

Palm-Oil-Derived Phase-Change Materials for Thermal Energy Storage: Molecular Design, Encapsulation, Heat-Transfer Enhancement, and Engineering Applications A Critical Review

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ABSTRACT

Phase-change materials (PCMs) can decouple thermal-energy supply from demand by absorbing and releasing latent heat across a narrow temperature interval. Bio-based PCMs have consequently attracted attention as renewable alternatives to petroleum-derived paraffins, yet most reviews treat plant oils as a single broad category and rarely examine the palm-oil platform as an engineerable family of thermal-storage molecules. This critical qualitative literature review evaluates palm oil, palm fractions, palm-derived fatty acids, esters, and related lipids as tunable PCMs rather than as a single biological material. It synthesizes recent evidence on molecular structure–transition relationships, eutectic design, hydrogenation and fractionation; low thermal conductivity and heat-transfer enhancement; encapsulation, form stabilization and leakage control; thermal cycling, corrosion and chemical stability; and emerging applications in buildings, cold chains, photovoltaic systems, battery thermal management, solar-thermal storage and low-grade industrial heat recovery. The analysis shows that palm-derived PCMs are technically credible where phase-transition temperature, latent-heat density and source sustainability are matched deliberately to the application. However, conductivity enhancement creates a recurring latent-heat dilution penalty, while encapsulation improves handling but introduces shell mass, interfacial resistance, processing cost and end-of-life complexity. The most promising research direction is therefore not a search for a universal palm PCM, but application-specific co-design of molecular composition, conductive architecture, containment and life-cycle strategy. A development roadmap is proposed for moving palm-derived PCMs from laboratory characterization toward standardized, safe and scalable thermal-energy-storage systems.

Keywords: Palm Oil, Phase-Change Material, Thermal Energy Storage, Fatty Acids, Palm Stearin, Eutectic Pcm, Encapsulation, Thermal Conductivity, Bio-Based Materials, Latent Heat

Introduction

Thermal energy storage has become increasingly important as electricity systems, buildings and industrial processes attempt to accommodate variable renewable energy, electrification and tighter efficiency requirements. Unlike sensible-heat storage, which raises or lowers the temperature of a storage medium, latent-heat thermal energy storage exploits the enthalpy absorbed or released during a phase transition. The ability of a PCM to buffer temperature while storing a relatively large quantity of heat in a compact mass makes it attractive for passive thermal regulation, peak-load shifting, and temporal coupling between heat generation and use. Recent reviews emphasize, however, that practical performance is governed not only by latent heat

but also by transition temperature, thermal conductivity, cycling reliability, leakage resistance, compatibility, geometry, and system-level heat transfer [1-3].

Organic PCMs such as paraffins have dominated the literature because they are chemically stable, exhibit limited supercooling, and are commercially available over broad temperature ranges. Their petroleum origin and flammability, together with the environmental burdens associated with extraction, refining and end-of-life management, have stimulated interest in renewable alternatives. Bio-based PCMs derived from fatty acids, fatty esters, plant oils, biowaxes and waste lipids can offer renewable carbon, biodegradability and the possibility of valorizing agricultural or food-system side streams. Yet renewable origin does not automatically guarantee a lower life-cycle impact: land use, refining intensity, hydrogenation or esterification energy, encapsulation materials, additive production and transport can

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dominate the environmental profile if they are not evaluated explicitly [4-6]. A recent synthesis of bio-based PCMs similarly argues that thermophysical performance, long-term stability, life-cycle impacts, and techno-economic feasibility must be assessed together when judging whether a renewable PCM is genuinely competitive [7].

Palm oil warrants specific analysis because its molecular and industrial characteristics differ from those of many other plant oils. It is naturally semi-solid at ambient conditions because of its substantial saturated-fatty-acid content, principally palmitic acid, combined with unsaturated components such as oleic acid. Industrial fractionation yields stearin and olein streams with different melting behavior, and downstream oleochemical processing can produce individual fatty acids, fatty alcohols and esters. Hydrogenation, interesterification and eutectic blending further expand the accessible phase-transition windows. Consequently, palm oil is better understood as a molecular platform from which a portfolio of PCMs may be designed than as a single PCM with a fixed melting point [8,5].

Evidence published since 2020 strengthens this proposition. Expired palm oil has been tested as a building-oriented bio-PCM with broad and multiple transitions, while blends of palm-derived fatty acids have been evaluated for seasonal building applications. More recently, hydrogenated palm stearin has moved beyond small material specimens into pilot- and field-scale solar-thermal storage, and palm-derived fatty acids have been subjected to extended thermal treatment, hundreds of thermal cycles, and metal-corrosion testing. These studies collectively shift the research question from whether palm-derived lipids can undergo useful phase transitions to how their chemistry, structure, containment, and heat-transfer architecture should be engineered for specific thermal duties [4,9-12].

The central technical obstacle remains heat transfer. Fatty acids and vegetable-oil-derived PCMs generally have modest thermal conductivity, so high latent-heat density can coexist with slow charging and discharging. Carbonaceous fillers, metallic or ceramic particles, foams, fins, and porous frameworks can raise effective conductivity, but every non-PCM addition occupies volume and often reduces gravimetric latent heat. The engineering target is therefore not maximum conductivity in isolation but an optimum balance between heat-transfer rate, PCM loading, phase-change enthalpy, mechanical stability, cost and cycle life [13-15,3].

A second obstacle is liquid management. Many promising palm-derived molecules melt into mobile liquids that can leak, migrate, or interact with adjacent materials. Microencapsulation, nanoencapsulation, macroencapsulation, polymer networks and porous supports can solve this handling problem and can increase surface area for heat exchange. However, shells and supports introduce their own penalties: additional mass, interfacial thermal resistance, possible shell cracking, compatibility concerns, manufacturing complexity, and end-of-life separation challenges. A submission-ready assessment of palm-derived PCMs therefore requires simultaneous consideration of molecular thermodynamics, composite design and system engineering rather than a simple comparison of melting points and latent heats [16-19].

