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Thermal Property Enhancement and Encapsulation Technologies for Phase Change Materials: A Review of Nanofillers, Porous Scaffolds, and Application-Oriented Strategies

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Abstract. Phase change materials offer high latent heat and isothermal operation, yet their real-world use is consistently blocked by low thermal conduction, melt leakage, and—for inorganic types—subcooling and segregation. Here this paper systematically benchmark three nanofiller families (carbon, metal, and ceramic) and three porous scaffold types (metal foam, carbon skeleton, and ceramic skeleton) in terms of thermal performance enhancement, thermal capacity retention, cycling durability, and economic cost. Carbon fillers give the largest conductivity jumps but consume latent heat; ceramic fillers keep capacity intact with only moderate conduction gains; scaffolds stop leakage effectively but impose distinct penalties in weight, strength, or manufacturing complexity. This paper also identify five obstacles that prevent these composites from reaching industry, suggest selection rules for different applications, and outline priorities for affordable synthesis, durable encapsulation, and system-level optimization.

Keywords: Phase changing materials, thermal conductivity enhancement, porous scaffolds, nanofillers, encapsulation technologies

1. Introduction

Renewable energy is intermittent. This intermittency demands storage, and thermal storage using PCMs has drawn steady attention because it packs more energy per volume than sensible storage and runs at nearly constant temperature [1, 2]. Applications range from battery thermal management and solar collectors to building envelopes and electronic chip heat sinks [3, 4].

Organic PCMs exhibit low thermal conductivity, typically 0.15-0.35 W/m·K, and suffer from melt leakage upon melting [5]. Inorganics store more heat but bring subcooling, phase separation, and corrosion (Table 1) [6]. Two broad modification strategies dominate the literature: incorporating conductive nanofillers to build heat-transfer pathways, and confining PCMs in porous scaffolds that immobilize molten PCMs via capillary action [7, 8].

It is difficult to find clear cross-category comparisons assessing filler performance in balancing conduction and capacity, scaffold stability across 1000 cycles, and the role of cost in

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decision-making. Most reviews focus on one material family, leaving these cross-cutting questions unaddressed [9, 10]. This review attempts to fill that gap with direct benchmarking and practical guidelines.

Table 1. Comparison of thermophysical properties between pure organic and inorganic PCMs

Property	Organic PCM	Inorganic PCM
Thermal conductivity	Very low	Moderate
Latent heat	Moderate	High
Leakage	Yes	Yes
Subcooling	No	Yes
Phase separation	No	Yes
Corrosion	Low	High
Cost	Moderate	Low

2. Nanofiller-modified composite PCMs

2.1. Carbon-based nanofillers

Graphene, nanotubes, expanded graphite—these are the most heavily researched additives [5]. Their intrinsic conductivity is exceptional, they are light, and their sheet or tube shapes can form connected networks at modest loadings. In principle, these characteristics perfectly match the requirements of organic PCMs [11].

In practical scenarios, however, the performance is far from ideal. Loadings beyond a few percent cause agglomeration. The carbon surfaces are hydrophobic and resist wetting, so each filler–matrix interface adds Kapitsa resistance that offsets part of the conductivity gain [12]. More importantly, the added filler occupies the volume of PCM: a 10 wt% addition typically reduces latent heat by 30–40% [6]. Viscosity climbs, processing gets difficult, and graphene/CNT costs remain prohibitive for most real projects [9].

Surface functionalization, hybrid fillers, and surfactants help around the edges [10]. Nevertheless, the core trade-off — thermal conductivity enhancement against latent heat capacity loss — has not been fundamentally resolved. This is not merely a materials-chemistry challenge but an inherent physical limitation for two-phase composites.

2.2. Metal-based nanofillers

Copper, aluminum, and silver are metallic materials that transfer heat via free mobile electrons, endowing them with superior heat-transfer performance compared with phonon-conductive carbon-based fillers [11]. Intrinsic conductivities are high: ~400 W/m·K for Cu, ~430 for Ag. Reported enhancements range from 80% to 250% depending on particle size, shape, and loading [3].

At filler loadings above 1 wt%, numerous studies have observed more than 50% degradation in thermal storage capacity after 50 phase-transition cycles At >1 wt% loading, many studies report >50% capacity degradation within 50 cycles [7].The oxidation of Cu and Al generates surface oxide layers with low thermal conductivity; Ag is too expensive for serious consideration at scale [12].

