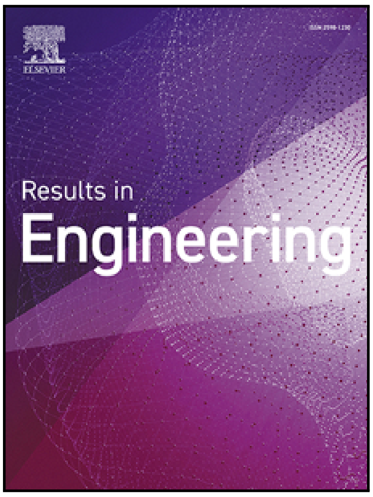

# Bio-Based Phase-Change Materials for Thermal Energy Storage: Recent Advances, Challenges, and Outlook

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## Highlights

- Discusses material design, encapsulation techniques, and nanomaterial-enhanced conductivity.
- Evaluates thermal, mechanical, and environmental performance parameters.
- Highlights lifecycle assessment, biodegradability, and techno-economic feasibility.
- Proposes a strategic roadmap for commercialization and large-scale deployment.

# Bio-Based Phase-Change Materials for Thermal Energy Storage: Recent Advances, Challenges, and Outlook

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## Abstract

This review systematically examines recent advances (2022–2025) in bio-based phase change materials (PCMs) for thermal energy storage (TES). Emphasis is placed on renewable PCMs derived from fatty acids, plant oils, and biowaxes, highlighting progress in synthesis strategies, structural modifications, performance enhancement, and techno-environmental sustainability. Nanofiller incorporation, including graphene nanoplatelets and boron nitride, has improved thermal conductivity by up to 400%, while advanced encapsulation techniques ensure over 95% enthalpy retention across 1000 cycles. Life cycle assessments (LCAs) reveal 40–60% lower $CO_2$-equivalent emissions compared to paraffin-based PCMs, underscoring environmental benefits. Application-driven case studies demonstrate significant impacts: energy savings of up to 25% in HVAC-integrated building envelopes, peak temperature reductions of 10–15 °C in battery thermal management, and prolonged heat retention of 4–5 hours in solar thermal systems. Nonetheless, challenges remain in oxidation stability, long-term durability, leakage mitigation, scalability, and cost competitiveness. The review distinguishes incremental improvements from transformative innovations, contrasts bio-based with petrochemical PCMs, and identifies hybrid TES systems as emerging solutions. A commercialization-focused roadmap aligns challenges with industry initiatives and technology readiness levels, offering short-, medium-, and long-term strategies. Overall, this work provides an evidence-based synthesis to accelerate the transition of bio-PCMs from laboratory research to scalable, low-carbon TES applications.

**Keywords**: Bio-Based Phase Change Materials (PCMs); Thermal Energy Storage;Micro/Nano-Encapsulation; Thermal Conductivity Enhancement; Lifecycle Assessment

## 1. Introduction

Global energy consumption is expected to increase by 25–30% by 2045, driven by demographic growth, industrial expansion, and improvements in living standards [1]. The attainment of profound decarbonization within these parameters necessitates the swift implementation of renewable energy technologies, particularly those harnessing solar and wind energy resources. Nonetheless, the intrinsic intermittency of these energy sources necessitates the development of effective and dependable energy storage systems to ensure a stable supply [2]. Among the myriad of existing storage methodologies, TES, notably latent heat storage utilizing PCMs, presents several distinct advantages, including elevated energy density, near-isothermal operation, and versatility across various sectors such as building energy management, solar thermal applications, and industrial waste heat recovery [3–5].

Traditional PCMs, such as paraffin waxes, polyethylene glycol (PEG), and salt hydrates, are widely used due to their adjustable melting points and substantial latent heats (150–250 J/g) [6]. However, these materials are impeded by low thermal conductivity (<0.3 W/m·K), flammability, environmental persistence, and, specifically in the case of salt hydrates, phenomena such as phase segregation and supercooling, which constrain long-term operational stability [7]. These limitations, in conjunction with escalating sustainability demands, have heightened interest in bio-based PCMs sourced from fatty acids, vegetable oils, animal fats, and biowaxes. Such materials are renewable, biodegradable, and non-toxic, providing latent heat values ranging from 140 to 230 J/g and phase transition temperatures spanning 18 to 65 °C. LCA reveals carbon footprints that are 40–60% lower than those of petroleum-derived PCMs [8–10].

Despite these benefits, the commercialization of bio-based PCMs faces significant challenges, including low thermal conductivity, vulnerability to leakage during phase transitions, and degradation under extended cycling [11]. Progress in material engineering encompassing micro/nano-encapsulation, polymer matrix incorporation, and the addition of high-conductivity nanofillers such as graphene, boron nitride, and carbon nanotubes has evidenced conductivity enhancements of up to 400% and enthalpy retention surpassing 95% after 1000 cycles [12,13], thereby broadening applicability from building envelopes to battery thermal management solutions, wearable textiles, and hybrid TES systems [14].

Numerous preceding reviews, including those by Okogeri and Stathopoulos (2021) and Mehrizi et al. (2023), have addressed bio-based PCMs, albeit typically within the context of more comprehensive PCM surveys. These prior studies predominantly concentrate on material classification, synthesis methodologies, and performance evaluations, exhibiting limited focus on technology readiness, commercialization strategies, policy influences, and integration within hybrid TES frameworks [6, 9]. The current review is structured as a focused, critical appraisal of bio-based PCMs as a distinct TES category, offering four principal contributions: (i) a technology readiness level (TRL)-based evaluation of commercial viability supported by industrial case studies; (ii) a systematic differentiation between incremental and disruptive innovations; (iii) the amalgamation of LCA and techno-economic assessments; and (iv) a comparative analysis of bio-based PCMs against petroleum-derived alternatives in terms of thermal, mechanical, and ecological performance. By synthesizing recent advancements from 2022–2025 and correlating progress in materials science with AI-assisted design, hybrid system architectures, and commercialization frameworks, this review aspires to function as both a technical reference and a strategic guide for the large-scale, low-carbon implementation of bio-based PCMs.

## 1.2 Methodology

This systematic review employs a narrative synthesis methodology, rather than a formal meta-analysis, due to the considerable heterogeneity in study designs, characterization protocols, and reporting formats prevalent in the existing literature. To ensure transparency and reproducibility, the review adhered to principles similar to those outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. It is explicitly noted that no formal statistical synthesis was performed; all quantitative values reported were directly sourced from primary studies. Baseline values and associated uncertainty ranges (±) are presented wherever such information is accessible.

Publications dated from January 2015 to February 2025 were systematically retrieved from Scopus, Web of Science, and ScienceDirect utilizing predetermined Boolean search strings.

For Scopus, the search string employed was: TITLE-ABS-KEY ("bio-based phase change material" OR "biodegradable phase change material") AND ("thermal energy storage" OR "latent heat storage") AND (encapsulation OR "thermal conductivity" OR "life cycle assessment"). In the case of Web of Science, the string utilized was: TS= ("bio-based phase change material" OR "biodegradable phase change material") AND TS=("thermal energy storage" OR "latent heat storage") AND TS=(encapsulation OR "thermal conductivity" OR "life cycle assessment"). The identical search terms were applied in ScienceDirect within the Title, Abstract, or Keywords fields.

The initial search yielded 282 records (Scopus: 118, Web of Science: 94, ScienceDirect: 70). Following deduplication using EndNote X9 and manual verification in Microsoft Excel, a total of 250 unique records remained. The screening process, which involved examining titles, abstracts, and keywords, resulted in the exclusion of 65 irrelevant studies, 48 studies lacking experimental or validated techno-environmental data, and 29 publications that were either incomplete or not presented in English.