This review addresses four research questions. First, how can the molecular diversity of palm oil and its derivatives be translated into tunable phase-transition behavior? Second, which conductivity-enhancement and containment strategies offer the best performance without excessive latent-heat dilution or sustainability burden? Third, which engineering applications align most closely with the accessible transition-temperature windows of palm-derived PCMs? Fourth, what evidence and qualification steps are still required for commercial scale-up? The objective is to develop an integrated interpretation that connects chemistry, thermal performance, durability, safety, sustainability, and application readiness, thereby positioning palm-derived PCMs within contemporary materials and energy engineering rather than within commodity-oil research alone.

Literature Review and Conceptual Foundation

A PCM stores heat through a reversible phase transition. For a solid-liquid PCM heated from an initial temperature below the melting interval to a final temperature above it, the total useful heat storage can be approximated as the sum of sensible heating of the solid, latent heat of fusion, and sensible heating of the liquid. This decomposition is conceptually important because a material with a large quoted melting enthalpy may still perform poorly if its transition occurs outside the operating window or if insufficient heat transfer prevents the stored latent capacity from being accessed during the available charging period [1,2].

For a PCM mass m , the simplified heat-storage relation in Equation (1) separates sensible heating of the solid, latent heat of melting, and sensible heating of the liquid. In the equation, $c_{p,s}$ and $c_{p,l}$ denote the solid- and liquid-phase specific heat capacities; T_i , T_m , and T_f are the initial, representative transition, and final temperatures; and ΔH_m is the latent heat of melting. For natural bio-based mixtures, a single T_m can still be an approximation because broad triglyceride distributions may exhibit multiple melting events. This behavior can widen the useful buffering interval, but it complicates direct comparison with highly purified single-component PCMs [4,9].

Fatty-acid chain length and degree of unsaturation are primary molecular determinants of thermal behavior. Longer saturated chains generally increase intermolecular van der Waals interactions and crystal stability, tending to raise melting temperature. Cis double bonds introduce kinks that hinder efficient packing and usually lower melting temperature. Triglyceride behavior is more complex because melting depends on the identities and stereochemical positions of three acyl chains, polymorphism, and processing history. Fractionation can enrich higher-melting saturated triglycerides in palm stearin and lower-melting unsaturated species in palm olein; hydrogenation decreases unsaturation and can raise transition temperature and oxidative stability. The literature on vegetable-oil PCMs therefore supports a structure-property approach in which chain length, unsaturation, ester architecture and mixture composition are treated as design variables [8,5].

Eutectic design offers a second route to tunability. Binary or multicomponent fatty-acid mixtures can melt at temperatures below those of the individual components, allowing a formulation to be targeted to building comfort, electronics, batteries or low-grade heat recovery. Recent fatty-acid studies

report useful transition temperatures from the high teens to above 50 °C, with latent heats remaining high enough for thermal storage. Importantly, eutectic composition can also influence supercooling, crystallization kinetics and cycle stability, so phase diagrams and calorimetric verification are preferable to simple arithmetic blending [20-22].

The thermal conductivity of many organic PCMs is low relative to metals, ceramics and graphitic materials. This creates internal temperature gradients and can leave a significant fraction of latent capacity unused during rapid duty cycles. Conductivity enhancement can be achieved by dispersing particles, forming continuous conductive networks, impregnating porous graphite or carbon frameworks, embedding metallic foams, or adding fins to the storage vessel. The effectiveness of these strategies depends on network continuity and interfacial resistance rather than filler conductivity alone. Highly conductive filler that is poorly dispersed can provide less benefit than a lower-conductivity support that forms a connected pathway through the PCM [13,21,23-27].

A useful dimensionless indicator of latent-dominated thermal buffering is the Stefan number defined in Equation (2), where ΔT is the relevant sensible-temperature span, and ΔH is the latent heat. A low Stefan number indicates that latent heat dominates sensible heat over the selected operating interval. For application design, however, this ratio must be interpreted together with charging time, heat-transfer coefficient, thermal diffusivity, and geometry because incomplete melting or solidification can prevent the nominal latent capacity from being fully used [28,3].

Containment strategies can be organized by scale. Macroencapsulation uses panels, pouches, tubes or tanks and can preserve high PCM mass fraction, but heat-transfer path lengths are often larger. Micro- and nanoencapsulation surround droplets or particles with polymeric, inorganic, or hybrid shells, increasing surface area and enabling dispersion in composites or slurries. Form-stable systems instead retain PCM in porous matrices or cross-linked polymer networks through capillary forces, surface tension, or physical confinement. The best strategy depends on application: building boards may tolerate polymer or mineral matrices, battery systems may prioritize thermal conductivity and fire behavior, and food logistics may emphasize non-toxicity and containment integrity [16,17,18,29].

Durability is the final conceptual gate between calorimetry and engineering qualification. Repeated melting and crystallization can alter phase segregation, polymorphic state, oxidation, crystallization temperature, and effective enthalpy. Fatty acids can also interact with metals, elastomers, polymers, or encapsulant shells. The 2026 palm-fatty-acid study is particularly important because it extends evaluation beyond initial DSC curves to long-duration thermal treatment, 350 cycles, and corrosion against stainless steel, aluminum, copper, and brass, demonstrating that palm-derived fatty acids can approach paraffin-like reliability when compatibility is verified [11]. Recent accelerated-cycling work also demonstrates the value of combining calorimetry with chemical and gravimetric analyses when evaluating long-term organic-PCM stability, rather than relying on DSC alone [30].

$$\begin{aligned} Q_{total} &= m [c_{p,s}(T_m - T_i) + \Delta H_m + c_{p,l}(T_f - T_m)] & (1) \\ Ste &= c_p \Delta T / \Delta H & (2) \end{aligned}$$

Equation (1) provides a readable first-order energy balance for a solid-liquid PCM, while Equation (2) highlights the ratio of sensible to latent heat over the operating interval. Both relations are screening tools; they do not replace transient heat-transfer analysis in modules where geometry, convection, contact resistance, and incomplete phase transformation can dominate performance.

Methodology

This study employed a critical qualitative literature review rather than a systematic literature review. The review was structured around the engineering problem defined in the proposed article: whether palm oil and its derivatives can function as a tunable molecular platform for thermal energy storage PCMs, and what material and system modifications are required for credible applications. Literature published primarily from 2020 to 2026 was prioritized, with emphasis on peer-reviewed journals in thermal energy storage, applied thermal engineering, materials science, energy conversion, buildings, and renewable-energy systems. Earlier studies were used only where necessary to explain established fatty-acid or PCM principles.

