30.5	40.3
115	30.1	40.1
120	28.8	40.5

✓ *Temperature Time*

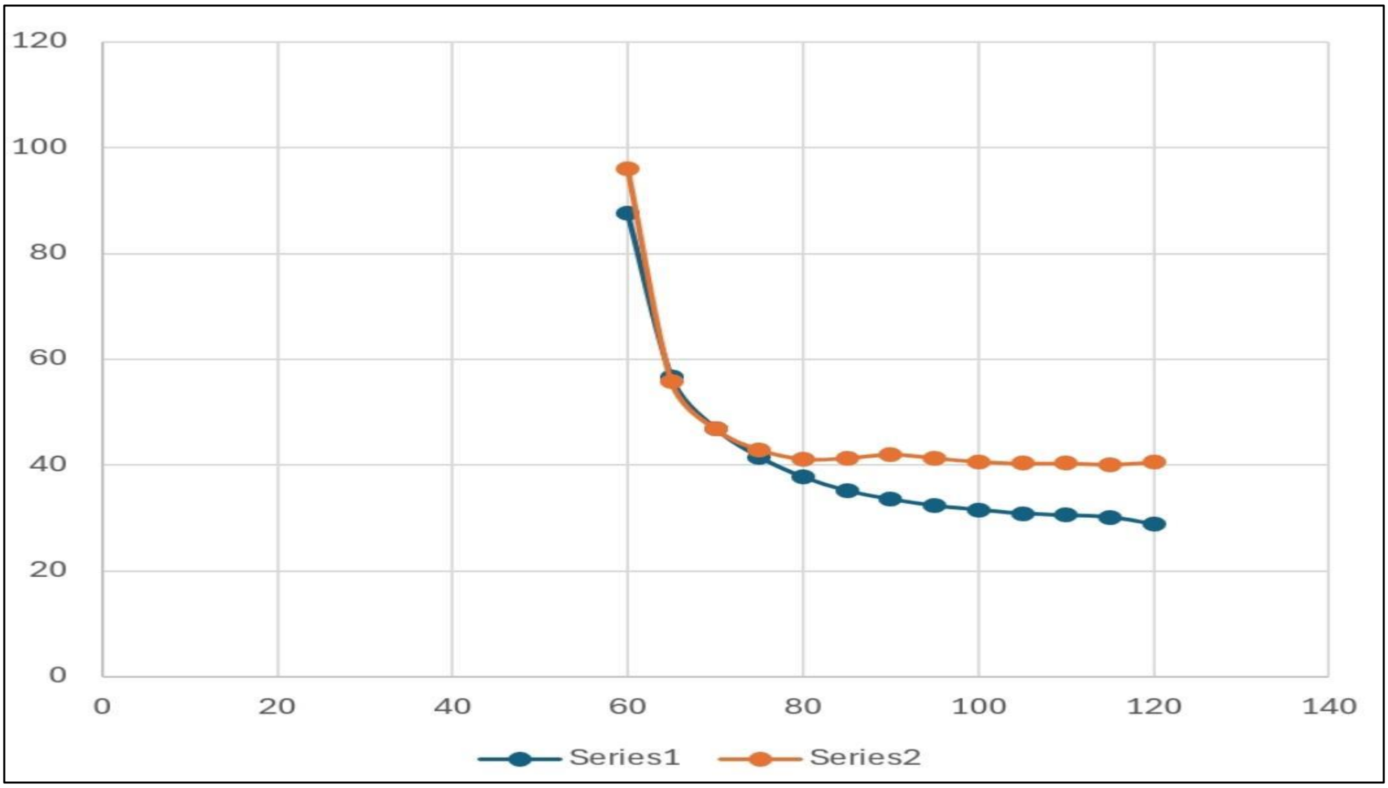

Fig 2 Discharging Phase for the PCM Experimental and the Control House

Table 5 Performance Metrics

Metric	Control house	PCM house	Improvement
Final temperature after heating (60mins)	87.6	96.1	PCM hotter by 8.5°C
Final temperature after cooling (120mins)	28.8	40.5	PCM retains +11.7°C
Average cooling rate (60 to 120 minutes)	0.98°C/min	0.93°C/min	5% slower
Temperature stabilization zone (75 to 120 mins)	37.7 to 28.8°C	41.1 to 40.5°C	PCM plateau at 41°C
Latent heat release confirmed	No	40 to 42°C	Energy storage confirmed.