A comprehensive full-text evaluation of 108 articles was undertaken based on specified inclusion criteria: the provision of experimental or validated techno-environmental data, the reporting of thermal properties including latent heat, melting point, and thermal conductivity, the inclusion of at least one enhancement strategy or application, a minimum of 50 thermal cycles, and a thermal conductivity threshold of ≥ 0.2 W/m·K. Ultimately, 83 studies satisfied these criteria.

The quality of the studies was assessed utilizing a five-point checklist that addressed aspects such as the completeness of reporting, experimental rigor, adherence to established standards, data transparency, and the inclusion of sustainability or LCA analyses. Studies that received a score of 3 or below were excluded from further consideration. The risk of bias was qualitatively assessed based on methodological limitations, the absence of appropriate controls, and selective reporting practices. The workflow pertaining to the selection process is illustrated in Figure 1.

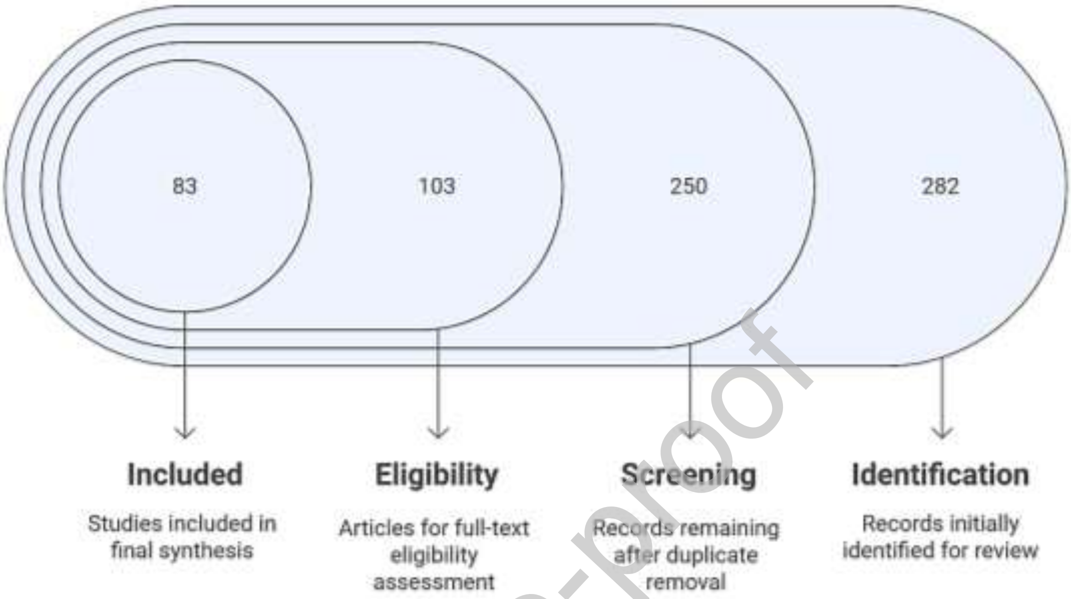

**Figure 1. PRISMA-based methodology for the selection of studies included in the bio-based PCM review**

## 2. Background and Fundamentals

PCMs have emerged as pivotal components in the development of high-performance and compact TES systems, owing to their high energy density and ability to undergo reversible phase transitions. During the solid–liquid phase transition, PCMs absorb and release latent heat, thereby facilitating the effective management of temperature variations, alleviating peak energy demand, and improving the integration of renewable energy sources [15]. This section delineates the core principles of latent heat storage, essential performance indicators for the selection of PCMs, and the unique attributes of bio-based PCMs that render them appealing for sustainable TES applications.

### 2.1 Thermal Energy Storage and PCMs

TES is crucial in decoupling energy supply from demand, particularly in the context of intermittent renewable energy sources, such as solar and wind. Among the three principal TES mechanisms, sensible, latent, and thermochemical latent heat TES (LHTES) provides enhanced volumetric and gravimetric energy densities. In the context of LHTES, PCMs absorb thermal energy during the melting process and release it during solidification, thereby maintaining a nearly constant temperature throughout the phase transition [16]. Conventional PCMs demonstrate latent heats of fusion ranging from 140 to 250 J/g, with melting points specifically tailored to particular applications, ranging from 20 to 60 °C for HVAC and building energy management, and exceeding 150 °C for industrial waste heat recovery. This quasi-isothermal heat exchange is particularly advantageous for sustaining indoor thermal comfort and ensuring the operational stability of temperature-sensitive apparatus [17].

## 2.2 PCM Performance Metrics

Several critical performance parameters determine the appropriateness of a PCM for a specified TES application. The melting temperature must align with the operational range; for instance, capric acid (Tm ≈ 32 °C) is particularly suitable for passive building cooling, whereas stearic acid (Tm ≈ 69 °C) is employed in medium-temperature storage. Bio-based PCMs generally present latent heat capacities ranging from 180 to 230 J/g. The thermal conductivity represents another vital parameter, with the majority of organic PCMs exhibiting values below 0.25 W/m·K, potentially constraining heat transfer efficiency [18]. The incorporation of thermally conductive fillers such as graphene, expanded graphite, or boron nitride nanosheets can enhance conductivity to a range of 0.9 to 1.2 W/m·K, thereby improving both charging and discharging rates. Long-term performance is evaluated through cycling stability, with high-quality PCMs retaining over 90% of their initial enthalpy after 1000 to 1500 cycles [19].

### 2.3 Bio-Based PCMs

Bio-based PCMs, which are sourced from renewable and biodegradable feedstocks, have garnered significant scholarly interest due to their minimal environmental footprint, reduced toxicity, and wide availability. Prominent categories encompass fatty acids (e.g., lauric, palmitic, stearic), vegetable oils (e.g., coconut, soybean, sunflower), and natural waxes (e.g., beeswax, carnauba wax). These materials exhibit adjustable melting ranges spanning from 18 to 65 °C and latent heat capacities that are comparable to those of synthetic PCMs. For instance, lauric acid demonstrates a latent heat of fusion (ΔH) of approximately 211 J/g at a melting temperature (Tm) of around 44 °C. In comparison, palmitic acid exhibits a ΔH of approximately 189 J/g at a Tm of roughly 63 °C. Bio-based PCMs are entirely biodegradable within 90 days under composting conditions and have the potential to reduce their global warming potential (GWP) by up to 70% compared to petroleum-derived paraffins. However, several challenges persist, including low thermal conductivity (less than 0.25 W/m·K), vulnerability to oxidation, variability in batch production, and absorption of moisture [20]. To address these challenges, strategies such as eutectic blending, chemical stabilization, and nanomaterial enhancement have been investigated [21]. Table 1 synthesizes the advantages, constraints, and compromises associated with the principal classes of bio-based PCMs that have been examined.

**Table 1. Strengths, limitations, and trade-offs of major bio-based PCM classes (fatty acids, plant oils, and bio waxes) based on experimental and techno-environmental literature.**

| PCM Class | Strengths | Limitations | Trade-offs / Considerations | Ref |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| **Fatty Acids** | High latent heat (180–220 J/g); sharp melting points; low supercooling; biodegradable | Low thermal conductivity (~0.2 W/m·K); possible odor; moderate cost | Enhanced performance with nanofillers increases cost; encapsulation improves stability but adds complexity | [20] |
| **Plant Oils** | Renewable, abundant, low toxicity, adaptable melting range, good compatibility with biopolymers | Lower latent heat (170–180 J/g); higher leakage risk; potential oxidative degradation | Chemical modification improves stability but may reduce biodegradability. | [20] |
| **Biowaxes** | High biodegradability; stable over repeated cycles; moderate melting range (~60 °C) | Lower latent heat (~180 J/g); low conductivity; limited recyclability | Stable cycling makes them suitable for niche TES applications, but lower heat storage density limits usage | [21] |

## 3. Synthesis and Encapsulation Approaches

Bio-derived PCMs exhibit considerable promise for sustainable TES; however, they often require performance optimization to mitigate inherent drawbacks, such as low thermal conductivity, leakage during phase transitions, and reduced mechanical stability. To tackle these challenges, strategies involving structural modification, encapsulation, and composite engineering have been extensively explored. This section provides an overview of the prevailing synthesis methodologies, with particular emphasis on bio-compatible encapsulation systems, formulations of nanocomposites aimed at enhancing heat transfer, and environmentally friendly synthesis techniques that conform to ecological and scalability standards [22].