The evidence was synthesized thematically rather than through PRISMA-style screening or meta-analysis. Themes were developed iteratively around molecular design and phase behavior; thermal-conductivity enhancement; encapsulation and form stabilization; thermal cycling, oxidation, leakage, corrosion and safety; application-temperature matching; and life-cycle, feedstock and scale-up considerations. Palm-specific studies were interpreted alongside broader fatty-acid, vegetable-oil and bio-based PCM research because the palm-specific engineering evidence base remains smaller than the general PCM literature.

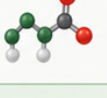
Critical synthesis focused on trade-offs rather than on ranking individual materials by a single property. Particular attention was given to latent-heat dilution caused by conductive fillers and support matrices; the relationship between broad melting ranges and thermal buffering; the distinction between material-level and system-level performance; and the need to match sustainability claims to feedstock source and processing intensity. Findings were then translated into an application-oriented temperature map and a staged development framework for future palm-derived PCM systems.

Results: Thematic Synthesis

The literature indicates that the technical value of palm-derived PCMs lies in portfolio design rather than in a single canonical formulation. Crude or refined palm oil provides a complex triglyceride mixture with multiple thermal events, while palm stearin, palm olein, isolated fatty acids, and downstream esters occupy different temperature domains. This portfolio logic is more useful for engineering than a binary comparison of “palm oil versus paraffin” because real applications impose distinct temperature targets and cycling schedules. The two 2020 building studies already illustrated this difference: expired palm oil and palm-derived fatty-acid blends exhibited broad or multiple transitions that could buffer building temperatures across more than one seasonal condition [4,9].

Table 1 summarizes the principal palm-derived material families and their design roles. It does not assign fixed melting points to all fractions because commercial and experimental materials vary with cultivar, refining route, purity, and formulation. Instead, it identifies the most defensible engineering function of each family and the key qualification need before deployment. The comparison should be read as a screening framework: each material family offers a distinct temperature and processing advantage, but each also carries a different qualification burden that must be resolved before system integration.

Table 1: Palm-derived material families as an engineering PCM platform

Palm material family	Design role	Likely engineering value	Primary qualification need
 Palm oil / expired palm oil	Broad natural triglyceride mixture	Wide thermal-buffering range; low processing intensity	Batch variability, oxidation, leakage, LCA
 Palm stearin	Higher-melting fraction	Solar heat, space heating, low-grade heat storage	Cycling, heat-transfer design, supply consistency
 Hydrogenated palm stearin	More saturated, stabilized fraction	Higher transition temperature and oxidative stability	Hydrogenation burden, long-term system cycling
 Palm olein / oleic-rich fractions	Lower-melting, more unsaturated fraction	Lower-temperature thermal regulation	Oxidation control and phase stability
 Palm fatty acids	Molecularly defined building blocks	Precise temperature selection; eutectic design	Purity, corrosion, compatibility
 Palm-derived esters / alcohols	Chemically tunable derivatives	Expanded transition windows and material compatibility	Synthesis energy, reversibility, cost

Palm stearin is a particularly promising platform for higher ambient and low-grade heating applications because fractionation concentrates higher-melting components. Hydrogenation can further reduce unsaturation, raise melting temperature and improve oxidative stability. The pilot-scale hydrogenated palm-stearin study in the Colombian Andes demonstrated storage of approximately 40 MJ over a seven-hour charging period in a 550 kg storage mass, with subsequent heat release contributing to nighttime indoor heating. The later 2026 field study extended this concept to a full thermally managed solar system and reported that the integrated system could meet a substantial share of annual dwelling thermal demand while maintaining PCM properties over extended operation [31], [32,10,12].

Individual palm fatty acids extend tunability further. Caprylic, capric, lauric, myristic, palmitic, stearic and oleic acids cover a wide spectrum of phase behavior, and binary or multicomponent formulations can shift transition temperature toward target applications. Ramli et al. showed that seven palm fatty acids retained generally stable phase-transition behavior after thermal treatment and cycling, while corrosion rates against common engineering metals were largely below critical long-term thresholds [11]. This finding is significant because material-selection discussions often assume that bio-based PCMs are inherently benign; in practice, compatibility data are required for tanks, fins, heat exchangers and encapsulation hardware.

The most important implication of the molecular evidence is that feedstock processing should be application-led. Fractionation can be used where broad triglyceride distributions are unsuitable; hydrogenation can be used where higher melting temperature and oxidative stability justify the added processing; esterification can reduce or redirect crystallization behavior; and eutectic blending can depress melting points for comfort-temperature applications. Such processing, however, consumes energy and reagents. Therefore, a lower-carbon design cannot be assumed from biological origin alone; the degree of chemical modification must be justified by system performance and life-cycle gain [4-6].

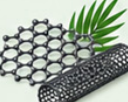
Heat-Transfer Enhancement: Conductivity Versus Latent-Heat Dilution

Low conductivity is the most consistently reported performance bottleneck for organic PCMs. In a large storage volume, the region

adjacent to the heat-transfer surface melts first and can create a liquid layer whose natural convection may help charging, but solidification is often conduction-dominated. If the conductive path is weak, the center of the PCM can remain untransformed while the heat exchanger reaches the operating limit. For a palm-derived PCM, this means that high latent heat measured by DSC does not guarantee high deliverable storage power at system scale [1,2].

Table 2 provides an application-oriented comparison of the main heat-transfer and containment strategies considered in the recent literature. It should be read as a trade-off matrix rather than a ranking, because the preferred intervention depends on whether thermal power, leakage control, mass, manufacturability, cost, or safety is the binding design constraint.

