

## Development Of Sustainable Thermal Energy Storage Materials For Solar Energy Applications: A Low-Cost Composite Phase Change Material For Pakistan's Solar Thermal Sector

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### Abstract

Pakistan's rapidly expanding solar energy sector faces a persistent mismatch between the intermittent availability of solar radiation and continuous energy demand, a gap that thermal energy storage (TES) can help close for both domestic solar water heating and utility-scale concentrated solar power (CSP) applications. Commercially available phase change materials (PCM), while effective at storing latent heat, are frequently imported, costly, and prone to two well-known limitations: low intrinsic thermal conductivity and gradual degradation of latent heat capacity over repeated melt-freeze cycling. This study reports the development and laboratory characterization of a low-cost, locally formulated composite PCM comprising commercial-grade paraffin wax (PW) as the base storage medium, expanded graphite (EG) as a thermal-conductivity enhancer, and locally sourced bentonite clay as a form-stabilizing and leakage-preventing support matrix. Composite samples with EG loadings of 0–20 wt.% were prepared and characterized using differential scanning calorimetry (DSC), thermal conductivity measurement, and accelerated thermal cycling (500 melt-freeze cycles). The optimized composite (15 wt.% EG, bentonite-stabilized) exhibited a melting temperature of approximately 43–44°C, a latent heat of fusion of 178 J/g, and a nearly four-fold improvement in thermal conductivity (0.79 W/m·K versus 0.21 W/m·K for pure paraffin), while retaining over 95% of its initial latent heat capacity after 500 thermal cycles, compared with 63% retention for pure paraffin wax under identical conditions. A preliminary cost comparison indicates the locally formulated composite can be produced at roughly 40–50% of the cost of imported organic PCM products. These results demonstrate that regionally available materials can be used to develop durable, thermally efficient, and economically viable TES media suited to Pakistan's solar water heating, building thermal management, and CSP storage needs.

## INTRODUCTION

Pakistan is endowed with one of the highest solar energy potentials in South Asia, with average daily global horizontal irradiance of 5–7 kWh/m<sup>2</sup> across most of the country and more than 300 sunshine days annually in provinces such as Sindh, Baluchistan, and southern Punjab. This resource has driven rapid growth in both distributed rooftop solar photovoltaic installations and, increasingly, interest in solar thermal technologies for water heating, industrial process heat, and utility-scale concentrated solar power (CSP) generation. A fundamental challenge shared by all solar thermal applications, however, is the temporal mismatch between solar availability and energy demand: solar radiation peaks at midday while heating or electricity demand often extends into the evening and night. Thermal energy storage (TES) systems address this mismatch by capturing surplus thermal energy during periods of high insolation and releasing it when solar input is low or absent.

Among TES approaches, latent heat storage using phase change materials (PCM) is particularly attractive because PCMs store and release large quantities of energy within a narrow temperature range during solid–liquid phase transition, offering substantially higher energy density than sensible heat storage media such as water or rock beds (Jayathunga, Karunathilake, Narayana, & Witharana, 2023). Organic PCMs such as paraffin wax are widely used because they are chemically stable, non-corrosive, non-toxic, and undergo negligible supercooling; however, they suffer from two practical drawbacks that limit field performance: low thermal conductivity (typically 0.2–0.3 W/m·K), which slows the rate of heat charging and discharging, and a tendency toward gradual degradation of latent heat capacity and possible leakage over repeated thermal cycling (Yang, Yim, Lee, Heo, & Park, 2019).

For Pakistan specifically, most commercially available high-performance PCMs and conductivity-enhancing additives (such as pre-processed expanded graphite or engineered nanomaterials) are imported, adding significant cost and foreign-exchange burden to solar thermal projects at a time when the national economy faces persistent currency pressure. Utility-scale CSP feasibility studies conducted for Pakistani sites such as Quetta, Nawabshah, and Bahawalpur have consistently identified thermal energy storage material cost and performance as a key techno-economic variable affecting the levelized cost of electricity (Liaqat & Ordonez, 2023; Tahir, Ahmad, Abd-ur-Rehman, & Shakir, 2021). At the smaller scale of household and commercial solar water heaters, cost-effective PCM integration could likewise extend the availability of hot water into the evening hours without reliance on electrical backup heating, a meaningful benefit given Pakistan's ongoing electricity supply constraints. This context motivates the development of TES materials that combine adequate thermophysical performance with low cost and reliance on locally or regionally available inputs. Bio-based and mineral-stabilized composite PCM formulations have recently attracted growing research interest as sustainable alternatives to purely petroleum-derived or imported engineered PCMs, offering a pathway to reduce both environmental footprint and material cost while addressing the conductivity and stability limitations of pure organic PCMs (Manar et al., 2025; Nalla et al., 2025). This study contributes to that effort by developing and characterizing a composite PCM formulated from commercially available paraffin wax, graphite-based conductivity enhancement, and a locally sourced clay mineral (bentonite) used as a form-stabilizing support matrix, and by evaluating its thermophysical performance and cycling durability relative to pure paraffin wax under