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Coatings and nanowire geometries can slow oxidation and reduce percolation thresholds. They do not solve the settling problem, because gravity does not care about particle coatings [5]. For static systems with short duty cycles, metals can work. For anything that moves or cycles repeatedly, they become a reliability risk [9].

2.3. Ceramic-based nanofillers

Al_2O_3, SiC, and hexagonal boron nitride represent electrically insulating and chemically inert filler candidates. Heat transfer is phonon-mediated. hBN, with its layered structure, shows in-plane conductivity near 400 W/m·K (though through-plane is far lower). In paraffin, hBN gives about 190% enhancement—less than graphene's 344% but still substantial [6].

The real advantage emerges in capacity retention. hBN disperses well and wets the PCM effectively, so latent heat loss stays under 10% at 5 wt% loading—far better than carbons or metals [10]. Ceramics also resist corrosion, insulate electrically, and process without excessive difficulty [11].

The ceiling is real. Above 10 wt% loading, effective conductivity rarely exceeds 2-3 W/m·K. That is simply not enough for applications with heat fluxes above 10 W/cm² [12]. Silane coupling and hybrid carbon-ceramic blends are being explored, but the trade-off between conduction and insulation seems inherent [3].

2.4. Comparison among the three nanofiller types

Table 2 summarizes these key trade-offs. Figure 1 schematically compares the heat-conduction mechanisms for three representative nano-fillers, namely PI, MXene, and etched ZIF-8, within the sphagnum-inspired aerogel system. Carbons deliver the highest conduction but at significant capacity and cost penalties. Metals respond fastest but settle and oxidize. Ceramics retain capacity and insulate but lack the conduction ceiling needed for high-power uses. The choice depends entirely on which constraint dominates the application.

Table 2. Quantitative comparison among carbon-based, metal-based, and ceramic-based nanofillers for PCM modification

Criterion	Carbon-Based	Metal-Based	Ceramic-Based
Maximum k Enhancement	344.1%	150-250%	192.2%
Latent Heat Retention	Poor (15~45% loss)	Poor (20~50% loss)	Best (<10% loss)
Density	Low (Best)	High (Worst)	Moderate
Cost Level	High-Very High	Moderate-Very High	Low-High
Electrical Insulation	No	No	Yes (Best)
Corrosion Resistance	Good	Poor-Moderate	Excellent
Dispersion Difficulty	High (Worst)	Moderate	Low (Best)
Cycling Stability	Moderate	Poor (Settling)	Good
Multifunctionality	Best	Moderate	Poor

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Figure 1. Comparison of the heat conduction mechanisms of three types of nano-fillers

3. Porous scaffold-stabilized PCMs

3.1. Metal foam scaffolds

Copper, aluminum, and nickel foams are essentially metal sponges with 90-98% void space [13]. They transfer heat via both electrons and phonons, immobilize molten PCM through capillary suction, and offer mechanical support. Reported conductivity gains run 100-300%. Copper foam at 95% porosity with paraffin gives about 210% enhancement, with leakage below 1% after 100 cycles [14].

Such performance metrics appear promising for battery packs, in which both heat spreading capability and structural performance are critical. But the downsides are substantial. Five volume percent of copper foam adds roughly 40% to the composite weight [13]. The foam oxidizes and corrodes, especially with salt hydrates. Its specific surface area is modest, so interfacial resistance is non-negligible. Fabrication is energy-intensive [14].

Coatings and pore-structure engineering are being investigated. However, there remain doubts regarding whether such approaches can address the inherent drawbacks of excessive weight and corrosion susceptibility [15]. Metal foams will likely remain limited to applications where those penalties are acceptable—vehicle batteries, perhaps, but not buildings or portable devices [13].

3.2. Carbon-based porous scaffolds

Carbon-based porous scaffolds, including expanded graphite and carbon aerogels, follow a different design philosophy. They feature ultra-low density, high porosity, and large specific surface areas [16]. They wick PCM into their pores while the carbon network enhances conduction and enables photothermal or electrothermal conversion [17].