Table 2: Heat-transfer and Containment Strategies and their Principal Trade-offs

Enhancement strategy	Main benefit	Key penalty / risk	Best-fit palm-PCM use
 Expanded graphite / porous carbon	Conductivity + shape stabilization	Latent-heat dilution; pore/loading optimization	Building modules, solar storage, form-stable composites
 Graphene / CNTs	Large conductivity gain at low loading	Cost, dispersion, aggregation, lifecycle burden	Compact high-power modules
 Metal / ceramic particles	Conductivity and possible mechanical benefit	Density, sedimentation, corrosion or processing cost	Battery/electronics composites
 Metal foams / fins	Shorter heat-transfer path without mixing large filler mass	Hardware mass and manufacturing complexity	Tanks, solar storage, industrial modules
 Micro/nanoencapsulation	Leakage control and high surface area	Shell mass, interfacial resistance, shell failure	Buildings, packaging, slurries
 Polymer network / form stabilization	Leakage control and mechanical integration	Polymer mass, fire/recyclability concerns	Battery and building composites

Expanded graphite is attractive because it can perform two functions simultaneously: provide a porous support that limits leakage and create a conductive network. Fatty-acid/expanded-graphite studies consistently show faster thermal response and conductivity gains, but also demonstrate the dilution principle. Zhou et al. observed that increasing expanded-graphite fraction substantially increased conductivity and shortened storage/release time, while the latent heat per unit mass of composite declined in proportion to the non-PCM fraction [26]. Wang et al. similarly reported an optimum region rather than a monotonic system benefit, because high graphite content eventually sacrifices too much storage mass [21].

Graphene, carbon nanotubes, and hybrid carbon nanostructures can raise thermal conductivity at lower mass fractions than conventional fillers, but dispersion, aggregation, viscosity, cost, and environmental burden become more prominent. Nano-enhanced PCM reviews emphasize that measured conductivity gains depend strongly on particle geometry, functionalization, and percolation. A small amount of well-connected two-dimensional filler may outperform a larger loading of isolated particles, whereas aggregation can produce sedimentation and local thermal pathways that deteriorate cycling reproducibility [14,15,3].

Metallic particles, metal foams, and ceramic fillers such as aluminum nitride are alternative routes where electrical properties, flame behavior, or mechanical strength matter. Su et al. demonstrated a bio-based lauric–stearic eutectic composite in an EVA matrix with aluminum nitride for battery thermal management; the conductive additive increased thermal performance while shape stabilization prevented gross leakage [33]. Although the fatty acids in that study were not necessarily palm-sourced, the formulation strategy is directly transferable to palm-derived lauric or stearic streams. The critical design rule is that filler selection should be based on required thermal power and safety rather than on headline thermal conductivity alone.

At system scale, fins and heat-exchanger geometry may offer a cleaner solution than heavy filler loading because they preserve a high fraction of active PCM. Fins, metal foams, heat pipes, or cascaded PCM layers can shorten conduction distances without mixing large quantities of inert material into the PCM. The trade-off shifts from latent-heat dilution to added hardware mass, manufacturing complexity, and potential corrosion. For palm-derived PCMs intended for tanks or modules, an integrated optimization of PCM conductivity and exchanger architecture is therefore preferable to maximizing either one independently [34,35,2].

Shape Stabilization and Encapsulation

Leakage during melting is a major barrier to direct incorporation of organic PCMs into walls, packaging, electronics or structural composites. Macroencapsulation is the simplest route and is compatible with palm-derived PCMs because it requires relatively little chemical modification. Pouches, plates, tubes, cartridges and tanks can maintain a high PCM fraction and simplify replacement. The disadvantage is a relatively low surface-area-to-volume ratio, which can intensify the conductivity problem and produce large thermal gradients unless the container geometry is optimized [17,2].

Microencapsulation reduces heat-transfer length by enclosing small PCM droplets or particles in polymeric, inorganic or hybrid shells. The shell prevents liquid migration and can improve mechanical integration with gypsum, concrete, textiles or slurries. However, encapsulation efficiency must be distinguished from apparent stability: a capsule can remain physically intact while losing latent capacity through shell mass, incomplete core loading or chemical interaction. Reviews published since 2021 therefore recommend evaluating core fraction, shell thickness, particle-size distribution, thermal cycling and mechanical damage together rather than reporting encapsulation yield alone [16,36,37,18,19].

Inorganic or hybrid shells can provide higher temperature resistance and lower flammability than many purely polymeric shells, but can be brittle or more energy intensive to synthesize. Polymeric shells are easier to process and more flexible, yet their fire performance and long-term permeability require scrutiny. These concerns are especially relevant for palm-derived fatty acids, which may oxidize or migrate if the shell is permeable to oxygen or if repeated volume change induces cracks. Building applications additionally require compatibility with cementitious alkalinity, moisture and mechanical loads [18,38].

Form-stable PCMs avoid discrete capsules by absorbing the molten PCM into porous structures or immobilizing it in polymer networks. Expanded graphite, porous carbon, diatomite, biochar and polymer matrices can hold liquid through capillary forces and surface interactions. This architecture is attractive for palm-derived PCMs because it can combine leakage control with thermal-conductivity enhancement. The main design challenge is pore matching: pores must be accessible enough to achieve high loading but capable of retaining the liquid during heating. Excessive support fraction lowers latent heat, while very large pores can permit seepage [29,27].

The sustainability advantage of bio-based PCMs can be weakened by a fossil-intensive encapsulant. For this reason,

current research increasingly considers cellulose, lignin, biochar and other bio-derived support materials. Recent bio-based PCM reviews identify bio-derived encapsulation and composites as an emerging route toward lower-impact TES, while emphasizing unresolved questions around moisture stability, fire behavior, microbial durability and industrial processability [39,40,6]. For palm systems, there is a particularly interesting circular-economy opportunity in combining a palm-derived PCM core with agricultural-residue-derived porous carbon or cellulose support, provided that the support's production energy and emissions are quantified rather than assumed to be negligible.

Thermal Reliability, Chemical Stability, Corrosion and Safety

A PCM intended for thousands of cycles must retain transition temperature, latent heat, chemical identity, and containment integrity. Thermal cycling can expose phenomena that are invisible in first-run calorimetry: phase segregation, changes in crystallization nucleation, oxidation and loss of volatile components. Fatty-acid eutectics have generally shown favorable cycling behavior when compositions are well selected, and several studies report only moderate shifts after repeated cycles. Nevertheless, small enthalpy losses become economically important when a storage system is expected to operate for years [20,1,11].