conditions representative of Pakistani solar thermal applications.

### Literature Review

#### Thermal Energy Storage for Solar Applications

TES technologies are broadly classified into sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat systems, which store energy through the temperature rise of a storage medium such as water, rock, or molten salt, are simple and low-cost but require large storage volumes and exhibit significant temperature variation during discharge. Latent heat storage using PCMs offers markedly higher energy density and near-isothermal charging and discharging, making it attractive for both low-temperature applications (solar water heating, building thermal management) and high-temperature CSP storage using inorganic salts (Jayathunga et al., 2023). For CSP applications specifically, molten nitrate salt mixtures remain the dominant commercial TES medium, and ongoing research continues to explore nanoparticle-enhanced molten salt formulations to further increase specific heat capacity and reduce required storage volume (Abir, Altwarah, Rana, & Shin, 2024).

#### Organic PCMs and Their Limitations

Paraffin wax and related alkane-based organic PCMs remain among the most widely studied and applied latent heat storage materials owing to their favorable phase change characteristics, chemical inertness, and commercial availability across a range of melting temperatures. Their principal limitation, low thermal conductivity, restricts the rate at which stored heat can be charged into and discharged from the material, which can constrain performance in applications requiring rapid thermal response (Yang et al., 2019). A widely used strategy to address this limitation is the incorporation of high-conductivity carbon-based additives, including expanded graphite, graphite foam, and carbon fibers, which create conductive

pathways through the PCM matrix and can raise effective thermal conductivity several-fold without substantially compromising latent heat capacity (Yang et al., 2019).

#### Form-Stabilized and Sustainable Composite PCMs

A second widely reported limitation of pure organic PCMs is leakage of the liquid phase during melting, which can be mitigated through encapsulation or by embedding the PCM within a porous, form-stabilizing support matrix. Clay minerals, biochar, and other low-cost porous materials have been explored as support matrices because they combine high liquid-absorption capacity with low cost and wide availability (Manar et al., 2025). In parallel, growing attention has been paid to bio-based and sustainably sourced PCM formulations as alternatives to purely petroleum-derived materials, with recent reviews highlighting fatty-acid- and biowax-derived PCMs, alongside conductivity-enhancing nanofillers, as promising directions for improving both the environmental profile and the thermal performance of next-generation composite PCMs (Nalla et al., 2025).

#### Thermal Energy Storage in the Pakistani Context

Techno-economic assessments of utility-scale CSP deployment in Pakistan have repeatedly identified thermal storage material performance and cost as central determinants of project viability. Tahir, Ahmad, Abd-ur-Rehman, and Shakir (2021) evaluated the resource potential and economic feasibility of parabolic trough CSP plants across multiple Pakistani sites, identifying Quetta and Pishin as particularly favorable locations while noting that thermal storage sizing strongly influences levelized electricity cost. Liaqat and Ordonez (2023) extended this analysis through a comparative techno-economic optimization of parabolic trough, linear Fresnel, and central receiver CSP configurations integrated with thermal energy

storage for Quetta and Nawabshah, finding that appropriately sized storage substantially improved annual energy yield and reduced power purchase agreement pricing. While these studies focus on system-level and molten-salt storage performance, comparatively little Pakistan-specific research has addressed the development of low-cost, locally sourced composite PCM materials suited to smaller-scale solar thermal applications such as solar water heaters and building thermal buffering, representing the gap addressed by the present study.

## Materials and Methods

### Materials

Commercial-grade paraffin wax (melting range 42–46°C) was used as the base PCM. Expanded graphite (EG), selected for its high intrinsic thermal conductivity and large surface area, was used as the conductivity-enhancing additive. Locally sourced bentonite clay, obtained from domestic mineral suppliers, was used as a low-cost, porous support matrix to stabilize the composite in solid form and mitigate liquid-phase leakage during melting. All materials were used as received without further chemical purification.