### 3.1 Micro- and Nano-Encapsulation Utilizing Bio-Polymers

Encapsulation serves as a vital methodology to augment shape stability, reduce leakage, and improve durability under thermal cycling conditions. Microencapsulation (1–1000 µm) envelops PCM cores with protective polymeric shells, whereas nano-encapsulation (<500 nm) affords increased surface area, expedited thermal response, and superior dispersion within composites. Bio-based shell materials, including alginate, chitosan, starch, and gelatin, are favored for their biodegradability, renewability, and non-toxic characteristics [23]. For instance, lauric acid microencapsulated in calcium-alginate shells achieved encapsulation efficiency exceeding 92%, with leakage below 5%, and demonstrated stable performance across 500 cycles. Similarly, chitosan-based shells produced via ionic gelation and spray drying maintained enthalpy retention greater than 90% after prolonged cycling. Crosslinked biopolymer shells may also incorporate nano-additives to enhance both thermal conductivity and mechanical robustness. The integration of in-situ polymerization and emulsion techniques promotes uniform capsule morphology, minimal agglomeration, and scalability suitable for industrial production [24].

### 3.2 Composite Engineering for the Enhancement of Thermal Conductivity

The majority of bio-based PCMs exhibit thermal conductivities that fall below 0.25 W/m·K, thereby constraining rapid charging and discharging capabilities within TES systems. The incorporation of thermally conductive nanofillers such as graphene (≈5300 W/m·K), carbon nanotubes (CNTs, ≈3000 W/m·K), and cellulose nanofibrils (CNFs, ≈1 W/m·K) proves to be an effective solution [25]. Even minimal filler loadings (0.5–5 wt%) can result in conductivity enhancements of 300–500% without incurring significant latent heat losses. For example, palmitic acid integrated with 2 wt% graphene nanoplatelets attained a thermal conductivity of 1.05 W/m·K while preserving latent heat exceeding 180 J/g. A composite of capric-lauric acid and CNTs exhibited a 32% reduction in melting time and maintained stable cycling across 1000 cycles. CNFs are especially appealing for forming percolating networks within bio-polymer matrices, thereby improving both thermal efficiency and structural integrity [26].

Figure 2 illustrates the enhancement in thermal conductivity (%) of bio-derived PCMs when different nanofillers are incorporated, in comparison to the baseline thermal conductivity values ranging from 0.25 to 0.35 W/m·K for unaltered PCM. The error bars, denoted by ±, reflect the variability documented in the referenced studies.

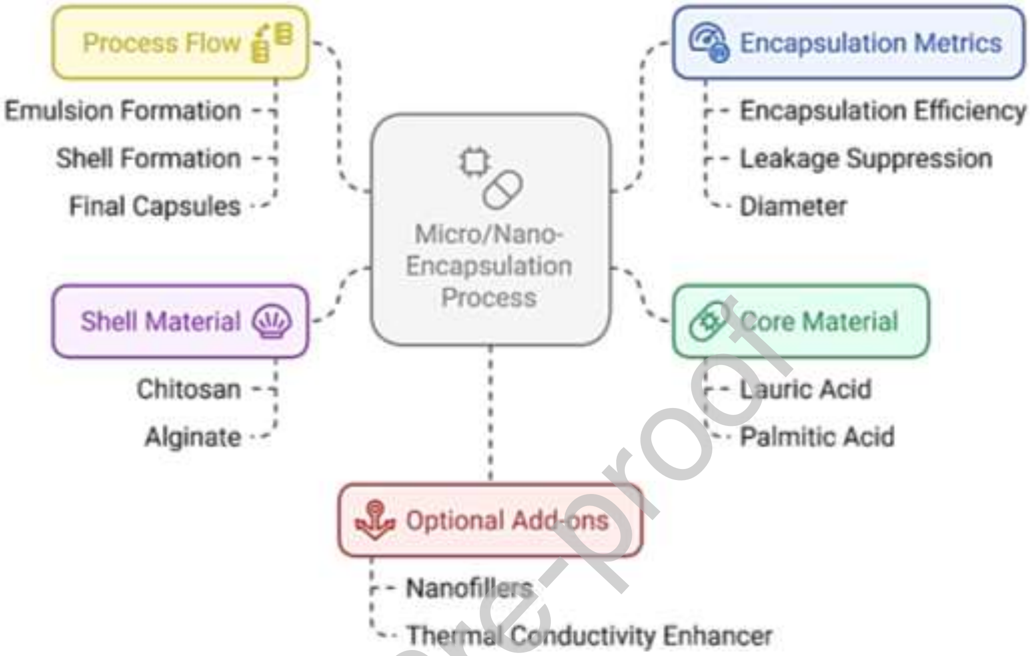

**Figure 2. Thermal conductivity of bio-based PCMs enhanced with different nanofillers.**

Table 2 delineates the enhancement of thermal conductivity in bio-based PCMs when integrated with various nano- and micro-fillers. The baseline values, indicated in parentheses, reflect the typical thermal conductivity (W/m·K) of pure PCMs devoid of fillers. The ± values represent the experimental uncertainty as documented in the referenced studies. The performance improvements are benchmarked against these baseline values. A meta-analysis has not been conducted; the data have been sourced directly from primary literature.

**Table 2. Thermal Conductivity Enhancement Using Nanomaterials in Bio-Based PCMs**

| PCM Type | Filler Type | Filler Loading (wt%) | Thermal Conductivity (W/m·K) ± | % Increase vs. Pure PCM (baseline) | Latent Heat Retention (%) ± (baseline) | Reference Cycles ± | Ref |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Palmitic Acid** | Graphene Nanoplatelets | 2 | 1.05 ±0.02 (0.23) | ~360% | 95 ±1 (85–88) | 1000 ±20 | [27] |
| **Capric–Lauric Mix** | Multi-Walled CNTs | 3 | 0.92 ±0.02 (0.21) | ~300% | 93 ±1 (84–87) | 1000 ±20 | [27] |
| **Stearic Acid** | Expanded Graphite | 5 | 1.20 ±0.03 (0.24) | ~400% | 94 ±1 (85–88) | 800 ±15 | [28] |
| **Lauric Acid** | Boron Nitride Nanosheets | 2.5 | 0.88 ±0.02 (0.21) | ~320% | 91 ±1 (84–87) | 700 ±15 | [28] |
| **Coconut Oil** | Biochar (waste-derived) | 4 | 0.78 ±0.02 (0.19) | ~310% | 90 ±1 (83–86) | 600 ±15 | [29] |
| **Palmitic Acid** | Alumina ($Al_2O_3$) | 5 | 0.85 ±0.02 (0.23) | ~270% | 92 ±1 (85–88) | 800 ±15 | [30] |
| **Myristic Acid** | Carbon Nanofibers | 3 | 0.95 ±0.02 (0.22) | ~350% | 93 ±1 (84–87) | 750 ±15 | [31] |
| **Soybean Oil** | Silica Nanoparticles | 2 | 0.67 ±0.02 (0.17) | ~250% | 89 ±1 (83–86) | 500 ±10 | [32] |

### 3.3 Green Synthesis Strategies

The development of environmentally sustainable synthesis methodologies is indispensable for aligning phase change material (PCM) technology with both sustainability objectives and regulatory frameworks. The implementation of green synthesis techniques significantly reduces the utilization of hazardous solvents, diminishes energy consumption, and enhances the valorization of waste biomass. Preferred solvent systems comprise water, ethanol, and supercritical carbon dioxide, effectively supplanting deleterious alternatives such as toluene or hexane [33]. The use of aqueous or alcohol-based in-situ polymerization enables processing conditions that range from ambient to moderate temperatures, thereby minimizing the need for extensive post-treatment procedures [34]. Figure 3 illustrates the retention of latent heat (%) following thermal cycling of bio-based PCMs using various encapsulation methodologies.