Oxidation is particularly relevant to unsaturated palm-derived fractions. Palm olein and oleic-rich derivatives may provide low transition temperatures but contain more double bonds than highly saturated stearin or hydrogenated products. Antioxidants, oxygen-barrier encapsulation, and partial hydrogenation can improve stability, but each introduces cost or processing burden. A rational design should therefore match oxidation resistance to actual operating temperature and exposure rather than automatically hydrogenating the feedstock to maximum saturation.

Corrosion must be treated as a coupled materials problem. Even relatively mild organic acids can interact with metals over long exposure periods, and the corrosion rate can depend on water contamination, temperature, and alloy composition. Ramli et al. provide valuable recent evidence that palm fatty acids can be compatible with stainless steel, aluminum, copper and brass under tested conditions, but the results should not be generalized to every alloy, weld, coating or additive package [11]. Prototype qualification should include the exact container and heat-exchanger materials proposed for service. A broader review of PCM corrosion likewise identifies container-PCM compatibility as a life-limiting design variable and recommends application-specific corrosion testing rather than generic material assumptions [41].

Flammability is another commercialization issue. Bio-based organic PCMs are combustible, and replacing paraffin with a renewable lipid does not remove fire risk. Conductive carbon additives can change heat-spreading behavior, polymer shells can add fuel, and metal powders may create separate hazards. Flame retardants, inorganic shells, and compartmentalized module design can reduce risk but may further dilute latent heat. Fire testing should therefore be considered a design requirement for building and battery applications rather than a late-stage certification task [42,43].

Temperature-Application Matching

The principal engineering advantage of the palm platform is the ability to target different transition windows through fractionation, fatty-acid selection, hydrogenation, and eutectic blending. Figure 1 translates this concept into an application map. The ranges are indicative design windows rather than fixed specifications, because the correct transition temperature depends on climate, equipment limits, control strategy, and heat-transfer approach. The figure is intended to prevent a common error in PCM literature: treating high latent heat as universally beneficial without first confirming that the phase change occurs where the application can use it. Figure 1 should therefore be interpreted horizontally, by matching the application duty window to an appropriate PCM transition range before optimizing latent heat or conductivity.

For building envelopes and passive indoor-temperature control, PCMs typically need transitions near the comfort range. Broad-melting palm-oil mixtures can be advantageous because they buffer a wider temperature swing, but the stored energy may be released less sharply than in a narrow-transition pure compound. Landi et al. showed that palm-based mixtures with multiple melting ranges could support seasonal building use, while broader building reviews emphasize that climate and PCM position within the envelope strongly influence benefit [9,44-46,38,47].

Battery and electronics thermal management typically requires a higher transition range, commonly around the upper end of safe or efficient operating temperatures. Fatty-acid eutectics can be tuned toward this region, and the lauric–stearic composite reported by Su et al. demonstrates how a bio-based formulation can combine phase-transition targeting, shape stabilization, and conductivity enhancement [33]. Palm-derived lauric and stearic streams could, in principle, supply the molecular core of similar systems, but battery qualification would additionally require abuse testing, flame propagation analysis, and integration with active cooling.

Solar photovoltaic thermal management overlaps the battery range but imposes outdoor cycling, irradiance, and weathering

conditions. PCM placement behind a PV panel can absorb transient heat and reduce peak cell temperature, but once the PCM is fully melted, its cooling benefit declines until solidification occurs. Conductivity-enhanced systems can delay overheating by spreading heat, while nighttime solidification restores storage capacity. Recent PV reviews confirm meaningful temperature reduction from PCM integration but also identify long-term durability and heat rejection as central challenges [48-50].

Solar-thermal storage and domestic hot water can use higher transition temperatures. Hydrogenated palm stearin is especially relevant because its more saturated molecular composition supports a higher melting window and improved oxidative stability. The Colombian pilot and field studies provide unusually strong palm-specific evidence at system scale and indicate that palm-derived PCM can serve not only as a passive buffer but as a genuine storage medium integrated with collectors, heat exchangers and control systems [31,32,10,12].

Cold-chain applications require lower transition temperatures and often demand narrow temperature control to protect foods, vaccines or other sensitive products. Conventional water/ice and salt systems dominate many sub-zero applications, but bio-based fatty-acid mixtures may be relevant for chilled—not deeply frozen-temperature bands. Cold-chain reviews emphasize the value of PCM packages for reducing temperature excursions and refrigeration load. Palm-derived lower-melting fatty acids or carefully designed eutectics may therefore be candidates for chilled transport, although food-contact safety, odor, leakage resistance and certification would be decisive [51]. Table 3 consolidates these application windows into a screening matrix that links target temperature range with palm-derived design logic and the additional qualification tests required for deployment. A 2025 critical review of cold thermal energy storage further identifies bio-based PCMs as promising for refrigeration and perishable-product protection, while emphasizing that material placement, transition temperature, and product-quality constraints must be assessed together [52]. Table 3 complements Figure 1 by translating the temperature windows into application-specific formulation logic and qualification tests, thereby linking materials selection to deployment requirements.

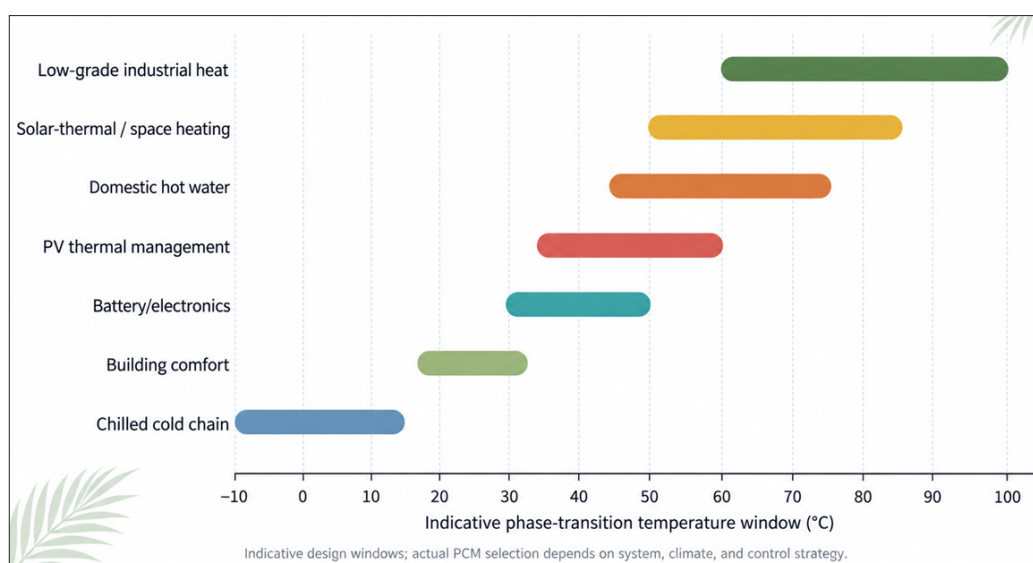


Figure 1: Temperature–application map for palm-derived and fatty-acid-based PCM design.