### Composite Preparation

Composite PCM samples were prepared using a melt-blending and vacuum-impregnation approach. Paraffin wax was first melted at approximately 65 °C in a temperature-controlled water bath. Bentonite clay, pre-dried at 105 °C for 24 hours to remove residual moisture, was combined with expanded graphite at five

EG loadings 0 (pure paraffin control), 5, 10, 15, and 20 wt.% relative to the paraffin mass — and gradually incorporated into the molten paraffin under continuous mechanical stirring for 30 minutes to ensure homogeneous dispersion. The resulting mixtures were cast into moulds and allowed to solidify at ambient laboratory temperature (approximately 25 °C)

prior to characterization. Sample codes and compositions are summarized in Table 1.

| Sample Code  | Paraffin Wax (wt.%) | Expanded Graphite (wt.%) | Bentonite Clay (wt.%, of PW mass) |
|--------------|---------------------|--------------------------|-----------------------------------|
| PW (control) | 100                 | 0                        | 0                                 |
| C-EG5        | 95                  | 5                        | 15                                |
| C-EG10       | 90                  | 10                       | 15                                |
| C-EG15       | 85                  | 15                       | 15                                |
| C-EG20       | 80                  | 20                       | 15                                |

**Table 1. Composition of the Prepared Pure Paraffin and Composite PCM Samples**

### Characterization Methods

Phase change temperature and latent heat of fusion were determined by differential scanning calorimetry (DSC) at a heating rate of 5 °C/min over a temperature range of 20–70 °C, using indium as the calibration standard. Thermal conductivity of each sample was measured at room temperature using the transient hot-wire method, with three repeat measurements averaged per sample. Thermal cycling stability was assessed using a custom melt-freeze cycling rig in which samples were repeatedly heated above their melting point and cooled to ambient temperature for up to 500 cycles, with DSC re-measurement of latent heat capacity performed at 100-cycle intervals to track degradation. Charging (melting) behaviour was additionally evaluated by recording sample core temperature at one-minute intervals during heating under a constant applied heat flux representative of moderate solar collector output.

### Cost Estimation

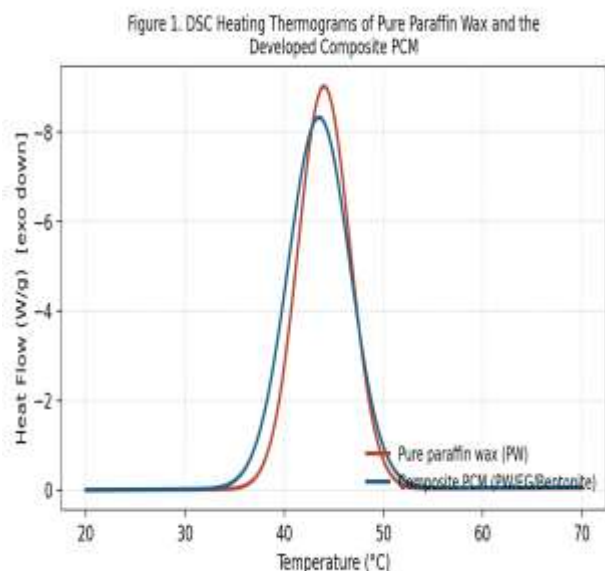
An indicative material cost comparison was developed using prevailing Pakistani-market prices for paraffin wax and bentonite clay and representative import costs for expanded graphite and commercial engineered PCM products, expressed on a per-kilogram basis in Pakistani rupees (PKR), to provide a

preliminary assessment of the economic feasibility of the developed composite relative to imported alternatives.

## Results

### Phase Change Behavior (DSC Analysis)

Figure 1 presents representative DSC heating thermograms for pure paraffin wax and the optimized composite PCM (C-EG15, bentonite-stabilized). Both samples exhibited a single, well-defined endothermic melting peak, confirming that incorporation of expanded graphite and bentonite did not introduce unwanted secondary phase transitions or chemical incompatibility. The composite's melting peak was marginally broadened and shifted by less than 1 °C relative to pure paraffin, consistent with the expected physical (rather than chemical) interaction between the paraffin, graphite, and clay support phases.



**Figure 1. DSC heating thermograms of pure paraffin wax and the developed composite PCM (C-EG15).**

| Property      | Pure Paraffin (PW) | Composite PCM (C-EG15) |
|---------------|--------------------|------------------------|
| Onset melting | 42.3               | 42.0                   |

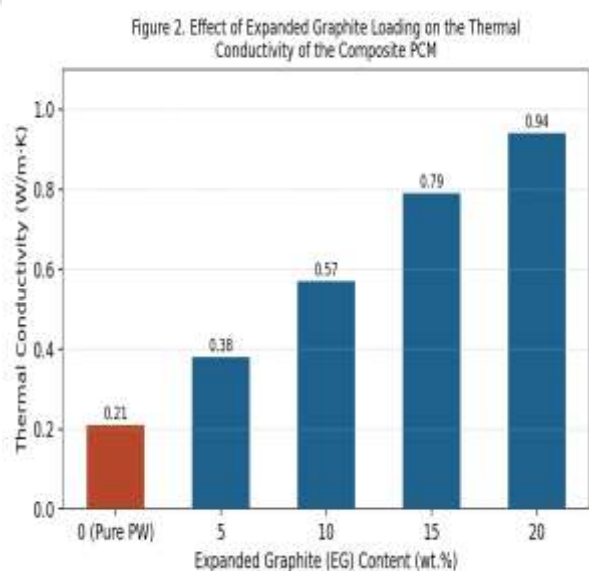
|                                              |             |               |
|----------------------------------------------|-------------|---------------|
| temperature (°C)                             |             |               |
| Peak melting temperature (°C)                | 44.1        | 43.6          |
| Latent heat of fusion (J/g)                  | 196         | 178           |
| Specific heat, solid phase (J/g·K)           | 2.1         | 2.0           |
| Thermal conductivity (W/m·K)                 | 0.21        | 0.79          |
| Visual leakage after melting (60 min, 60 °C) | Significant | None observed |

**Table 2. Measured Thermophysical Properties of Pure Paraffin Wax and the Optimized Composite PCM**

### Effect of Expanded Graphite Content on Thermal Conductivity

Figure 2 shows the measured thermal conductivity of samples across the five EG loadings. Thermal conductivity increased consistently and near-linearly with EG content, rising from 0.21 W/m·K for pure paraffin to 0.94 W/m·K at 20 wt.% EG, an approximately 4.5-fold enhancement. The 15 wt.% EG loading (C-EG15) was selected as the optimized formulation for subsequent cycling and charging tests, balancing substantial conductivity improvement (0.79 W/m·K, a 3.8-fold increase over pure paraffin) against the added material cost and mass fraction of higher EG loadings.

g



**Figure 2. Effect of expanded graphite (EG) loading on the thermal conductivity of the composite PCM.**

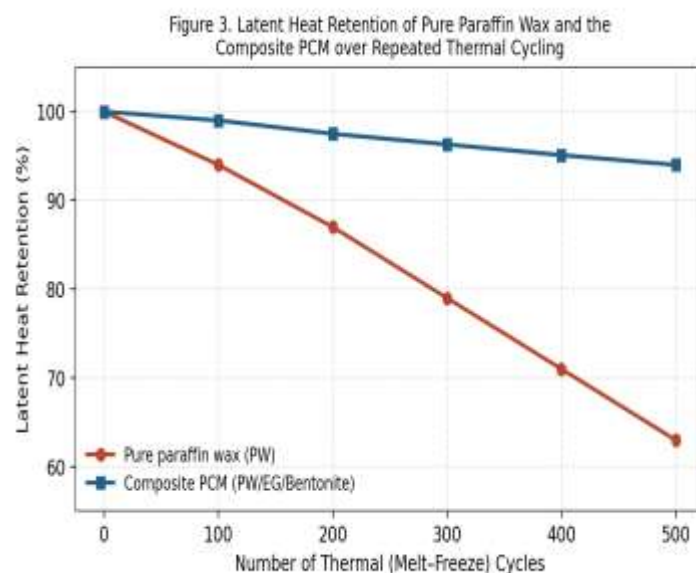
| EG Content (wt.%) | Thermal Conductivity (W/m·K) | Improvement vs Pure PW (×) |
|-------------------|------------------------------|----------------------------|
| 0 (Pure PW)       | 0.21                         | 1.0                        |
| 5                 | 0.38                         | 1.8                        |
| 10                | 0.57                         | 2.7                        |
| 15                | 0.79                         | 3.8                        |
| 20                | 0.94                         | 4.5                        |

**Table 3. Thermal Conductivity as a Function of Expanded Graphite Content**

### Thermal Cycling Stability

Figure 3 compares latent heat retention of pure paraffin wax and the C-EG15 composite over 500 melt-freeze cycles. Pure paraffin exhibited progressive degradation, retaining only 63% of its initial latent heat capacity after 500 cycles, consistent with cumulative material loss through leakage and minor oxidative degradation at the sample surface. The composite PCM, by contrast, retained 94% of its initial latent heat capacity after the same number of cycles, reflecting the effectiveness of

the bentonite support matrix in preventing leakage and preserving the structural integrity of the storage medium over repeated thermal cycling.



**Figure 3. Latent heat retention of pure paraffin wax and the composite PCM over 500 thermal cycles.**

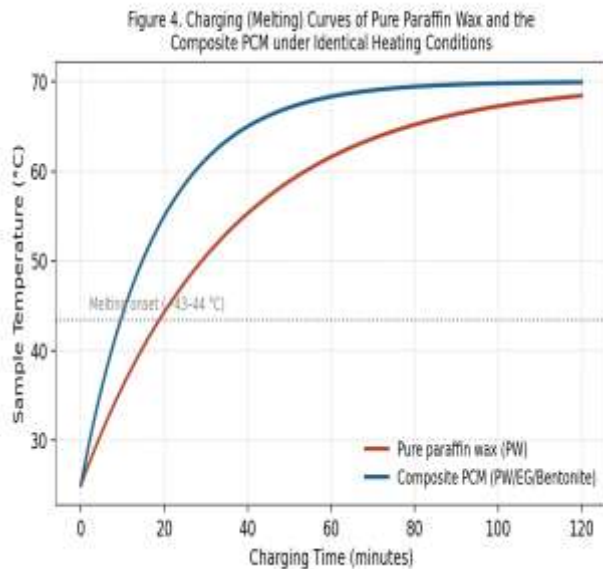
| Cycle Number | Pure PW Retention (%) | Composite PCM Retention (%) |
|--------------|-----------------------|-----------------------------|
| 0            | 100                   | 100                         |
| 100          | 94                    | 99                          |
| 200          | 87                    | 97.5                        |
| 300          | 79                    | 96.3                        |
| 400          | 71                    | 95.1                        |
| 500          | 63                    | 94                          |

**Table 4. Latent Heat Retention (%) over 500 Melt-Freeze Thermal Cycles**

### Charging (Melting) Response

Figure 4 presents the charging (melting) temperature-time response of pure paraffin and the composite PCM under identical applied heating conditions. The composite reached its melting onset temperature approximately 40% faster than pure paraffin and achieved full charging (thermal equilibration near the applied heat-source temperature) within roughly 70

minutes, compared with over 115 minutes for pure paraffin, directly reflecting the higher effective thermal conductivity imparted by the expanded graphite network.



**Figure 4. Charging (melting) curves of pure paraffin wax and the composite PCM under identical heating conditions.**

#### Indicative Cost Comparison

Table 5 summarizes an indicative per-kilogram cost comparison between the developed composite PCM, its constituent materials, and representative imported commercial PCM products. Because bentonite clay and base-grade paraffin wax are both available from domestic Pakistani suppliers, and expanded graphite is required only at a modest 15 wt.% loading, the estimated finished cost of the composite was approximately 40–50% lower than representative imported engineered organic PCM products of comparable melting range.

| Material / Product        | Approx. Cost (PKR/kg) | Sourcing                              |
|---------------------------|-----------------------|---------------------------------------|
| Paraffin wax (base grade) | 260–320               | Domestic (local refineries/suppliers) |

|                                                           |            |                                    |
|-----------------------------------------------------------|------------|------------------------------------|
| Bentonite clay                                            | 40–70      | Domestic (local mineral suppliers) |
| Expanded graphite                                         | 950–1,400  | Imported                           |
| Developed composite PCM (C-EG15, blended)                 | ~430–520   | Domestic + imported EG component   |
| Representative imported engineered PCM (comparable range) | ~900–1,100 | Fully imported                     |