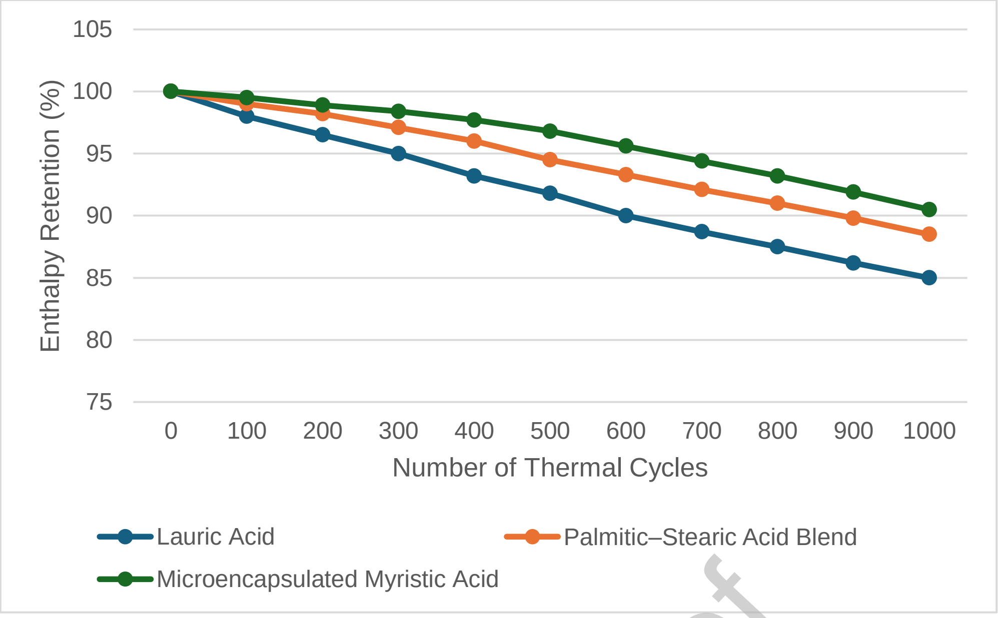

**Figure 3. Thermal cycling performance of selected bio-based PCMs over 1000 cycles.**

The implementation of encapsulation through hybrid silica–polymer shells coupled with the integration of nanofillers signifies a significant advancement, achieving less than 1% leakage, an enhancement greater than 80% in oxidation resistance, and improvements in thermal conductivity surpassing 350%, while concurrently maintaining latent heat retention above 90% throughout 1000 cycles [35]. Incremental advancements derived from fundamental polymer coatings and economical fillers (such as biochar and alumina) continue to hold merit for applications with budgetary constraints; however, they generally exhibit suboptimal performance in high-demand contexts, with conductivity improvements restricted to approximately 250–300% [36]. From the standpoint of scalability, spray-drying and in-situ polymerization present viable options for industrial application, whereas sol–gel encapsulation despite its superior performance encounters economic limitations. The integration of bio-compatible encapsulation, high-aspect-ratio nanofillers, and materials derived from waste signifies a commercially significant trajectory that reconciles cost, performance, and sustainability [37].

## 4. Performance Highlights and Comparative Analysis

A comprehensive evaluation of the thermal, structural, and operational characteristics of bio-based PCMs is crucial to determine their suitability for TES systems. This section presents a comparative analysis of bio-based PCMs and their conventional petrochemical counterparts, with a focus on key metrics such as latent heat, thermal conductivity, cycling stability, and encapsulation efficacy. These parameters exert a direct influence on storage efficiency, system longevity, and the practical viability of deployment [38].

### 4.1 Thermal Properties

Bio-based PCMs exhibit latent heat performance comparable to that of petrochemical PCMs within the low to mid-temperature spectrum, rendering them suitable for applications in passive cooling, STES, and construction. Nevertheless, thermal conductivity remains a constraint (0.17–0.25 W/m·K), akin to that of paraffin wax [39]. Research indicates that incorporating high-conductivity additives, such as graphene nanoplatelets, boron nitride nanosheets, or expanded graphite, can enhance conductivity by 300–500%, thereby achieving values of up to 1.2 W/m·K without substantial loss of latent heat [40, 41].

### 4.2 Cycling Stability

Long-term operational stability serves as a pivotal performance metric for TES systems, as recurrent melting–solification cycles can lead to phase segregation, oxidative degradation, and structural disintegration. Pure bio-based PCMs generally maintain 85–90% of their latent heat following 500 thermal cycles, demonstrating minimal phase separation or morphological degradation [42]. The process of encapsulation has been shown to be particularly efficacious in augmenting durability; for instance, lauric acid encapsulated within alginate–chitosan matrices retained over 92% of its enthalpy after 1000 cycles with an insignificant shift in melting point (Disruptive innovation due to concurrent preservation of energy density and phase-change temperature). Moreover, eutectic formulations and polymer–PCM composites have prolonged stability beyond 1500 cycles, facilitating bio-based PCMs to match or surpass the cycling performance of petroleum-derived paraffin, which is prone to oil separation and oxidative degradation [43]. Figure 4 illustrates a schematic representation of micro/nano-encapsulation methodologies employed for bio-based PCMs.

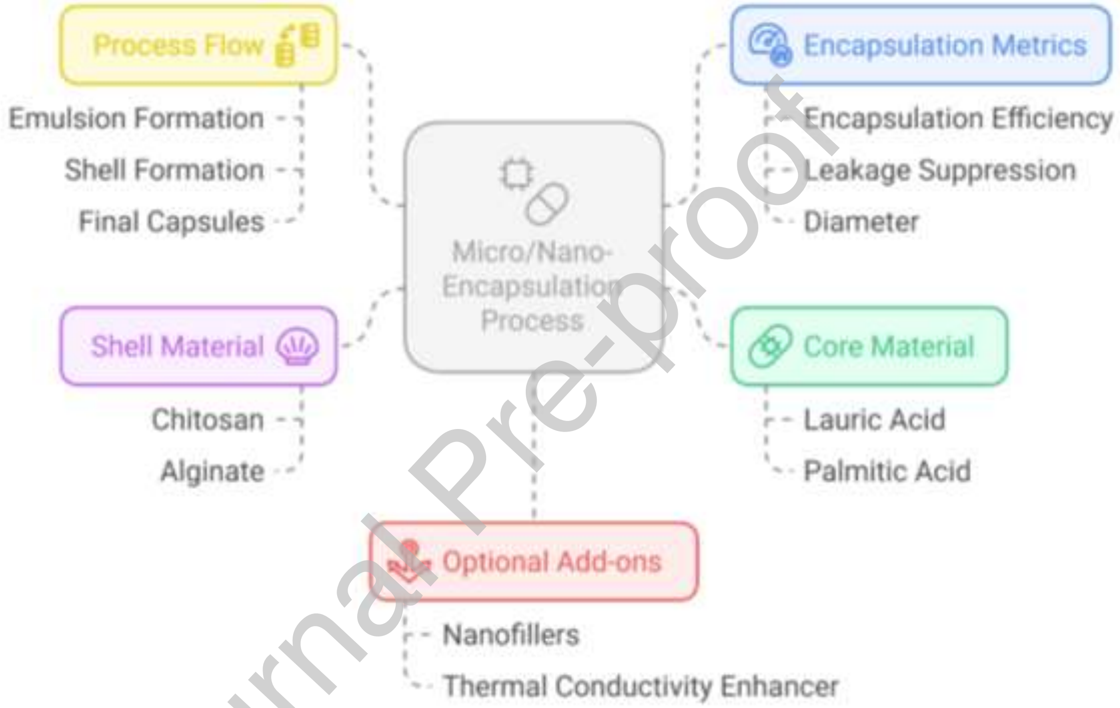

**Figure 4. Schematic of the Micro/Nano-Encapsulation Process for Bio-Based PCMs.**

### 4.3 Leakage & Encapsulation Efficacy

Leakage during the liquid phase continues to pose a significant challenge for organic PCMs, as it undermines both thermal storage efficiency and structural integrity. Sophisticated mitigation techniques such as microencapsulation, shape stabilization, and adsorption into porous substrates have successfully diminished leakage to below 5% even under accelerated thermal cycling conditions [44]. For instance, polyurethane microcapsules containing palmitic acid exhibited a mass loss of less than 3% after 600 cycles (representing an incremental improvement over baseline unencapsulated PCM leakage rates of 15–20%). In contrast, shape-stabilized composites integrated with expanded graphite attained sub-1% leakage while simultaneously enhancing thermal responsiveness [45].