Table 3: Application-oriented Screening Windows for Palm-derived PCM Development

Application	Indicative PCM transition window	Palm-derived design logic	Critical additional tests
 Chilled cold chain	~ -10 to 15 °C	Low-melting fatty-acid/ester or eutectic formulations	Food-contact safety, odor, leakage, transport cycling
 Building comfort	~18–32 °C	Broad palm-oil transitions or fatty-acid eutectics	Climate-specific annual cycling, fire, envelope compatibility
 Battery/electronics	~30–50 °C	Lauric/stearic-type eutectics with conductive support	Abuse, fire, electrical insulation, vibration
 PV thermal management	~35–60 °C	Fatty-acid or stearin composite behind PV module	Outdoor aging, weathering, heat rejection, fire
 Domestic hot water	~45–75 °C	Stearin/hydrogenated fractions or higher-melting fatty acids	Corrosion, tank cycling, heat exchanger design
 Solar-thermal / space heating	~50–85 °C	Hydrogenated palm stearin and engineered composites	Field cycling, control, freeze/overheat protection
 Low-grade industrial heat	~60–100 °C	Higher-melting derivatives or tailored blends	Chemical compatibility, process integration, economics

Engineering Applications Beyond Material Characterization

The building sector remains the most accessible application because PCMs can be incorporated in envelopes, panels, floors, ceilings or dedicated thermal stores, and operating temperatures often align with fatty-acid and plant-oil transitions. Palm-based PCM studies have already demonstrated thermal buffering and life-cycle potential, but large-scale deployment will depend on module durability, fire compliance and climate-specific optimization. A PCM that performs well in a controlled chamber may deliver limited annual savings if it does not fully solidify overnight or if its transition range is mismatched to seasonal conditions [4,46,38].

Cold-chain logistics offers a second opportunity because passive latent storage can protect products during transport interruptions, door openings, or last-mile delivery. The economic value can be high even when total energy stored is modest, since the main benefit is temperature stability and product protection. For palm-derived formulations, this application favors non-toxic, odor-controlled, leak-proof encapsulation and a phase transition tightly matched to the permissible product-temperature band. Feedstock purity and regulatory status may be more important than maximum conductivity.

Photovoltaic and photovoltaic-thermal systems benefit when the PCM limits short-term temperature peaks. Bio-based PCMs are attractive because the sustainability narrative aligns with renewable electricity, but outdoor exposure adds cyclic stress. A palm-derived composite with a conductive support could be designed as a removable back-panel module, allowing material replacement without altering the PV laminate. Such modularity would also simplify fire testing and end-of-life recovery compared with permanently embedding the PCM into the panel structure [48,50].

Battery thermal management is technically demanding but strategically important. A passive PCM can absorb transient heat and homogenize cell temperature during high-rate operation, yet repeated high-power cycling may exceed the PCM's heat-rejection capacity. Hybrid systems that combine PCM with air, liquid cooling, heat pipes, or thermoelectrics are therefore more realistic than stand-alone PCM for demanding traction batteries. Palm-derived fatty-acid eutectics may contribute to such hybrid systems if they meet flammability, electrical insulation, mechanical, and long-term stability requirements [33,53]. Recent reviews of hybrid battery thermal-management systems indicate that combining PCMs with active cooling, heat pipes, or other phase-transition strategies can address the limited heat-rejection capacity of passive PCM-only designs under severe duty cycles [54].

Industrial waste-heat recovery and process-temperature smoothing constitute a broader but less developed field. Low-grade heat streams are often intermittent and too cool for efficient power generation, making latent storage potentially attractive. The palm platform may be especially valuable in palm-oil mills or oleochemical facilities because feedstock availability, on-site processing,

and heat demand could be co-located. However, using food-grade palm oil directly for storage would be difficult to justify if higher-value uses exist. Side streams, off-spec fractions, used oils or locally produced fatty-acid cuts are more defensible candidates where material quality can still be controlled [5,27,43].

Sustainability, Feedstock Hierarchy, Economics and Scale-Up

Bio-based does not mean impact-free. Palm oil is associated with well-documented land-use, biodiversity and governance concerns in parts of its supply chain. A PCM application that consumes additional virgin edible oil could therefore shift environmental burden rather than eliminate it. The strongest sustainability case is likely to involve certified feedstock, non-food fractions, side streams, expired material, off-spec batches, recovered fatty acids or industrial residues that do not stimulate additional land conversion. Fabiani et al. demonstrated the conceptual value of expired palm oil, while the hydrogenated palm-stearin fieldwork highlights the potential of local industrial streams for thermal storage [4]. Recent work on industrial- and agricultural-waste-derived PCMs reinforces the case for residue-based feedstock hierarchies because waste-derived formulations can couple thermal-storage functions with circular-economy benefits when source variability and processing burdens are controlled [55].

Lifecycle assessment should compare functionally equivalent systems rather than equal masses of PCM. A palm PCM with lower conductivity may require a larger heat exchanger; a composite may require graphite, polymer and aluminum; an encapsulated PCM may last longer than an uncontained material. The correct functional unit could therefore be delivered kilowatt-hours of thermal storage over the service life, including replacements and recovery, rather than one kilogram of material. Recent bio-PCM reviews increasingly call for this system-level framing and for life-cycle comparison at the functional-system level rather than by renewable feedstock label alone [5,6,56,57].