Expanded graphite–paraffin gives 80-150% enhancement; graphene aerogels push that to 150-200% at densities of 10-50 mg/cm³ [16]. Leakage stays under 2% over 200 cycles. The attractions are obvious: light weight, multifunctional potential.

The problems are equally obvious. Fabrication requires sol-gel, supercritical drying, and high-temperature carbonization—none of which scales cheaply [18]. Mechanical strength is poor;

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compressive moduli often below 1 MPa. Cost is prohibitive: graphene aerogel production is estimated above $500/L [17].

Biomass precursors and reinforcing phases are being explored [19]. The deeper issue is structural: high porosity and low density are inherently incompatible with mechanical robustness. These materials will find niche uses in lightweight applications but are unlikely to become the backbone of industrial thermal storage [18].

3.3. Ceramic porous scaffolds

Silicon carbide, diatomite, silica, and expanded perlite can construct porous networks with multiscale pore structures [20]. They confine PCMs by capillary action, conduct heat through phonons (modestly), and offer electrical insulation and chemical resistance [21].

SiC foam improves conductivity by 50-100%; diatomite by 30-60%; perlite by less [20]. Hydrophilic surfaces keep latent heat loss small, and leakage stays below 3% after 100 cycles. Costs are low, thermal stability is high, and corrosion resistance is excellent [21]. These are the materials for stationary systems—industrial waste heat recovery, building envelopes—where longevity matters more than peak performance [22].

The limitation is conduction: effective k rarely exceeds 1-2 W/m·K. That will not handle heat fluxes above 10 W/cm² [20]. Porous ceramics are also mechanically fragile. Surface treatments and carbon hybrids are being studied, but the fundamental trade-off between porosity, conduction, and mechanical strength persists [21].

3.4. Cross-comparison of porous scaffolds

Table 3 and figure 2 summarize these key selection criteria. Metal foams give the best conduction and strength but are heavy and corrode. Carbon scaffolds are light and multifunctional but expensive and weak. Ceramics offer stability and low cost with the lowest thermal gains. None does everything; each serves a distinct set of applications.

Table 3. Quantitative comparison among metal foam, carbon-based, and ceramic-based porous scaffolds

Criterion	Metal Foam	Carbon Scaffold	Ceramic Scaffold
K Enhancement	Highest	Moderate-High	Lowest
Leakage Prevention	Excellent	Good-Excellent	Good
Lightweight	No (heavy)	Yes	Moderate
High-Temperature Resistance	Poor-Moderate	Good	Excellent
Mechanical Strength	Highest	Poor-Moderate	Low-Moderate
Corrosion Resistance	Poor	Good	Excellent
Electrical Insulation	No	No	Yes
Material Cost	Moderate-High	High-Very High	Low-Moderate
Scalability	High	Low-Moderate	High
Multifunctionality	No	Yes	No
Best Application	EV batteries	Lightweight/multifunctional	Stationary

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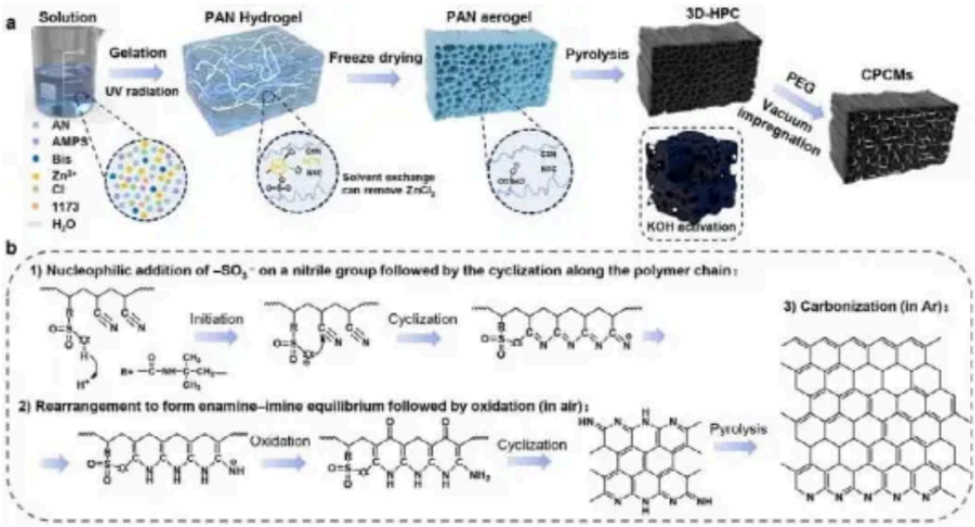


Figure 2. Physical model of capillary force leakage prevention for porous scaffolds

4. Application-oriented performance

Different application scenarios call for tailored solutions. For EV battery thermal management, expanded-graphite-paraffin composites exhibit satisfactory performance: they facilitate heat spreading and maintain temperature uniformity, reducing the peak temperature rise by approximately 30 % [14]. The weight penalty is acceptable in this context.