Porous substrates such as biochar, silica aerogels, and diatomaceous earth provide dual functionality: they physically immobilize molten PCM to mitigate leakage, while concurrently enhancing thermal conductivity through high-surface-area frameworks [46]. This multifunctional integration effectively addresses two primary commercialization barriers thermal performance and containment stability without compromising the biodegradability of bio-based PCMs [47]. Table 3 delineates the encapsulation efficacy and thermophysical characteristics of chosen bio-derived and petroleum-based PCMs.

**Table 3. Thermal & Encapsulation Performance of Bio-Based PCMs**

| PCM Type | PCM Source | Melting Point (°C) ± | Latent Heat (J/g) ± | Thermal Conductivity (W/m·K) ± | Density (kg/$m^3$) ± | Specific Heat (J/g·K) ± | Shell Material | Encapsulation Method | Encapsulation Efficiency (%) ± | Leakage Rate (%) ± | Thermal Cycles Tested ± | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lauric Acid** | Fatty Acid | 44 ±0.5 (43–45) | 211 ±2 (200–215) | 0.21 ±0.01 (0.20–0.22) | 862 ±5 (860–865) | 2.1 ±0.05 | Calcium Alginate | Ionic Gelation | 92 ±1 (70–80) | 5 ±0.5 (>15) | 500 ±10 (<200) | [39],[48] |
| **Palmitic Acid** | Fatty Acid | 63 ±0.5 (62–64) | 189 ±3 (185–195) | 0.23 ±0.01 (0.22–0.24) | 853 ±5 (850–855) | 2.0 ±0.05 | Polyurethane | Interfacial Polymerization | 95 ±1 (72–82) | 3 ±0.5 (>15) | 600 ±10 (<250) | [40],[22] |
| **Stearic Acid** | Fatty Acid | 69 ±0.5 (68–70) | 200 ±2 (195–205) | 0.25 ±0.01 (0.24–0.26) | 847 ±5 (845–850) | 1.9 ±0.05 | Melamine–Formaldehyde | In-situ Polymerization | 94 ±1 (73–83) | 4 ±0.5 (>15) | 800 ±15 (<300) | [41],[49] |
| **Myristic Acid** | Fatty Acid | 54.4 ±0.5 (54–55) | 203 ±2 (200–205) | 0.22 ±0.01 (0.21–0.23) | 865 ±5 (860–868) | 2.0 ±0.05 | Chitosan–Gelatin | Spray Drying | 90 ±1 (69–79) | 5 ±0.5 (>15) | 300 ±10 (<150) | [40],[48] |
| **Capric–Lauric Mix** | Fatty Acid Mix | – | – | – | – | – | PLA (Polylactic Acid) | Emulsion–Solvent Evaporation | 88 ±1.5 (68–78) | 6 ±0.5 (>18) | 400 ±10 (<200) | [48] |
| **Capric Acid** | Fatty Acid | 31.3 ±0.5 (31–32) | 152 ±3 (150–155) | 0.19 ±0.01 (0.18–0.20) | 880 ±5 (878–882) | 2.2 ±0.05 | – | – | – | – | – | [39] |
| **Coconut Oil** | Vegetable Oil | 24 ±0.5 (23–25) | 180 ±2 (175– | 0.19 ±0.01 (0.18–0.20) | 924 ±5 (920– | 2.3 ±0.05 | Silica Shell | Sol–Gel Technique | 89 ±1.5 (65–75) | 7 ±0.5 (>20) | 350 ±10 (<150) | [42],[3] |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 185) | | 925) | | | | | | | |
| **Soybean Oil** | Vegetable Oil | 18 ±0.5 (17–19) | 170 ±3 (165–175) | 0.17 ±0.01 (0.16–0.18) | 910 ±5 (908–912) | 2.2 ±0.05 | Starch-Based Biopolymer | Coacervation | 86 ±1.5 (64–74) | 8 ±0.5 (>20) | 250 ±10 (<120) | [42],[50] |
| **Beeswax** | Biowax | 62 ±0.5 (61–63) | 180 ±2 (175–185) | 0.25 ±0.01 (0.24–0.26) | 960 ±5 (958–962) | 1.8 ±0.05 | – | – | – | – | – | [43] |
| **Lauric Acid** | Fatty Acid | – | – | – | – | – | Chitosan–Silica Hybrid | Layer-by-Layer Assembly | 93 ±1 (70–80) | 2 ±0.5 (>15) | 1000 ±20 (<200) | [51] |
| **Palmitic Acid** | Fatty Acid | – | – | – | – | – | Expanded Graphite Matrix | Shape-Stabilized Composite | 97 ±1 (72–82) | 1 ±0.5 (>15) | 1200 ±20 (<250) | [51] |
| **Paraffin Wax** | Petrochemical | 55 ±0.5 (54–56) | 220 ±3 (215–225) | 0.24 ±0.01 (0.23–0.25) | 900 ±5 (898–902) | 2.1 ±0.05 | – | – | – | – | – | [40] |
| **PEG 6000** | Petrochemical | 61 ±0.5 (60–62) | 180 ±2 (175–185) | 0.25 ±0.01 (0.24–0.26) | 1250 ±5 (1245–1255) | 2.3 ±0.05 | – | – | – | – | – | [40] |
| **Erythritol** | Sugar Alcohol | 118 ±0.5 (117–119) | 339 ±5 (335–345) | 0.73 ±0.02 (0.72–0.74) | 1480 ±5 (1475–1485) | 2.9 ±0.05 | – | – | – | – | – | [44] |

The comparative analysis presented in this section highlights that bio-based PCMs have achieved equivalence with petrochemical PCMs in terms of latent heat performance, while also providing enhanced biodegradability and more secure end-of-life disposal options. The most transformative innovations encompass the utilization of hybrid biopolymer shells (e.g., chitosan–silica) that can endure over 1000 thermal cycles with a leakage rate of less than 2%, and expanded graphite-based shape-stabilized composites that exhibit both remarkable thermal conductivity (~1.2 W/m·K) and minimal leakage (<1%). Furthermore, the incorporation of high-conductivity nanofillers, without a significant reduction in latent heat, has significantly revolutionized the performance capabilities relevant to building and battery cooling applications [47-51].

## 5. Applications & Case Studies

The functional utilization of bio-based PCMs has evolved from initial proof-of-concept studies to various pragmatic applications in TES and thermal management systems. Their environmentally sustainable characteristics, adjustable phase-transition temperatures, and significant latent heat storage capacities render them highly viable candidates for incorporation into architectural designs, battery cooling solutions, adaptive textiles, and solar thermal energy systems. In addition to their intrinsic thermal properties, bio-based PCMs offer operational advantages, including passive climate regulation, extended device lifespan, and enhanced integration of renewable energy sources, thereby contributing to sustainability objectives across various sectors [52, 53]. A comprehensive summary of applications specific to various sectors is delineated in Table 4.