Cost analysis also needs to distinguish feedstock price

from installed storage cost. Highly purified fatty acids and nanomaterials can make a nominally bio-based PCM more expensive than paraffin, while crude or side-stream palm fractions may be inexpensive but thermally heterogeneous. Encapsulation equipment, mixing, vacuum impregnation, hydrogenation, quality control, and module fabrication can dominate the final cost. Commercialization therefore depends on minimizing unnecessary purification and selecting processing steps that materially improve application performance.

Standardization is a major gap. Laboratory studies use different DSC heating rates, sample masses, cycling conditions, leakage tests, and conductivity methods, making direct comparison difficult. For palm-derived PCM development, a common test matrix should include phase-transition temperature and enthalpy by standardized calorimetry; thermal conductivity in relevant phases; thermal cycling to application-relevant counts; oxidation and chemical stability; leakage and dimensional stability; corrosion with actual construction materials; fire behavior; and module-level charging/discharging performance. Without such harmonization, high-performance results remain difficult for engineers and investors to compare.

Figure 2 summarizes the resulting development logic. Molecular feedstock selection is the first stage, followed by deliberate chemical or physical tuning, containment and conductive architecture, and then full system qualification. Sustainability and scale-up are shown as a gate across the entire process rather than as an assessment performed after technical optimization. This integrated pathway is essential because a highly modified PCM may achieve excellent thermal metrics while losing the environmental or economic rationale that motivated a bio-based material in the first place. Table 4 operationalizes the framework as a staged qualification roadmap, linking each development stage to a minimum evidence package and a decision gate. The arrows indicate a gated progression rather than a purely linear sequence: molecular and formulation choices feed heat-transfer engineering and qualification in parallel before an application is considered ready for scale-up.

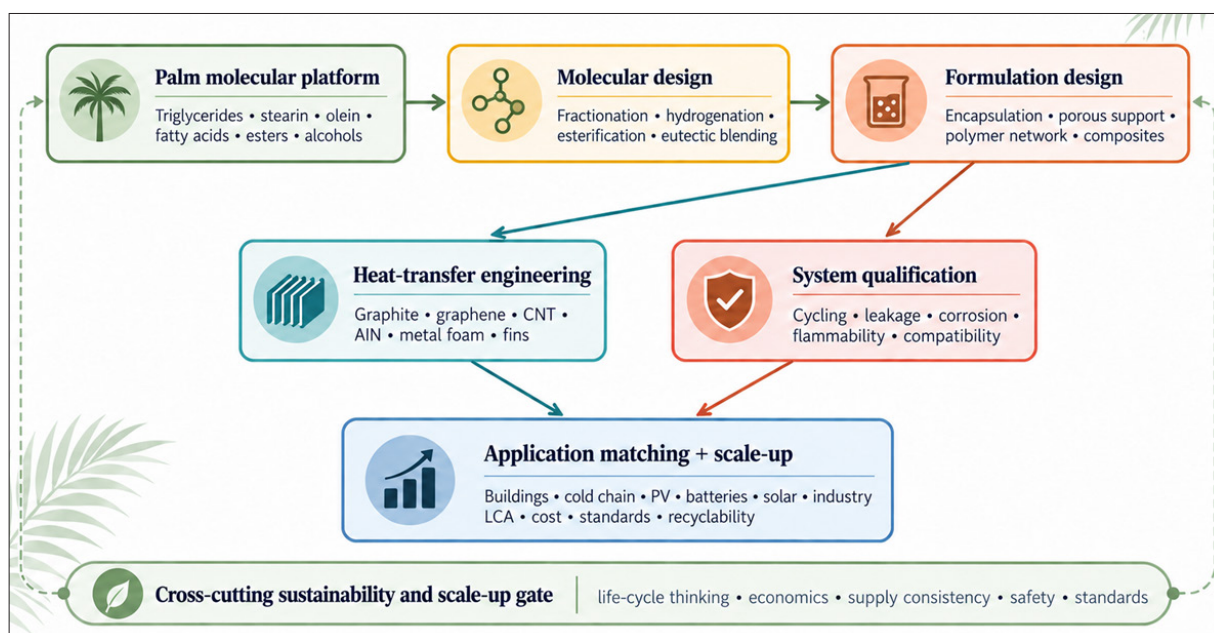


Figure 2: Integrated design framework from palm molecular platform to application-qualified thermal storage.

Table 4: Proposed Staged Qualification Roadmap for Palm-derived PCM Systems

Development stage	Minimum evidence package	Decision gate
 1. Molecular screening	DSC, transition range, latent heat, TGA/FTIR, conductivity	Does the feedstock match the target temperature window?
 2. Formulation	Eutectic/chemical tuning, additive screening, leakage testing	Is useful performance improved without excessive processing?
 3. Composite/module design	PCM fraction, effective conductivity, containment, mechanical integrity	Is deliverable thermal power adequate?
 4. Reliability and safety	Extended cycling, oxidation, corrosion, fire, environmental exposure	Can the system meet service-life and code requirements?
 5. Scale-up	Pilot operation, TEA, LCA, quality control, standards	Is the system competitive and environmentally defensible?

Discussion and Critical Analysis

The evidence supports the central argument that palm oil should be conceptualized as a tunable molecular platform for thermal storage. This framing is more technically productive than classifying it simply as a plant-oil PCM. Palm fractions and derivatives span broad molecular structures and transition temperatures, and recent studies demonstrate that fractionation, hydrogenation, fatty-acid selection, and eutectic formulation can move the material across distinct application windows. The strongest evidence is no longer limited to small calorimetry specimens: pilot and field solar-storage studies using hydrogenated palm stearin demonstrate that material-level promise can translate into operating systems [31,32,10,12].

At the same time, the literature reveals a recurring optimization paradox. The intrinsic strengths of lipid PCMs—high latent heat, reversible melting, and renewable sourcing—are accompanied by weak thermal conductivity and liquid mobility. Engineering interventions improve one weakness by creating another penalty. Graphite and ceramic fillers improve heat transfer but dilute latent heat. Encapsulation suppresses leakage but adds shell mass and interfacial resistance. Polymer networks provide shape stability but can increase flammability and hinder recyclability. Hydrogenation increases stability and transition temperature but requires additional processing energy. The design objective must therefore be multicriteria optimization rather than maximizing any single thermophysical property [14,2,3].