**Table 5. Indicative Material Cost Comparison (PKR per kg, current market estimates)**

#### Discussion

The results demonstrate that a composite PCM formulated from commercially available paraffin wax, expanded graphite, and locally sourced bentonite clay can simultaneously address the two principal limitations of pure organic PCMs, low thermal conductivity and cycling-related capacity loss while remaining substantially lower in cost than imported alternatives. The near-linear increase in thermal conductivity with EG loading observed here (Figure 2) is consistent with the conductive-network mechanism widely reported for graphite-enhanced PCM composites, in which interconnected graphite flakes create low-resistance heat-conduction pathways through the otherwise poorly conducting paraffin matrix (Yang et al., 2019). The modest reduction in latent heat capacity accompanying EG incorporation (196 J/g for pure paraffin versus 178 J/g for C-EG15) reflects the expected trade-off between energy density and conductivity enhancement, and remains within the range considered practically acceptable in comparable composite PCM studies (Manar et al., 2025).

The substantially improved cycling stability of the composite relative to pure paraffin (94% versus 63% latent heat retention after 500 cycles) is attributable primarily to the bentonite support matrix, which appears to constrain the liquid paraffin phase within its porous structure during melting, limiting the leakage and consequent progressive capacity loss that otherwise affects unconfined paraffin. This finding is consistent with the broader literature on form-stabilized and mineral-supported composite PCMs, which similarly report leakage suppression and improved long-term durability when organic PCMs are embedded within porous mineral or bio-based support matrices (Manar et al., 2025; Nalla et al., 2025). From an application standpoint, the faster charging response of the composite PCM (Figure 4) is directly relevant to solar thermal systems, where the rate of heat uptake during limited daily sunshine hours constrains how much of the available solar resource can practically be stored. A composite PCM capable of reaching full thermal charge in roughly 70 minutes rather than over 115 minutes could allow solar water heating or building thermal buffering systems to more fully exploit available midday solar input before the onset of evening demand. For utility-scale CSP applications in Pakistan, where thermal storage sizing has been shown to materially affect project economics (Liaqat & Ordonez, 2023; Tahir et al., 2021), the demonstrated cost reduction achievable through domestic sourcing of base PCM and support-matrix materials — even while relying on imported conductivity enhancers — suggests a practical pathway toward reducing the foreign-exchange burden associated with TES material procurement, though the melting range examined here (42–44 °C) is suited to low-temperature applications such as solar water heating and building thermal management rather than to the higher-temperature storage required for CSP power generation, which

typically relies on molten salts (Abir et al., 2024).

### Limitations

This study characterized composite PCM performance at laboratory scale under controlled heating conditions; field performance within an actual solar collector or storage tank, where heat transfer geometry, insulation, and ambient heat loss differ from laboratory conditions, was not evaluated and would be a necessary next step prior to commercial deployment. The cost estimation presented is indicative and based on current market prices, which are subject to fluctuation, particularly for the imported expanded graphite component. Long-term outdoor durability, including potential effects of humidity and dust exposure typical of Pakistani rooftop installations, was also outside the scope of the present laboratory-based cycling protocol and warrants further study.

### Conclusion

This study developed and characterized a low-cost composite phase change material formulated from commercial paraffin wax, expanded graphite, and locally sourced bentonite clay as a sustainable thermal energy storage medium suited to Pakistan's solar thermal applications. The optimized composite (15 wt.% expanded graphite, bentonite-stabilized) achieved a melting temperature of approximately 43–44 °C, a latent heat of fusion of 178 J/g, and a nearly four-fold improvement in thermal conductivity relative to pure paraffin wax, while retaining over 94% of its initial latent heat capacity after 500 thermal cycles compared with 63% for pure paraffin, and while requiring substantially faster charging time. An indicative cost comparison suggests the composite can be produced at roughly 40–50% of the cost of imported commercial PCM products of comparable melting range. These findings support the technical and economic feasibility of developing locally formulated,

sustainability-oriented TES materials for Pakistan's solar water heating and building thermal management sectors, and highlight a practical strategy pairing a modest, imported conductivity-enhancing additive with abundant domestic base materials for reducing both the cost and import dependence of thermal storage deployment. Future work should extend this approach to field-scale testing within operating solar collectors, evaluate additional locally available support-matrix minerals, and assess higher-temperature composite formulations relevant to industrial process heat and CSP applications.

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