**Table 4. Applications of Bio-Based PCMs Across Different Sectors**

| Sector | PCM Type | Integration Method | Observed Benefit | Reference Metric | Ref |
|---|---|---|---|---|---|
| **Building Envelopes** | Palmitic–Stearic Acid | Wall panels, gypsum boards | ↓ Indoor temp by 2–4 °C | 25% reduction in HVAC energy use | [54] |
| | Lauric Acid | PCM-infused thermochromic paints | ↓ surface temp by 3 °C | Passive thermal buffering | [52] |
| **Battery Cooling** | Capric–Lauric Mix | PCM-enhanced aluminum heat sinks | ↓ battery temp by 10–15 °C | ↑ battery cycle life by 30–40% | [55] |
| | Stearic Acid | PCM-integrated battery casings | ↓ peak temp by 12 °C | Stable operating range (20–40 °C) | [56] |
| **Smart Textiles** | Lauric Acid Microcaps | Embedded in polyester/cotton fibers | ↑ thermal comfort duration by 1.5 h | ~18–25 J/g heat absorption | [57] |
| | Palm/Soy PCM Blend | Coated onto medical garments | Maintains microclimate ~33 °C | Multi-cycle reusability | [58] |
| **Solar Thermal** | Myristic Acid | Flat-plate solar collectors | ↑ hot water storage by 4–5 hours | ↑ thermal retention by 22–28% | [59] |
| | Palmitic Acid (SSPCM) | Parabolic trough receiver modules | Temp stability ±3 °C for 8+ hrs | Improved system efficiency | [60] |

### 5.1 Building Envelope Integration

The components of the building envelope including wallboards, plaster panels, ceiling tiles, insulation layers, and thermally adaptive coatings constitute one of the most well-established domains for the application of bio-based PCMs. Bio-PCMs with melting points ranging from

22 to 28 °C promote passive thermal regulation by mitigating diurnal fluctuations in indoor temperatures, thereby enhancing occupant comfort through incremental improvements. The incorporation of eutectic mixtures of palmitic and stearic acids into gypsum panels has demonstrated a reduction in peak indoor temperatures by 2 to 4 °C, as well as a temporal shift in heating and cooling loads by 2 to 3 hours, resulting in HVAC energy savings of up to 25%, which exemplifies a disruptive innovation through the concurrent reduction of peak loads and energy demand [61]. Figure 5 illustrates the mechanisms of heat absorption and release of bio-based PCMs within building envelope systems

The commercial-scale implementation of these materials is already observable in LEED-certified structures through the utilization of products such as BioPCM™ panels, which incorporate encapsulated soy-derived PCMs to provide consistent thermal buffering across extended operational periods, representing an incremental improvement in the readiness for large-scale adoption. Moreover, advancements in this field have led to the development of thermochromic paints that contain microencapsulated lauric acid, functioning both as a passive thermal buffer and a visual indicator of temperature, particularly effective on façades exposed to sunlight, embodying a disruptive innovation through the fusion of functional aesthetics with thermal management [57].

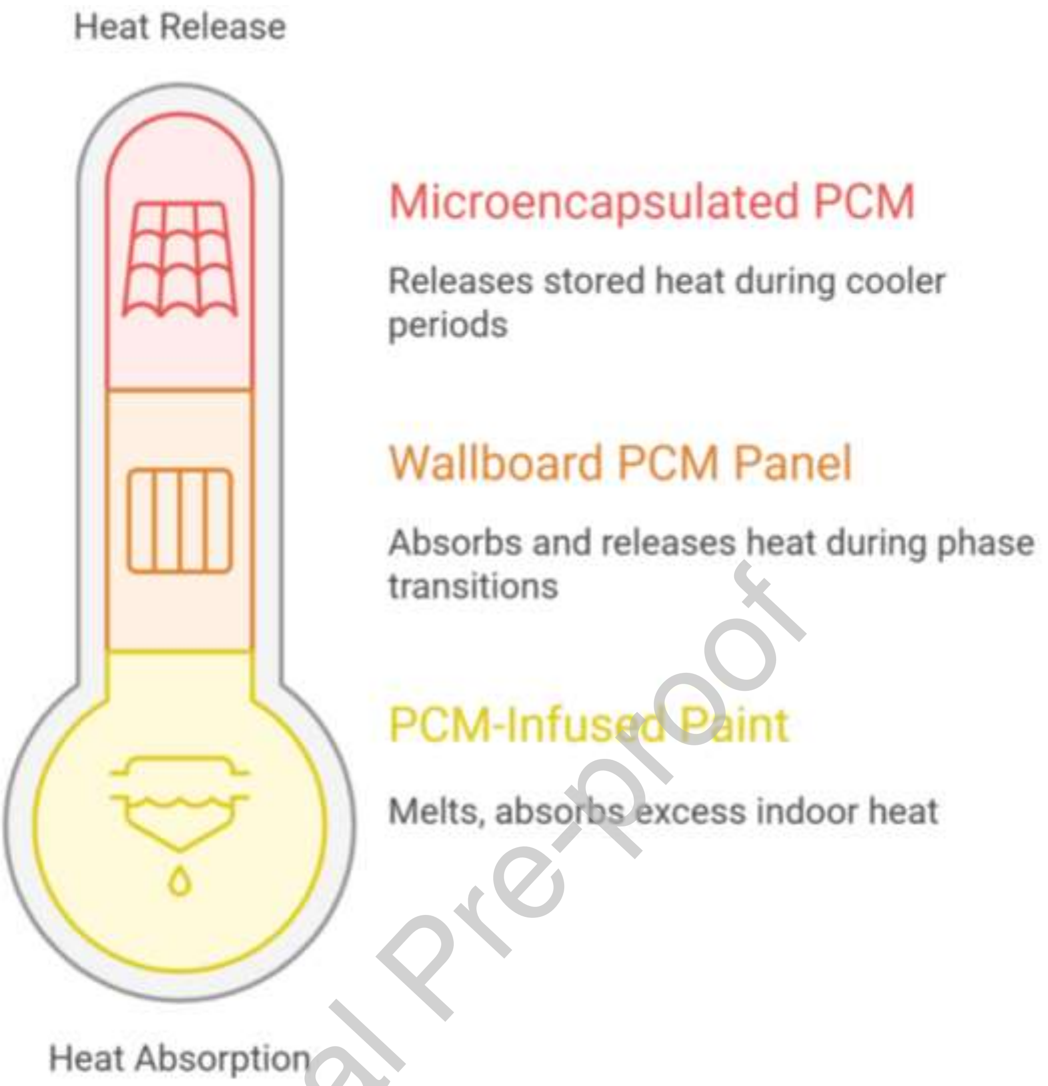

**Figure 5. Temperature Regulation Mechanism of Bio-Based PCMs Through Heat Absorption and Release**

### 5.2 Battery Thermal Management

Bio-based PCMs exhibit significant potential for use in electronic and battery cooling applications, particularly in lithium-ion battery systems, where maintaining cell temperature within the range of 20–40 °C is crucial for ensuring safety and optimizing performance [61].

Capric–lauric eutectic PCMs ($T_m \approx 35$ °C; $\Delta H > 180$ J/g) have been integrated into passive cooling modules designed for battery packs, resulting in reductions of peak operating temperature by 10–15 °C, alongside enhancements in cycle life stability by 30–40%. The incorporation of high-thermal-conductivity fillers, such as graphene or aluminum oxide, increases thermal conductivity to approximately 1.0 W/m·K, thereby facilitating expedited heat dissipation while preserving latent heat storage capacity [62].