This trade-off can be formalized as a system-level performance problem. A practical PCM should maximize deliverable thermal energy within a required time while remaining inside constraints

on peak temperature, mass, volume, cost, safety, and cycle life. A high-enthalpy but poorly conducting material may have lower deliverable power than a composite with lower enthalpy but faster internal heat transfer. Conversely, excessive conductive filler can make charging fast but reduce total stored energy. This implies that comparative studies should report not only DSC enthalpy and conductivity but also complete melting/solidification time, usable storage energy, and heat-transfer rate in representative modules.

The palm-specific evidence base is still uneven. Buildings and solar thermal storage have direct palm-oil or palm-stearin studies, whereas batteries, electronics, PV cooling and cold chains are supported more strongly by general fatty-acid or bio-based PCM literature. The transferability is scientifically plausible because the relevant molecules—lauric, palmitic, stearic and oleic acids—can be palm-derived, but source equivalence should not be assumed. Purity, minor components, and refining history may alter crystallization, oxidation, and compatibility. Future palm-specific studies should therefore reproduce promising generic fatty-acid formulations using traceable palm-derived feedstocks.

A second gap is long-duration evidence. Hundreds of laboratory cycles are useful, but building and industrial systems may experience thousands of phase transitions over service life. Ramli et al. strengthen the evidence by combining prolonged thermal treatment, hundreds of cycles, and corrosion testing, yet larger datasets are required across encapsulated and composite formulations [11]. Accelerated aging should incorporate oxygen exposure, humidity, vibration, freeze–thaw conditions where relevant, and realistic thermal gradients rather than repeated idealized DSC cycles alone.

A third gap concerns sustainability accounting. Many reviews present bio-based PCMs as environmentally preferable, but the conclusion depends on feedstock and processing. A palm PCM made from certified side streams and stabilized with low-impact porous carbon may provide a compelling circular-economy pathway. A highly purified virgin palm fatty acid combined with energy-intensive graphene, fluorinated shell polymers, and aluminum hardware may not. Future studies should disclose feedstock origin and include cradle-to-grave or cradle-to-cradle assessment at functional-system level.

A fourth gap is safety and regulation. Building and battery adoption requires fire testing, toxicological assessment of additives, smoke characterization, leakage containment, and compatibility with codes. Cold-chain applications may require food-contact or pharmaceutical packaging compliance. Solar and industrial storage tanks require pressure, corrosion, and thermal-expansion design. These are not peripheral commercialization details; they influence material choice from the beginning. For example, an inorganic shell might be selected primarily for fire resistance, even if a polymer shell offers higher encapsulation efficiency.

The research roadmap should therefore progress through five stages. Stage one is molecular mapping of palm fractions and derivatives using standardized DSC, thermal conductivity and chemical characterization. Stage two is application-targeted formulation, including eutectic design and controlled hydrogenation or esterification. Stage three is composite optimization for conductivity and containment using minimum necessary inactive mass. Stage four is module-level testing under realistic charging rates, environmental exposure and safety conditions. Stage five is techno-economic, life-cycle and standards-based qualification at pilot scale. This staged logic avoids the common failure mode of optimizing a laboratory PCM without a defined system or market requirement.

From a strategic perspective, palm-producing countries could use this technology to diversify oleochemical value chains toward advanced thermal-management materials rather than additional bulk fuels or commodity chemicals. The opportunity is particularly relevant where palm side streams can be upgraded locally and deployed in buildings, solar heat or cold-chain infrastructure. However, industrial policy should prioritize high-value and residue-based pathways to avoid creating a new demand pressure on edible oil. The long-term advantage would come from combining existing palm-processing infrastructure with materials engineering, quality standards, and thermal-system manufacturing rather than from feedstock abundance alone.

Conclusion

Palm oil and its derivatives constitute a credible platform for bio-based phase-change materials because their molecular diversity can be used to tune thermal behavior across multiple engineering temperature windows. Palm stearin, palm olein, individual fatty acids, esters, and tailored eutectic mixtures should therefore be regarded as members of an adaptable material family rather than as interchangeable versions of a single PCM. This perspective opens a more rigorous route to matching chemistry with building

comfort, cold-chain stabilization, photovoltaic cooling, battery thermal buffering, solar-thermal storage and selected low-grade industrial heat duties.

The principal engineering challenge is not the existence of latent heat but its practical accessibility. Low thermal conductivity can make a high-enthalpy material charge and discharge too slowly, while leakage during melting can prevent direct incorporation into devices and structures. Conductive fillers, porous frameworks, fins, foams, encapsulation, and polymer networks can address these limitations, but every intervention introduces penalties in latent-heat fraction, mass, cost, interfacial resistance, fire performance, recyclability, or manufacturing complexity. Future development should therefore optimize complete storage modules rather than isolated material properties.

Recent palm-specific evidence substantially improves confidence in the platform. Building-oriented palm bio-PCMs, hydrogenated palm-stearin solar-storage systems, and palm-fatty-acid reliability and corrosion studies show that the field is moving from exploratory calorimetry toward engineering validation. The next threshold is long-duration, application-specific qualification under realistic thermal gradients, environmental exposure, mechanical loads, and safety requirements, supported by harmonized test methods.

Sustainability must be demonstrated rather than inferred. The strongest pathways are likely to use certified feedstocks, side streams, expired oils, off-spec fractions or non-food palm derivatives, combined with low-impact supports and recoverable module designs. Lifecycle and techno-economic assessments should be based on delivered thermal-storage service over the system lifetime, not on feedstock mass alone.

The most defensible development strategy is consequently application-first co-design: define the required operating temperature and thermal duty; select or create an appropriate palm-derived molecular composition; engineer conductivity and leakage control with minimum inactive mass; qualify durability, compatibility, and safety; and then validate environmental and economic performance at module and system scales. Pursued in this sequence, palm-derived PCMs can become a technically sophisticated branch of advanced oleochemical materials and a practical component of sustainable thermal-energy management.

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