For building energy-saving applications, ceramic-supported organic PCMs represent a highly competitive option. They are cheap, last a long time, and reduce indoor temperature swings by 3-5°C. That translates directly into HVAC energy savings [22].

For concentrated solar power at high temperature, metal foam–molten salt combinations offer a reasonable balance of corrosion resistance and thermal stability, improving overall efficiency by 15-20% [15]. Electronics cooling favors microencapsulated slurries because of their fast response and long cycle life [23]. Cold-chain logistics rely on microencapsulated organics to maintain steady low temperatures for up to 48 hours [24].

A general conclusion can be drawn: there exists no one-size-fits-all solution. Each application imposes a different set of constraints—weight, cost, power density, cycle life, temperature range, safety—and the modification strategy must be tailored accordingly [25].

5. Challenges and future directions

Several critical challenges still remain unresolved. This review highlights five of them that are deemed most practically significant.

Conduction versus capacity. This is the fundamental conflict. Higher filler loading improves conduction but displaces PCM and reduces latent heat [5]. Hybrid fillers and hierarchical structures soften the trade-off but do not eliminate it. What the field needs is a genuinely multifunctional architecture that handles thermal transport, storage, and containment simultaneously [6].

Cycling durability. Most studies report 100 or 200 cycles and call it progress. Real systems need thousands. Fillers settle, scaffolds crack, shells rupture [7]. Surface functionalization and flexible designs help incrementally. Self-healing materials and high-durability coatings are the longer-term answer [9].

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Subcooling and segregation in salt hydrates. These are old problems that have resisted simple fixes. Nano-nucleating agents and microencapsulation show some effect [10]. What would be transformative is a single surface-engineered additive that addresses both issues at once [11].

Material cost. Graphene, silver, and aerogels do not belong to low-cost commodity materials. It is impractical to construct building-scale thermal storage systems using aerogel materials costing $500/L [17]. Biomass-derived carbon materials and natural mineral-based scaffolds serve as promising alternatives [19]. Scalable green synthesis routes utilizing industrial byproducts deserve high-priority research attention [26].

High-temperature corrosion and system-level coupling. Molten salts corrode metals above 300°C. Ceramic coatings and corrosion-resistant alloys are partial solutions [15]. The bigger challenge is integration: PCM storage does not operate in isolation. Multi-physics simulation of PCM-PV-battery-HVAC systems is needed to optimize overall performance [26].

6. Conclusion

This paper have benchmarked three nanofiller families and three scaffold types on thermal enhancement, capacity retention, durability, and cost. Carbons give the largest conductivity gains but exact substantial penalties in latent heat. Metals respond fast but settle, oxidize, and add weight. Ceramics preserve capacity and insulate well but deliver only moderate conduction improvement. Scaffolds eliminate leakage effectively: metal foams offer strength and conduction but are heavy and corrosion-prone; carbon scaffolds are light and multifunctional but expensive and fragile; ceramic scaffolds are stable and affordable but poorly conductive.

For practical selection: carbons for lightweight multifunctional devices; metals when rapid response outweighs weight; ceramics where insulation and corrosion resistance are critical. Metal foams suit EV batteries; carbon scaffolds fit lightweight solar and flexible electronics; ceramic scaffolds are the natural choice for stationary high-temperature storage.

Five major bottlenecks still remain: the intrinsic trade-off between thermal conductivity and latent-heat capacity, cycling performance instability, supercooling, material cost, and high-temperature corrosion. Future research should prioritize low-cost synthesis routes, high-durability encapsulation technologies, and system-level optimization supported by multi-physics simulation. Closing the gap between laboratory-scale progress and practical industrial deployment relies on all the above-mentioned strategies.

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