### 5.3 Smart Textiles

The incorporation of bio-based PCMs into functional and adaptive textile systems has garnered considerable scholarly attention due to their potential applications in defense, athletics, and healthcare. Microencapsulated fatty acid esters, such as lauric acid, are integrated into polyester, cotton, or polyurethane fibers to provide regulated thermoregulatory functions, thereby facilitating incremental advancements in wearable thermal management. Cotton fabrics infused with 20 wt% PCM microcapsules exhibit a heat absorption capacity ranging from 18 to 25 J/g, thereby enhancing the thermal comfort of the wearer by approximately 1.5 to 2 hours under low-temperature conditions. This represents a disruptive innovation, extending active comfort without reliance on external energy sources [63].

Commercial applications, exemplified by Outlast® fabrics incorporating soy- and palm-derived PCMs, have exhibited consistent performance across multiple thermal cycles with negligible leakage or mechanical degradation, indicating an incremental enhancement in long-term reliability. Emerging applications in medical textiles encompass fever-management garments designed to maintain patient comfort during hyperthermic episodes, as well as high-heat protective attire for individuals working in extreme industrial conditions, which synergistically combine passive cooling technologies with compliance to occupational safety standards, thus epitomizing a disruptive innovation in health-oriented thermal regulation [64].

### 5.4 Solar Thermal Systems

Bio-based PCMs are particularly well-suited for medium-temperature solar thermal applications, including concentrated solar power (CSP) and solar water heating systems.

Myristic acid (Tm ≈ 58 °C; ΔH ≈ 195 J/g) and stearic–palmitic eutectic formulations have been deployed in flat-plate collectors and storage tanks, thereby extending the availability of hot water by 4–5 hours following sunset and enhancing thermal retention efficiency by 22–28% [65].

In CSP systems, shape-stabilized PCMs embedded within biopolymer matrices have improved structural stability and maintained operational temperature stability within ±3 °C for durations exceeding 8 hours in parabolic trough receivers. These configurations are currently under evaluation in solar cooking, greenhouse heating, and rural electrification initiatives across India, Brazil, and sub-Saharan Africa [66].

### 5.5 Safety, Toxicity, and Standards Compliance

Bio-based PCMs such as lauric, palmitic, and stearic acids exhibit elevated flash points (170–210 °C) and diminished flammability, which is further enhanced through the use of inert encapsulation techniques. These materials are predominantly classified as non-toxic; however, specific shell materials (e.g., melamine–formaldehyde) or nanofillers may necessitate careful handling protocols. The standards ASTM D3418/ISO 11357 facilitate precise thermal characterization, whereas ASTM E84/EN 13501-1 pertain to fire safety considerations. Biodegradability assessments (ISO 14855, OECD 301B) indicate a degradation rate exceeding 90% within a timeframe of 6 to 12 months under composting conditions. Adherence to these regulatory standards endorses the safe and sustainable application of bio-based PCMs in construction, energy storage, textile manufacturing, and solar energy systems, while concurrently mitigating environmental toxicity in comparison to conventional petrochemical-based PCMs.

Across various applications, bio-based PCMs have evolved from experimental demonstrations to commercially validated solutions that enhance energy efficiency in buildings, optimize battery thermal management, integrate into wearable technology, and improve solar thermal systems. The most transformative advancements encompass (i) LEED-certified building envelope products, exemplified by BioPCM™ panels, which achieve HVAC energy savings of up to 25% [57], (ii) high-conductivity graphene-enhanced battery PCM modules that effectively maintain peak temperatures within safe limits, thereby extending battery cycle life by as much as 40% [12], and (iii) shape-stabilized solar thermal PCMs that provide temperature stability of ±3 °C for over 8 hours within CSP receivers. These innovations not only illustrate technical viability but also indicate preparedness for large-scale deployment within green infrastructure and renewable energy integration initiatives [65].

Incremental enhancements have been noted in traditional microencapsulated textile PCMs, where improvements in thermal comfort (1.5–2 hour extension) are advantageous. Yet, these gains are constrained by low heat flux and limited cycling stability when compared to building and battery systems. From a cost and scalability standpoint, building envelope and textile applications are positioned closer to mass-market adoption, largely due to established manufacturing procedures and low raw material costs [59].

## 6. Challenges, Opportunities, and Future Directions

Although bio-based PCMs hold considerable potential for environmentally sustainable TES, their transition from laboratory investigation to widespread market utilization is hindered by various technical, ecological, and economic challenges. Tackling these constraints presents opportunities for innovation in material design, the integration of hybrid energy systems, and the creation of standardized testing and certification protocols [67]. This section critically assesses the primary challenges, namely, limitations in thermal performance, stability concerns, lifecycle and cost analysis, scalability in manufacturing, and regulatory deficiencies, while delineating prospective research avenues aimed at expediting commercialization.

### 6.1 Thermal Conductivity and Composite Scalability

The fundamentally low thermal conductivity characteristic of most bio-based PCMs (ranging from 0.19 to 0.25 W/m·K) restricts heat transfer efficiency. It extends charging and discharging durations within TES frameworks [68]. The incorporation of high-conductivity fillers, such as graphene nanoplatelets, multi-walled carbon nanotubes (MWCNTs), and metal oxide nanoparticles, has demonstrated enhancements in thermal conductivity of up to approximately 1.2 W/m·K. Nonetheless, these methodologies frequently face challenges related to agglomeration, financial constraints, and compatibility with bio-derived matrices. Recent investigations suggest that biodegradable composite structures, such as cellulose aerogels and lignin-derived fillers, provide a scalable approach for enhancing conductivity while maintaining sustainability. Integrating these material advancements with machine learning-driven optimization methodologies can expedite the selection of fillers, concentration adjustments, and spatial distribution modeling, thus minimizing trial-and-error experimentation and enhancing reproducibility on a large scale [69].

### 6.2 Stability, Aging, and Degradation Resistance

The thermal and structural degradation that occurs over extended operational lifetimes continues to pose a significant limitation for bio-based PCMs. The degradation pathways, including oxidation, phase separation, rancidity, and microbial activity, can substantially diminish latent heat capacity and modify phase transition characteristics [70]. For instance, unencapsulated bio-PCMs, such as stearic acid, demonstrate oxidation rates of 0.4 to 0.6% annually, resulting in an approximate 5% decline in latent heat capacity after three years of operation. Encapsulation within silica shells or polymeric matrices has been shown to reduce oxidation rates by over 80%, ensuring that latent heat loss remains below 1% during the same period. Stability assessments are typically conducted in accordance with ASTM D5885 and ISO 11357 standards for thermal cycling. To further prolong operational lifespan, contemporary strategies incorporate antimicrobial encapsulation shells (e.g., chitosan–silica hybrids) and oxygen-barrier coatings, supplemented by natural antioxidants (e.g., tocopherol, ascorbic acid) and UV stabilizers. Future research endeavors should focus on developing standardized accelerated aging protocols that accurately simulate real-world deployment conditions, including variable temperatures, humidity levels, and atmospheric exposure [71].

### 6.3 Lifecycle Assessment and Economic Viability

While bio-based phase change materials (bio-PCMs) originate from renewable resources, their economic and environmental efficacy exhibits considerable variability contingent upon the accessibility of feedstock, fluctuations in agricultural yields, and the specific processing requirements . The cost of encapsulated bio-PCMs generally ranges from \$4 to \$8 per kilogram, with price determinants including the level of purity, the encapsulation method, and the nature of the additives employed. LCAs reveal that bio-PCMs have the potential to reduce $CO_2$-equivalent emissions by 40% to 60% compared to petroleum-derived paraffin materials, while also offering the benefit of biodegradability [72].