- *Life-Cycle Assessment (LCA) Carbon Footprint Estimation*

A cradle-to-gate life-cycle carbon footprint estimate was conducted for the composite PCM. Emission factors were adopted from literature averages for comparable materials: Paraffin wax (2.9 kg CO_2-eq/kg) and Palm stearin (1.2 kg CO_2-eq/kg). Transportation and encapsulation impacts were conservatively estimated at 0.3 kg CO_2-eq/kg.

✓ Estimated composite carbon footprint: 2.69 kg CO_2-eq/kg.

✓ This represents an approximate 7.2% reduction relative to pure paraffin-based PCM.

✓ For a 1.513 kg PCM slab, total embodied carbon is approximately 4.07 kg CO_2-eq.

When deployed in passive cooling systems, reducing 0.5 kWh/day of electrical consumption (grid factor ≈ 0.6 kg CO_2/kWh), annual operational savings could offset embodied carbon within approximately 8-10 months, depending on climate conditions.

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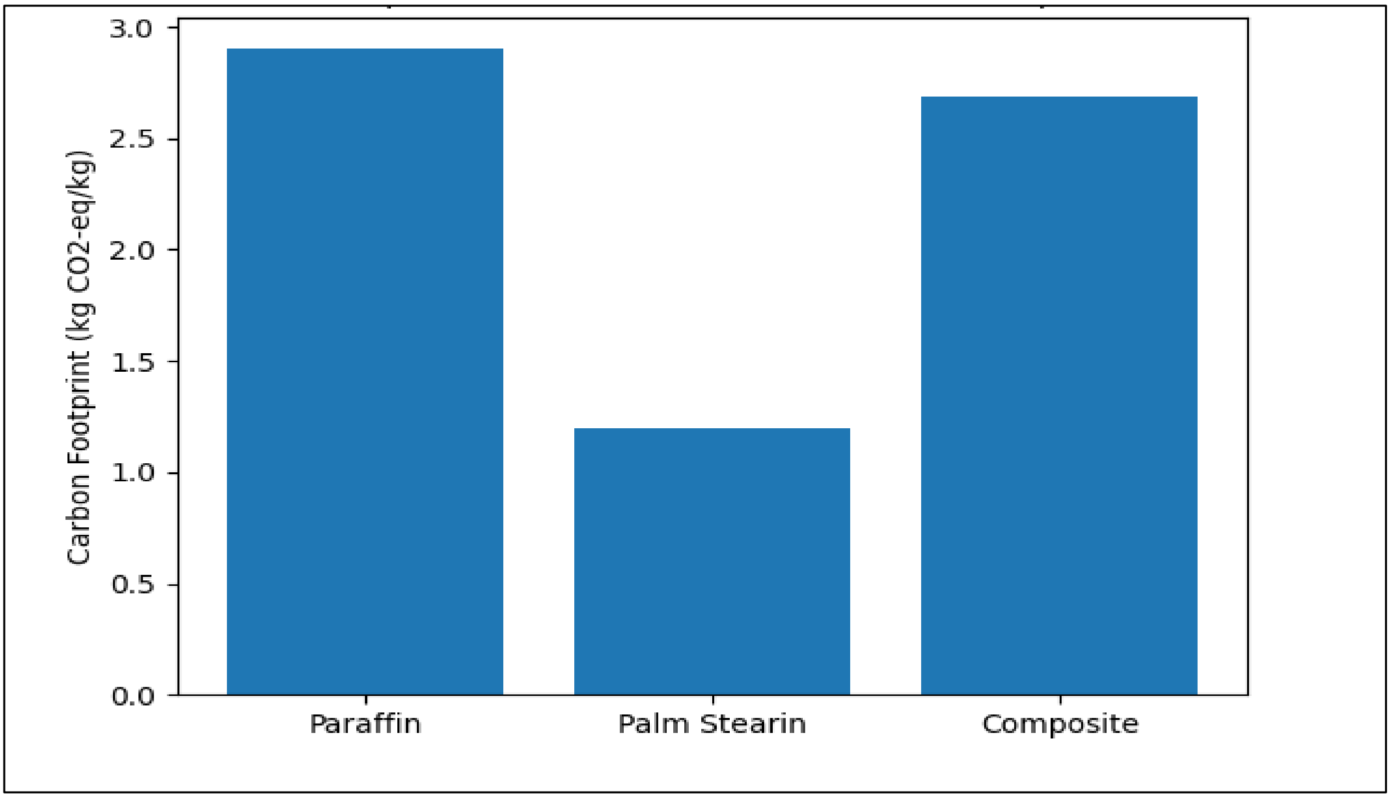

Fig 3 Comparative Cradle-to-Gate Carbon Footprint

The results indicate that partial substitution with palm stearin significantly reduces embodied carbon intensity while maintaining thermophysical performance.

➢ *Discussion*

- *Heating Phase*

The PCM chamber reached 96.1°C after 60 minutes, compared to 87.6°C in the control chamber. Faster heating is attributed to radiative coupling between the bulb and the aluminium-encapsulated PCM slab. No distinct melting plateau was observed during heating due to direct radiant exposure.

- *Cooling Phase*

A clear discharge plateau between 40–42°C was observed from 75 to 120 minutes.

- ✓ Control chamber cooled to 28.8°C.
- ✓ PCM chamber stabilized at 40.5°C.

Temperature retention after 60 minutes of cooling:

$$\Delta T = 11.7^{\circ}C$$

Average reduction in cooling rate: 5%.

Table 6 Composite Properties

Property	Composite (70:30)
Density	0.80 g/cm³
Latent heat	184.5 kJ/kg
Cp (solid)	2030 J/kg·K
Thermal conductivity	0.21 W/m·K
Melting range	50–53°C

Observed discharge plateau slightly lower (40–42°C) due to test configuration.

The composite PCM successfully demonstrated latent heat storage and release behaviour. The cooling plateau confirms phase transition-driven thermal buffering. Radiative heating influenced charging behaviour, masking the melting plateau. Future experiments should optimize PCM positioning to reduce direct radiation exposure.

- *The Composite Provides:*

- ✓ Reduced material cost compared to pure paraffin
- ✓ Improved mechanical stability
- ✓ Partial renewable substitution
- ✓ Effective thermal buffering

Limitations include the absence of Differential Scanning Calorimetry **(**DSC) analysis and limited long-term cycling validation.

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Table 7 Summary of Key Findings

Parameter	Value
Composition ratio	70:30 (Paraffin: palm stearin)
Theoretical latent heat	184.5 kj/kg
Total latent heat (1.5kg slab)	276.75 kj/kg
Observed phase change release	40 -42°C (cooling)
Temperature retention after 1hr cooling	+11.7 vs control
Thermal energy storage	Confirmed via latent heat release

IV. CONCLUSION

A 70:30 paraffin wax–palm stearin composite PCM was developed and experimentally validated.

➢ *Key Outcomes:*

- Theoretical latent heat: 184.5 kJ/kg
- Total storage capacity: 276.75 kJ
- Clear latent heat discharge plateau (40-42°C)
- 11.7°C temperature retention advantage
- Successful macro-encapsulation stability
- Indication of that partial substitution of paraffin wax with palm stearin significantly reduces embodied carbon intensity while maintaining thermophysical performance.

The composite shows promise for passive cooling and solar thermal storage applications in tropical climates.

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