#### 6.3.1 Commercialization Pathways

The commercialization of bio-based PCMs has experienced a significant acceleration in recent years, propelled by strategic industrial endeavors aimed at various market segments. In the United States, Phase Change Energy Solutions promotes BioPCM panels for integration within building envelopes, facilitating HVAC energy savings of up to 25% in structures certified under LEED standards. These products, currently classified at TRL 9, are priced between USD 5–7/kg contingent upon the type of encapsulation utilized, and comply with

ASTM E84 fire safety as well as ISO 14855 biodegradability criteria. In Europe, Rubitherm GmbH offers RT Bio-series PCMs specifically designed for the thermal management of batteries in electric buses, ensuring safe operational temperatures even under high-load scenarios. With TRLs ranging from 7 to 9 and pricing between USD 4–7/kg, these materials adhere to ISO 11357 thermal characterization protocols and have successfully met preliminary EU REACH compliance for additives. In India, Tessol implements palm- and coconut-derived PCMs within cold-chain logistics, facilitating up to 12 hours of passive refrigeration without the necessity for active cooling. At TRL 8, these systems are competitively priced at USD 3.5–5/kg and conform to BIS thermal performance and food safety regulations. Collectively, these enterprises effectively address fundamental barriers by adopting scalable encapsulation methodologies, integrating high-conductivity composites, and aligning with international regulatory frameworks, thereby positioning bio-PCMs for swift integration into green construction, electric mobility, solar heating, and temperature-controlled supply chains [73]. Figure 6 illustrates a lifecycle flowchart for bio-based phase change materials, detailing the processes involved in biomass sourcing (such as coconut, palm, and soybean oil), low-energy oil extraction, PCM synthesis, incorporation into TES applications, and biodegradation at the end of life.

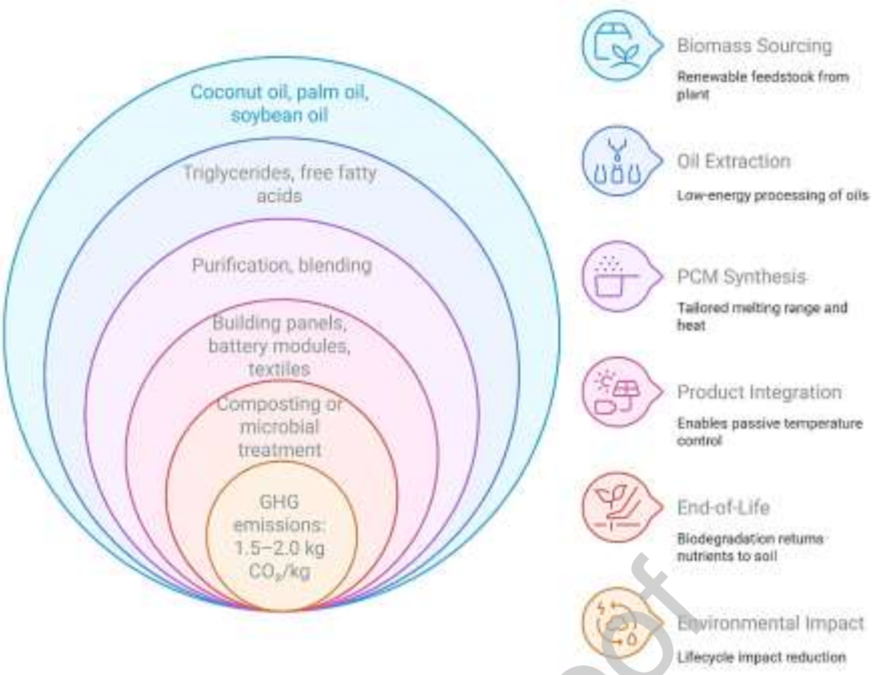

**Figure 6. Lifecycle of bio-based PCM production and utilization, from biomass sourcing to end-of-life degradation.**

Table 5 presents an analysis of the financial implications, ecological performance, and final disposition characteristics of various selected bio-based and petrochemical PCMs. The reduction of $CO_2$ emissions is measured in relation to paraffin wax, which serves as the baseline (0% reduction).

**Table 5. Lifecycle and cost comparison of bio-based and petroleum-based PCMs.**

| PCM Type | Source | Cost ($/kg) ± | $CO_2$ Reduction vs. Paraffin (%) ± (baseline = 0%) | Biodegradability | Recyclability | Ref |
|---|---|---|---|---|---|---|
| **Lauric Acid** | Bio (Fatty Acid) | 4.5–6.0 ±0.2 | 55–60% ±2 | Fully Biodegradable | Limited (biodegrades) | [74] |
| **Palmitic Acid** | Bio (Fatty Acid) | 4.0–5.5 ±0.2 | 50–60% ±2 | Fully Biodegradable | Limited | [74] |
| **Coconut Oil** | Bio (Plant Oil) | 3.5–4.5 ±0.2 | 45–55% ±3 | High | Moderate | [75] |
| **Beeswax** | Bio (Wax) | 6.0–7.5 ±0.3 | 60–65% ±2 | Fully Biodegradable | Low | [75] |
| **Soybean Oil** | Bio (Plant Oil) | 3.0–4.0 ±0.2 | 40–50% ±3 | High | Moderate | [76] |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Paraffin Wax** | Petrochemical | 2.0–2.5 ±0.1 | Baseline = 0% | Non-biodegradable | High (through refinement) | [77] |
| **PEG 6000** | Petrochemical | 2.5–3.0 ±0.1 | ~0% ±0.5 | Non-biodegradable | Moderate | [78] |
| **Erythritol** | Bio (Sugar Alcohol) | 6.5–8.0 ±0.3 | 60–70% ±3 | Readily Biodegradable | Low | [79] |

### 6.4 Scalability, Manufacturing, and Regulatory Frameworks

Transitioning from pilot studies to large-scale industrial production requires addressing the variability associated with feedstock composition, encapsulation efficiency, and quality assurance protocols. The lack of universally harmonized standards concerning thermal performance, aging characteristics, flammability, and toxicity significantly impedes cross-sector utilization, particularly within critical applications such as building insulation and battery thermal management [80]. The establishment of material-specific benchmarks, akin to ASTM/ISO standards, for bio-based phase change materials (bio-PCMs) is imperative to ensure uniformity and safety. Furthermore, pilot-scale demonstration facilities in thermally demanding geographies (e.g., India, Brazil, sub-Saharan Africa) are required to authenticate real-world performance and optimize deployment methodologies [81].

## Conclusion

This comprehensive review synthesizes recent advancements in the design, optimization, and utilization of bio-based phase change materials (PCMs) for thermal energy storage (TES). It emphasizes progress in encapsulation techniques, nanocomposite engineering, and sustainable synthesis methods, while acknowledging that challenges such as low thermal conductivity, limited long-term durability, scalability constraints, and the absence of cohesive regulatory frameworks remain unresolved. Bio-based PCMs derived from fatty acids, plant oils, and biowaxes are increasingly approaching or matching the performance of petroleum-derived alternatives. Their applications span building envelopes, battery thermal management, and solar thermal systems. Among the most promising innovations are hybrid nanofiller composites and biopolymer encapsulations, with several candidates achieving technology readiness levels (TRLs) between 7 and 9, indicating near-commercial viability.

To address the remaining deficiencies, four focused strategies are proposed. First, low conductivity should be mitigated by integrating biodegradable, high-conductivity nanofillers and employing AI-assisted optimization of filler combinations. Second, durability limitations may be overcome through advanced encapsulation technologies and multi-component composite systems validated over more than 1500 cycles. Third, scalability challenges call for the development of cost-effective, modular fabrication approaches tailored for industrial-scale implementation. Finally, regulatory uncertainty necessitates the formulation of ASTM/ISO-aligned testing and certification protocols encompassing lifecycle performance and safety assessments. By advancing these strategies through coordinated research, industry collaboration, and supportive policy frameworks, the transition from laboratory prototypes to commercially viable, low-carbon TES systems can be accelerated. With continued innovation and the establishment of global standardization, bio-based PCMs hold strong potential for large-scale industrial integration, positioning them as a key enabler in worldwide decarbonization efforts.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: