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Progress in PCM-Assisted Indirect Solar Dryers: Design, Performance Enhancement, and Future Perspectives

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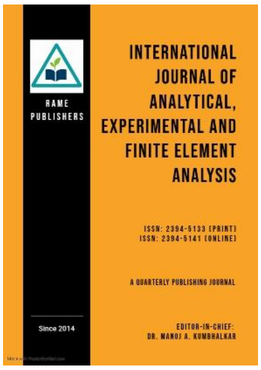

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Abstract. Phase change materials (PCMs) are increasingly integrated into indirect solar dryers to buffer the intermittency of solar radiation, extending useful drying operation into the evening and low-insolation hours by storing latent heat during peak sunshine and releasing it later at a near-constant temperature. This review synthesizes the peer-reviewed literature on PCM-assisted indirect solar drying, covering PCM classification and thermophysical selection criteria, indirect-dryer design fundamentals, PCM integration configurations (macro-encapsulated cans, tubes, fin-enhanced and multi-grade storage banks), and quantitative performance evidence from thirteen independently verified experimental and numerical studies published between 2014 and 2025. Across these studies, reported collector- or drying-efficiency gains attributable to PCM integration range from a modest 6–8% up to 77%, and reported drying-time reductions relative to each study's own stated baseline range from 5.3% (PCM alone, in a PCM-plus-infrared hybrid system) to 50% (combined sensible-and-latent storage); the two configurations most consistently associated with the largest gains are heat-transfer-enhanced PCM (finned or tubed) and combined sensible-plus-latent storage rather than bulk PCM alone. Techno-economic assessments identified in the literature report simple payback periods as short as 0.74–1.29 years for a PCM-integrated active indirect dryer, though dedicated economic modelling for smallholder or rural-farmer adoption contexts is essentially absent from the reviewed literature. Persistent technical challenges include the low thermal conductivity of most organic PCMs, subcooling and phase segregation in salt hydrates over repeated cycling, PCM leakage and container corrosion, and the site- and crop-specific task of matching PCM melting point to locally achievable collector-outlet temperatures. Of the 61 references synthesized in this review, 46% were published between 2023 and 2026, reflecting a rapidly accelerating research interest that has not yet been matched by standardized testing protocols, multi-year field validation, or life-cycle/rural-economics studies. The review closes by situating these findings against an energy-storage-based indirect solar dryer for orange peel drying under development in Nagpur, Maharashtra, India, and identifies a fatty-acid or paraffin PCM in the 50–60°C range, combined with a low-cost finned or expanded-graphite conductivity enhancement, as the most literature-consistent starting point for that application, while flagging the absence of dedicated Indian smallholder PCM-dryer economics as an open research question this project could help address.

Keywords: phase change material; latent heat thermal energy storage; indirect solar dryer; solar drying; thermal energy storage; drying kinetics; techno-economic analysis; review.

1. Introduction

Solar drying is among the oldest and most widely practised methods of agricultural post-harvest preservation, and open (uncovered) sun drying remains the dominant approach across much of the developing world because it requires no capital investment beyond open ground or drying mats [13,14]. Open sun drying is nonetheless slow, weather-dependent, and exposes the product to dust, insects, and microbial contamination, motivating the development of enclosed solar dryers that control airflow and temperature while still relying on a free, renewable heat source [13,14,15]. Indirect solar dryers, in which solar radiation is absorbed and converted to heat in a separate air collector rather than falling directly on the product, are generally preferred over direct-type designs for food products because they avoid photodegradation and give more uniform drying [15,16].

A limitation shared by every solar dryer, direct or indirect, is the intermittent and diurnal nature of the solar resource: insolation is zero at night and falls sharply under cloud cover, interrupting drying at exactly the point many products should ideally be dried continuously to avoid case-hardening or microbial regrowth [15,17]. Thermal energy storage (TES) is the standard engineering response, and while sensible-heat media such as rock, sand, or pebbles are simple and inexpensive, phase change materials (PCMs) offer five- to fourteen-fold higher energy-storage density per unit volume for a practical temperature swing, because they store and release energy largely isothermally as latent heat of fusion rather than as a temperature rise [1,3].

PCM-assisted indirect solar drying has consequently become one of the most active sub-fields of solar drying research over the past decade. This review synthesises that literature under four linked questions: (i) what PCMs and selection criteria are relevant to the 45–70°C temperature window typical of indirect solar drying; (ii) how are PCM storage units physically integrated into indirect-dryer collectors and drying chambers; (iii) what quantitative performance gains — in collector and drying efficiency, drying-time reduction, and extended off-sunshine operation — have been independently verified in the peer-reviewed literature; and (iv) what technical, economic, and environmental barriers and research gaps remain. Figure 1 shows the publication-year distribution of the 61 references synthesised in this review: 46% (28 of 61) were published in 2023–2026 alone, against only 21% (13 of 61) before 2014, indicating a research field that is both maturing and still rapidly accelerating.

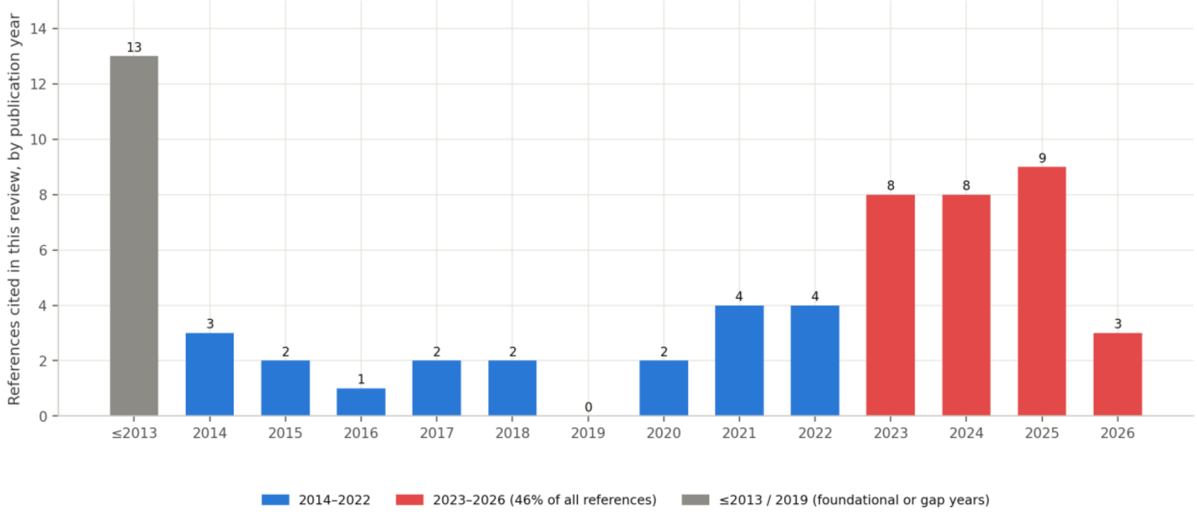

Figure 1. Publication-year distribution of the 61 references synthesized in this review. Bars are colour-coded by period; nearly half of all cited literature was published in the last three years.

This review is deliberately structured around the drying-application literature rather than the general PCM-materials-science literature: general PCM property reviews [1,2,3,4] are drawn upon for foundational classification and thermophysical data (Section 4), but the evidentiary core of the review (Section 6) is built from studies that experimentally or numerically evaluated a PCM integrated specifically into an indirect solar dryer, rather than PCM performance in isolation or in unrelated building/battery-thermal-management contexts. The review closes (Section 10) by relating these findings to an energy-storage-based indirect solar dryer for orange peel drying under development in Nagpur, Maharashtra, India — the same case-study application addressed by a companion Analytic Hierarchy Process (AHP) material-selection study on the dryer's absorber, glazing, and insulation subsystems.

2. Review Methodology and Scope

This review follows a literature-synthesis rather than a formal systematic-review (e.g., PRISMA) protocol, but applies an explicit verification discipline given the well-documented risk of citation and numeric fabrication in AI-assisted literature synthesis. Candidate sources were identified through targeted searches of major solar-energy and energy-storage journals (Renewable and Sustainable Energy Reviews, Solar Energy, Renewable Energy, Journal of Energy Storage, Applied Thermal Engineering, Energy Conversion and Management, and others) and cross-checked against publisher pages, Crossref metadata, or independent bibliographic aggregators (Semantic Scholar, IDEAS/RePEc, OSTI, PubMed/PMC) before inclusion. Every reference cited in this review corresponds to a real, independently locatable publication with a verifiable digital object identifier (DOI) or publisher record; no author, title, journal, or quantitative finding has been invented. Where a specific numeric finding could only be traced to a secondary source (i.e., quoted inside another paper rather than confirmed against the original publication directly), it has either been reported with an explicit hedge ("as reported by...") or, where the underlying citation itself could not be confidently verified, omitted from this review rather than presented as fact. A small number of secondary-source case studies encountered during research — reported only inside a citing review's summary table, with author names or exact figures that could not be independently confirmed — have accordingly been excluded from the reference list rather than cited with uncertain provenance; interested readers are directed to the secondary reviews themselves (e.g., Kavya and Ramana [29]) for those additional, not-independently-re-verified case studies.

Section 6 draws primarily on thirteen studies for which both the bibliographic record and, in most cases, the specific quantitative results were independently confirmed; three of these thirteen (Chaatouf et al. [40], Madhankumar et al. [41], and Radhakrishnan et al. [42]) have confirmed bibliographic details but their headline numeric results were not independently re-extracted for this review and are described only qualitatively here; this is flagged explicitly at first mention in Section 6.1 rather than left implicit. Reference coverage is weighted toward 2020–2026 by design, consistent with the field's rapid recent growth documented in Figure 1, while retaining the foundational general-PCM reviews [1,2,3,4] that establish the classification and terminology used throughout.

3. Fundamentals of Indirect Solar Drying

3.1 Classification

Solar dryers are classified along two largely independent axes (Figure 2). By radiation exposure, they are grouped into direct (open or greenhouse-type) dryers, in which the product is exposed to solar radiation directly, often through a transparent enclosure; indirect dryers, in which solar radiation is absorbed and converted to heat in a separate air collector and only the resulting heated air reaches the product; and mixed-mode dryers, which combine both mechanisms [13,14,15]. By air-circulation mechanism, dryers are further divided into passive (natural-convection, typically chimney-driven) and active (forced-convection, fan- or blower-assisted) designs, with active systems generally achieving higher, steadier airflow and shorter drying times at the cost of additional capital and electrical (or photovoltaic) energy for the fan [15]. These two axes are independent: an indirect dryer, the focus of this review, may be built as either a passive or an active system.

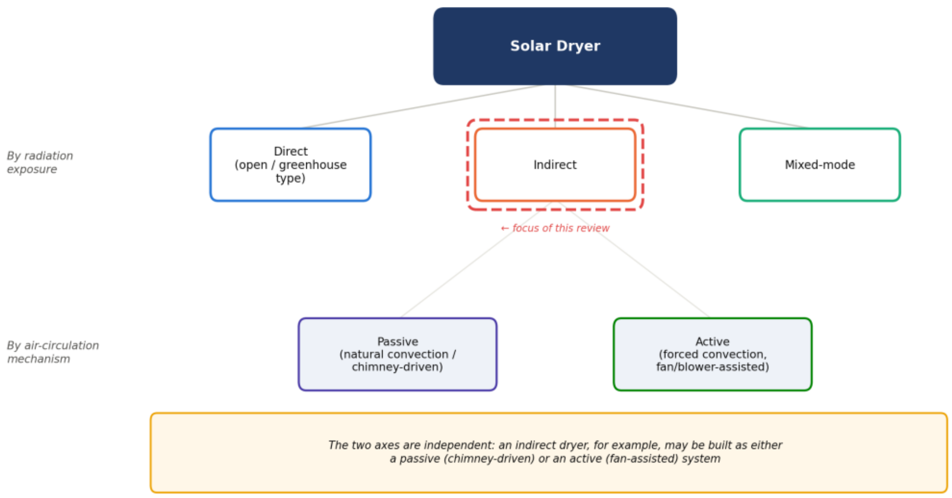

Figure 2. Classification of solar dryers by radiation exposure and by air-circulation mechanism. Indirect dryers, the focus of this review, may be passive or active.

3.2 Construction, Working Principle, and PCM Integration Point

An indirect solar dryer comprises a solar air collector, a drying chamber, and a chimney or exhaust, with an optional fan for active operation (Figure 3) [15,16]. Ambient air is drawn through a duct-shaped collector consisting of a transparent glazing cover and a blackened absorber plate; solar radiation passes through the glazing and is absorbed by the plate, which transfers heat by convection to the air flowing beneath it. This heated air is then ducted into an opaque, insulated drying chamber holding the product on perforated trays, and exits through a chimney or exhaust after picking up moisture. Because the drying chamber is opaque, the product is never directly exposed to solar or ultraviolet radiation, which the literature associates with reduced photodegradation, better colour and nutrient retention, and more uniform drying relative to direct-type cabinets [15,19]. A PCM thermal-storage unit, where present, is typically located immediately downstream of the collector or within the ducting to the drying chamber — the position shown schematically in Figure 3 — so that surplus heat generated during peak insolation charges the PCM, which subsequently discharges into the air stream once the collector output falls below the drying-chamber requirement.

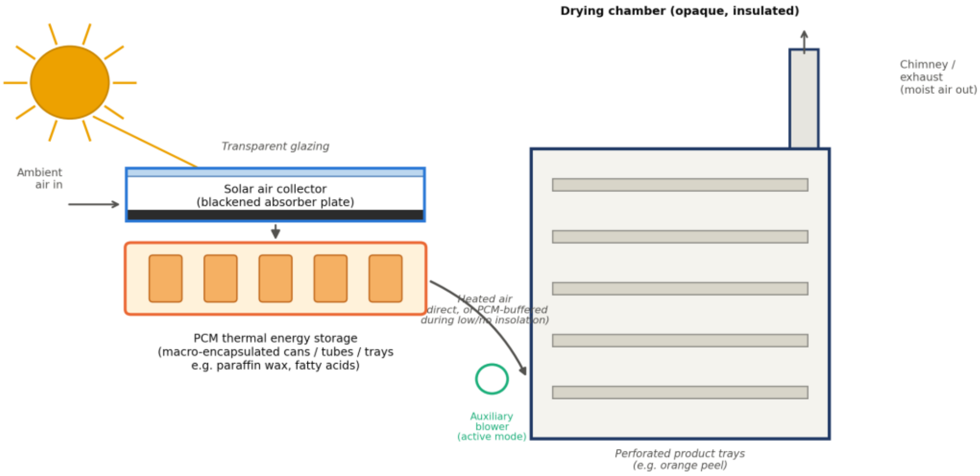

Figure 3. Schematic of a PCM-integrated active indirect solar dryer, showing the solar air collector, PCM thermal energy storage unit, drying chamber with product trays, chimney/exhaust, and optional auxiliary blower.

3.3 The Intermittency Problem and Thermal Energy Storage

Because solar insolation is zero at night, falls sharply under cloud cover, and follows a diurnal profile even on clear days, the drying-air temperature delivered by an unbuffered solar collector fluctuates over the course of a day and disappears entirely for extended periods — one of the two central technical barriers to solar dryer performance identified across the review literature, alongside airflow/temperature uniformity [15,17]. Bal, Satya, and Naik [17] distinguish sensible heat storage, in which a medium such as rock, sand, or water stores energy as a temperature rise and is inexpensive but comparatively bulky, from latent heat storage, in which a PCM stores much more energy per unit mass/volume at a near-constant temperature during melting and solidification, enabling a smaller, more thermally stable storage unit at higher material cost and, for many PCMs, added engineering complexity (Section 8). This sensible-versus-latent distinction, and the specific goal of extending drying operation into non-sunshine hours, is the motivating rationale for essentially the entire body of literature reviewed in Section 6.

3.4 Performance Metrics

Reviews of solar dryer performance converge on a common set of metrics: collector (thermal) efficiency, the ratio of useful heat gained by the collector air stream to incident solar radiation; drying (system) efficiency, broadly the ratio of energy used to evaporate moisture to total energy input; specific moisture extraction rate (SMER), the mass of water removed per unit of energy consumed; moisture ratio and drying rate, used to characterise drying kinetics against thin-layer models; pickup efficiency, the fraction of the drying air's theoretical moisture-carrying capacity actually utilised; and, increasingly in the 2020s literature, exergy efficiency and techno-economic indicators such as payback period [15,20,21]. Ahmadi et al. [21] note that exergy-based and techno-economic metrics have become increasingly prominent as complements to first-law efficiency, because they better capture the thermodynamic quality of the heat used in drying and the economic case for adopting solar drying over the alternatives; this shift toward combined energy–exergy–economic ("3E") and energy–exergy–economic–environmental ("4E") analysis is directly visible in the PCM-specific literature reviewed in Section 7.

4. Phase Change Materials for Solar-Drying Thermal Storage

4.1 Classification

PCMs are conventionally classified into organic, inorganic, eutectic, and — increasingly — bio-based, composite, or form-stable categories (Figure 4) [1,2,3]. Organic PCMs comprise paraffins (n-alkane mixtures) and non-paraffin organics such as fatty acids, esters, and sugar alcohols; paraffins are chemically stable, non-corrosive, and show negligible subcooling, but have low thermal conductivity (≈0.2 W/m·K) and are flammable, while fatty acids show largely congruent melting and good cycling stability but are more costly and mildly corrosive to some metals [1,2]. Inorganic PCMs comprise salt hydrates — the most widely studied low-to-moderate-temperature inorganic PCMs, offering high latent heat per unit volume and relatively high thermal conductivity but prone to subcooling and incongruent melting with phase segregation over repeated cycles [1,9] — and metallics, which are seldom used in solar drying owing to weight and cost. Eutectic PCMs are mixtures of two or more organic and/or inorganic components that melt and freeze congruently at a sharp point usually below either constituent alone, allowing the melting point to be tuned to a specific application temperature [1,3]. Bio-based, composite, and form-stable PCMs — for example, paraffin or fatty acids impregnated into an expanded-graphite or porous-matrix host — are a more recent category that combines renewable/biodegradable sourcing with improved thermal conductivity and shape stability [10].

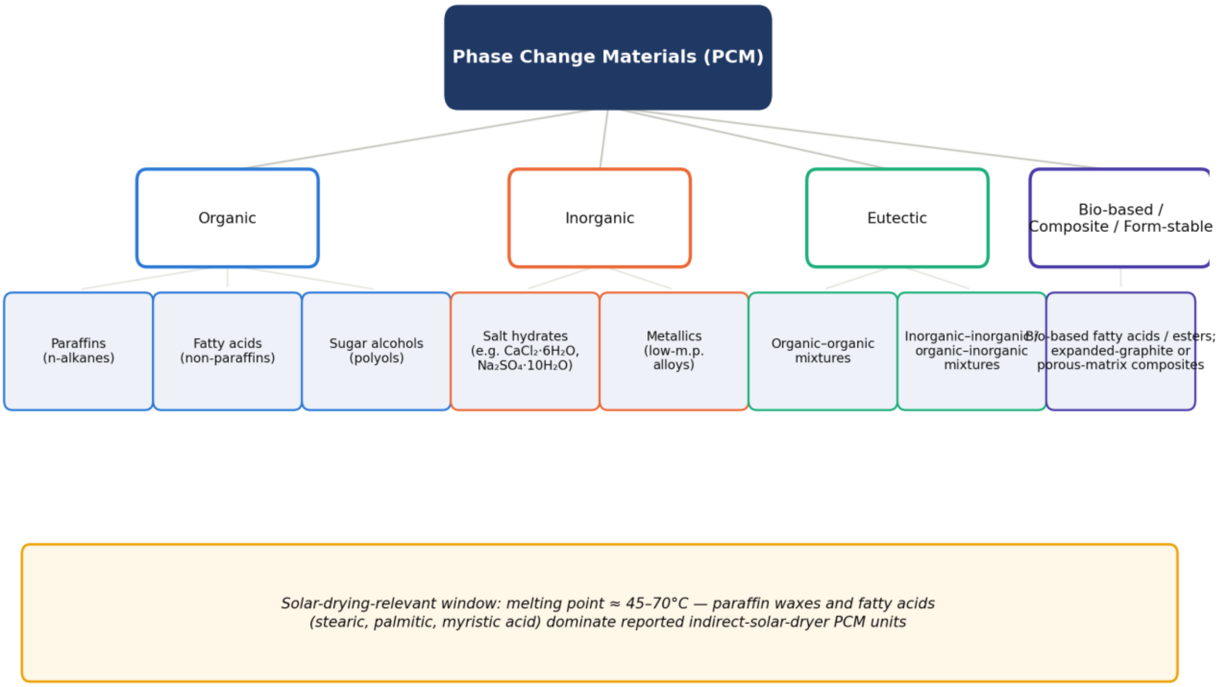

Figure 4. Classification of phase change materials by chemical nature, with representative sub-classes. Paraffins and fatty acids dominate reported PCM units in the 45–70°C indirect-solar-dryer window.

4.2 Selection Criteria

Selecting a PCM for an indirect solar dryer requires balancing thermophysical, kinetic, chemical, and economic criteria simultaneously; no single PCM satisfies all criteria, and the choice is application-specific [1,4]. Key thermophysical requirements are a melting point within the collector/drying-chamber operating window — generally cited as roughly 45–70°C for indirect solar drying, so that the PCM charges during peak insolation and discharges near the desired drying-air temperature [43,24] — high latent heat of fusion per unit mass and volume to minimise storage-unit size, and high thermal conductivity to enable rapid charging and discharging (Section 4.4, since most PCMs are poor conductors). Kinetic criteria include minimal subcooling, so that the material crystallises at or near its equilibrium freezing point rather than releasing heat later than needed, and congruent melting, so that the material does not separate into different phases and lose storage capacity over repeated cycles — a property in which many salt hydrates are deficient relative to paraffins and fatty acids [1,9]. Chemical criteria include long-term cycling stability [8], compatibility (non-corrosivity) with the containment material [51], and non-toxicity, particularly important given that indirect solar dryers process edible produce. Economic and practical criteria — availability, cost, and environmental impact — complete the checklist first tabulated by Abhat [4] and Sharma et al. [1], and remain the standard reference framework cited throughout the solar-drying-specific PCM literature [25,24].

4.3 Properties of Common Solar-Drying PCMs

Table 1 and Figure 5 summarise literature-reported melting points and latent heats of fusion for PCMs that recur most frequently in the solar-drying literature because their melting points fall within, or close to, the 40–70°C band relevant to indirect solar drying. Paraffin wax (melting range approximately 42–72°C, latent heat approximately 150–220 kJ/kg) is by far the most common organic PCM in solar dryer prototypes, owing to low cost, chemical stability, and negligible subcooling [1,4]. Fatty acids — stearic, myristic, palmitic, and capric acid — offer comparable or higher latent heat with generally congruent melting, at higher material cost [1,5]. Acetamide, evaluated for solar thermal storage by Sharma, Sharma, and Buddhi [5], has a melting point (≈79–81°C) somewhat above the typical drying window and is more relevant to higher-temperature collector designs. The inorganic salt hydrates $CaCl_2\cdot 6H_2O$ and $Na_2SO_4\cdot 10H_2O$ offer very high latent heat (particularly the latter, ≈250–254 kJ/kg) but melt below the ≈45°C lower bound typically sought for indirect solar drying and are, correspondingly, discussed more often in the general PCM-classification literature than actually deployed inside solar-dryer prototypes, where paraffin wax and fatty acids dominate [43,24].

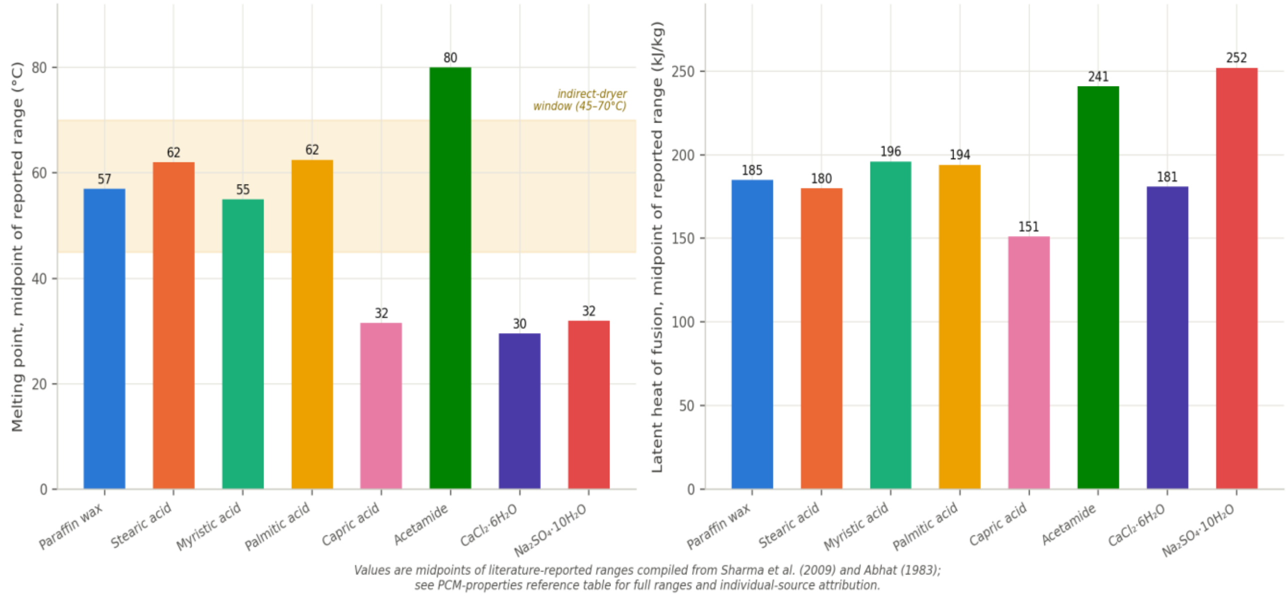

Figure 5. Reported melting point and latent heat of fusion (midpoints of literature ranges) for PCMs commonly used or discussed in indirect-solar-dryer research. The shaded band marks the 45–70°C window typically targeted for indirect solar drying.

Table 1. Literature-reported thermophysical properties of PCMs commonly used or discussed in indirect-solar-dryer research. Ranges are compiled from cited property reviews; exact values vary with material purity/grade and measurement technique.

PCM	Class	Melting point (°C)	Latent heat (kJ/kg)	Notes
Paraffin wax	Organic	42–72	150–220	Dominant PCM in solar-dryer prototypes; λ≈0.2 W/m·K [1,4]
Stearic acid	Organic (fatty acid)	55–70	160–200	Congruent melting; mildly corrosive to some metals [1,5]
Myristic acid	Organic (fatty acid)	52–58	187–205	[1]
Palmitic acid	Organic (fatty acid)	61–64	185–203	[1]
Capric acid	Organic (fatty acid)	31–32	150–153	Useful as eutectic-blend component [1]
Acetamide	Organic (amide)	79–81	≈241	Above typical 45–70°C drying window [5]
$CaCl_2\cdot 6H_2O$	Inorganic (salt hydrate)	29–30	170–192	Subcooling, incongruent melting [1,9]
$Na_2SO_4\cdot 10H_2O$	Inorganic (salt hydrate)	≈32	250–254	Highest latent heat listed; pronounced subcooling unless nucleated [1,9]

4.4 Thermal Conductivity Enhancement

The most consistently cited practical limitation of PCMs used in solar dryers — including virtually all the organics of Section 4.3 — is low thermal conductivity (typically 0.15–0.5 W/m·K for organics), which slows charge/discharge rate and can limit the effective power output of the storage unit even though its energy capacity is high [6,2]. Several enhancement strategies recur in the literature: embedding metal fins or fin arrays to increase heat-transfer surface area, a common and structurally simple approach adopted directly in solar-dryer PCM units (Section 5) [6]; dispersing high-conductivity nanoparticles (nano-enhanced PCM), which raises effective conductivity at the cost of some dilution of latent-heat capacity and long-term dispersion stability [6]; impregnating an open-cell metal foam with PCM, which provides a continuous conductive skeleton at the cost of reduced PCM volume fraction [11]; and impregnating PCM into an expanded-graphite or other porous-carbon matrix, which Sarı and Karaipekli [10] showed substantially raises the thermal conductivity of a paraffin composite while largely preserving its latent-heat storage capacity and also improving shape stability against leakage. Qureshi, Ali, and Khushnood [6] conclude, after reviewing these techniques comparatively, that the optimal method depends on the required charging/discharging rate, tolerable loss of storage density, and cost — a trade-off directly relevant to selecting an enhancement strategy for a low-cost, farmer-deployable indirect solar dryer (Section 10).

4.5 Encapsulation and Containment

Because most useful PCMs are liquid in their charged state, they must be contained to prevent leakage, accommodate volume change on melting, and — in food-drying contexts — prevent any direct contact between the PCM and the product. Encapsulation is generally classified by scale into macro-, micro-, and nano-encapsulation [7]. Macro-encapsulation, confining relatively large PCM quantities inside discrete metal or plastic containers (cans, tubes, trays, or panels), is by far the dominant containment approach in experimental indirect-solar-dryer designs, offering simple fabrication, ease of retrofitting, and straightforward inspection [12]; the schematic PCM unit in Figure 3 reflects this dominant macro-encapsulated-can/tube configuration. Micro- and nano-encapsulation, which enclose much smaller PCM particles within a thin shell to dramatically increase surface area and largely eliminate bulk-leakage risk, remain comparatively more common in building, textile, and battery-thermal-management research than in solar drying to date [7]. Direct metal-PCM contact in macro-encapsulated units also raises a corrosion concern: Ostrý, Bantová, and Struhala [51] gravimetrically measured corrosion rates of organic and salt-hydrate PCMs against aluminium, brass, carbon steel, and copper, finding aluminium the most corrosion-resistant container material of those tested — a finding of direct practical relevance given aluminium's prevalence as a low-cost solar-dryer construction material.

5. PCM Integration Configurations in Indirect Solar Dryers

Reviewing the configurations reported across Section 6's verified studies reveals several recurring integration strategies. The most common is a discrete PCM storage module — a tray, can bank, or tube bundle — positioned immediately downstream of the solar air collector and upstream of the drying chamber, as in the conic thermal-energy-storage module of Senthil Kumar et al. [30] and the Cudappah-stone-plus-paraffin unit of Govindan et al. [32]. A second strategy embeds the PCM directly within or adjacent to the absorber plate to shorten the heat-transfer path from collection to storage, exemplified by the copper-fin-and-paraffin flat-plate collector of Venkatesh et al. [31] and the fins-inserted PCM configuration of Madhankumar, Viswanathan, and Wu [41]. A third strategy uses PCM-filled tubes distributed through the collector or duct airflow path to maximise surface-area contact with the moving air stream, as in the natural-convection PCM-tube dryer of Chaatouf et al. [40]. A fourth, increasingly reported strategy combines two or more PCM grades with different melting points in series — for example, the three-paraffin-grade bank (45–60°C, 60–70°C, and 80–100°C fractions) of Hari Krishnan, Dhanushkodi, and Sudhakar [34] and the dual paraffin-wax-plus-RT-42 configuration of Hamad, Hussien, and Faraj [35] — intended to better match the PCM phase-change temperature to the time-varying collector-outlet temperature across the day. A fifth strategy, and one of the two patterns most consistently associated with the largest reported gains (Section 6.2), combines sensible and latent storage in the same unit, pairing black pebbles or stones with a PCM such as lauric acid [38] or paraffin [32]. Container material is overwhelmingly aluminium or steel cans, trays, or tubes (macro-encapsulation, Section 4.5), consistent with the practical, low-fabrication-complexity bias of the reviewed prototype and pilot-scale literature.

6. Performance Enhancement: Evidence from The Literature

6.1 Verified Quantitative Studies

Table 2 summarises thirteen independently identified studies reporting the experimental or numerical performance of a PCM integrated into an indirect solar dryer. Ten of the thirteen have both their bibliographic record and their headline quantitative findings independently confirmed against the original publication or a reliable indexing service; the remaining three (Chaatouf et al. [40], Madhankumar et al. [41], and Radhakrishnan et al. [42]) have confirmed bibliographic details, described qualitatively in Section 5 above, but their specific numeric results were not independently re-extracted for this review and are marked accordingly in the table.

Table 2. Verified experimental/numerical studies of PCM-integrated indirect solar dryers. Percentage gains and time comparisons are each study's own reported comparison against its own stated baseline; baselines are not uniform across studies (see Section 6.2).

Study	PCM / storage	Product	Key reported performance
Senthil Kumar et al. [30]	Paraffin wax, conic TES	Turkey berries	Collector eff. 89.6%; system eff. 15.23% (with TES) vs 14.8% (without); simple payback 0.74–1.29 yr
Venkatesh et al. [31]	Paraffin + Cu fins	Banana, potato	Collector eff. +77% (banana), +43% (potato) vs baseline
Govindan et al. [32]	Paraffin (m.p. 60°C) + stone	Coconut	Drying time −28 h (100 g PCM) to −52 h (200 g PCM) vs open sun
Majeed et al. [33]	Dual-grade paraffin wax	Potato slices	10% moisture reached in 24 h (PCM) vs 33 h (no PCM) vs 38 h (open sun)
Hari Krishnan et al. [34]	3-grade paraffin bank (16 kg)	—	Collector eff. 85%; 7 h (indirect+TES) vs 8 h (direct) vs 11 h (open sun)
Hamad et al. [35]	Dual paraffin (wax + RT-42)	Chili	Collector eff. +43%; 47 h (forced+PCM) vs 87 h (natural, no PCM)
Mugi et al. [36]	PCM-based TES device	Muskmelon	Drying eff. 11.37%→16.93% (+49% relative); SMER +74%
Moradi et al. [37]	Paraffin wax + IR hybrid	Potato slices	PCM alone: −5.3% drying time; combined with IR, greatest reduction
Deepak & Behura [38]	Lauric acid + pebbles	Cucumber	Energy eff. +53%; drying time −50% (6 h vs 12 h); EPBP 1.82 yr
Behera et al. [39]	Paraffin wax	Tomato, potato, banana, gourd	Collector eff. +6–8%; drying eff. +4–5%; drying rate +27–30%
Chaatouf et al. [40]	PCM tubes	—	Configuration confirmed; quantitative results not independently extracted
Madhankumar et al. [41]	Fin-inserted PCM	—	Configuration confirmed; quantitative results not independently extracted
Radhakrishnan et al. [42]	PCM-based storage	Mango pulp	Configuration confirmed; quantitative results not independently extracted

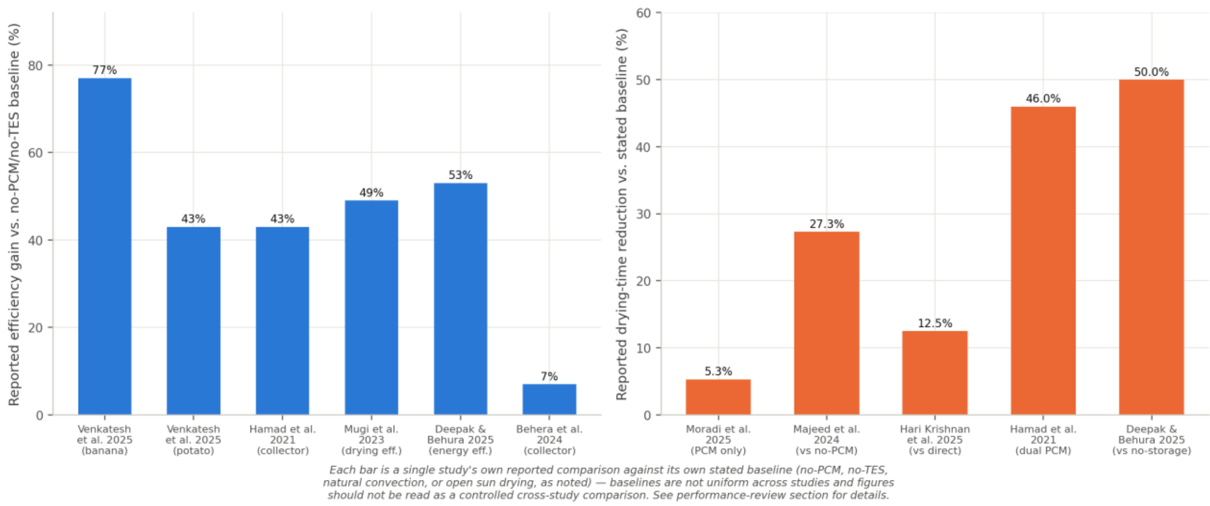

Figure 6. Reported collector/drying-efficiency gains (left) and drying-time reductions (right) from a subset of the studies in Table 2, each plotted against its own study-stated baseline.

A non-PCM baseline worth noting separately is Ennissioui, Benghoulam, and El Rhafiki [44], whose natural-convection indirect solar dryer (no PCM) achieved 23.4% average collector efficiency, 18.8% dryer thermal efficiency, and 74.8% moisture removal for banana slices versus 39.1% for open sun drying — a useful same-design reference point for "typical PCM-free indirect-dryer performance" against which the PCM-integrated gains in Table 2 can be read, though it must not be treated as a controlled comparator for any single PCM study since collector design, climate, and product all differ.

6.2 Cross-Cutting Synthesis

Reported collector- or drying-efficiency gains attributable to PCM integration span a wide range, from a modest 6–8% relative increase (Behera et al. [39]) up to 77% (Venkatesh et al., banana [31]); overall system/drying-efficiency gains cluster somewhat more narrowly when comparing "with TES" against "without TES" configurations of the same rig, for example a 49% relative increase (Mugi et al. [36]) and a 53% relative increase (Deepak and Behura [38]). This spread reflects genuine differences in baseline (open sun versus PCM-free indirect dryer versus a lower-mass PCM configuration), PCM mass and placement, and which efficiency definition is used (collector, drying, or exergy efficiency are not interchangeable), and Table 2's figures should accordingly be read as thirteen individually meaningful results rather than as a single controlled cross-study comparison.

Reported drying-time reductions relative to each study's own baseline span roughly 5% to 50%. Two configuration patterns recur among the studies reporting the largest gains. First, combining sensible and latent heat storage in a single unit — black pebbles or stone plus a PCM such as lauric acid or paraffin — tends to outperform either storage mode alone, as in Deepak and Behura's 50% drying-time reduction [38] and Govindan et al.'s stone-plus-PCM coconut-drying system [32]. Second, enhancing heat transfer into and out of the PCM via fins (Venkatesh et al. [31]; Madhankumar et al. [41]) or tube/capsule geometries (Chaatouf et al. [40]) is consistently associated with the largest reported efficiency gains, consistent with the thermal-conductivity limitation discussed in Section 4.4: bulk PCM without enhanced heat-transfer surfaces charges and discharges too slowly to realise its full latent-heat advantage. Multi-grade or multi-PCM systems (Hari Krishnan et al. [34]; Hamad et al. [35]) are a third recurring strategy, aimed at better matching the PCM's phase-change temperature to the time-varying collector-outlet temperature across the day. By contrast, where PCM was combined with a second enhancement technology of a different kind (infrared heating, in Moradi et al. [37]), the PCM's own marginal contribution to drying-time reduction (5.3%) was substantially smaller than that of the other technology (≈40% for infrared alone) — a reminder that PCM addition is not always the dominant lever in a hybrid system and that its incremental contribution should be assessed and reported separately, as Moradi et al. did.

Methodologically, the confirmed studies mostly follow a consistent protocol: outdoor field testing under natural solar radiation, compared against either a PCM-free version of the same dryer or open sun drying; instrumentation with thermocouples at ambient, collector inlet/outlet, drying-chamber, and PCM-container locations; moisture content determined by mass-loss tracking combined with an oven-drying reference method; solar radiation measured with a pyranometer; and, increasingly in 2023–2025 papers, exergy efficiency, specific energy consumption, and payback-period reporting alongside first-law efficiency. A minority of recent studies pair the experimental campaign with a numerical or CFD model of PCM heat transfer validated against measured temperature profiles, exemplified by Chaatouf et al. [40].

7. Techno-Economic and Environmental Assessment

A growing share of the recent literature reports combined energy–exergy–economic ("3E") or energy–exergy–economic–environmental ("4E") assessments specifically for PCM-integrated indirect solar dryers, reflecting the shift toward techno-economic reporting noted in Section 3.4. The clearest quantitative figures identified are from Senthil Kumar et al. [30], who report a simple payback period of roughly 0.74–1.29 years for a PCM-integrated active indirect dryer (depending on electricity-price and capital-cost assumptions) against a 35-year assumed system lifetime, an Energy Payback Period of about 1.42 years, and an Environmental Payback Period computed alongside it from embodied-energy accounting; the study also reports that realistic long-term CO_2-mitigation, once system degradation is accounted for, runs 18–22% below a simple linear extrapolation. Deepak and Behura [38] separately report an Energy Payback Period of 1.82 years and an estimated CO_2-mitigation potential of approximately 84 t/year for their combined sensible-and-latent mixed-mode dryer. Several further 3E/4E studies were identified and bibliographically confirmed — Alktranee et al. [45] on PCM-can indirect dryers, Rajesh et al. [46] on drying kinetics with combined economic analysis, Brahma, Shukla, and Baruah [47] (notably an Indian, Assam-based research group, making it one of the more directly comparable studies for an Indian rural-deployment context), and El-Bayeh et al. [48] on a larger-scale Scheffler-dish solar drying plant using eutectic PCM storage — but their specific numeric cost figures were not independently re-extracted for this review and are cited here only as confirming that this analytical framework is actively and increasingly applied to PCM solar dryers, not as a source of additional quoted numbers.

The founding economic rationale for PCM over sensible-heat storage — higher energy-storage density per unit volume/mass, and hence a smaller, lighter, cheaper storage unit for equivalent thermal buffering — is reiterated as motivation in nearly every PCM solar-dryer paper reviewed here and in dedicated reviews of the sub-field [26,27]. No source identified in this review, however, provides a rigorously quantified side-by-side cost comparison between a PCM store and an equivalent sensible-heat store for the same dryer design, and no dedicated economic-viability analysis specifically for smallholder or rural-farmer adoption (willingness-to-pay, subsidy scenarios, village-scale financing) was located; both are stated here as explicit research gaps (Section 9) rather than implied to exist.

On environmental and life-cycle aspects, a directly relevant comparative life-cycle assessment (LCA) of solar drying systems was identified — Nakum, Sharma, Panwar, and Gande [49] — though it was not confirmed during this review whether it specifically evaluates PCM-integrated configurations against PCM-free ones, a point that should be checked in full text before further reliance on it. A dedicated PCM life-cycle study was also identified, but for a solid-solid perovskite PCM in general energy-storage/electronics applications rather than a drying-relevant organic PCM [50]; it is cited here only as an example of LCA methodology applied to PCM cycling, not as evidence about drying-relevant PCM environmental impact. No citation-quality, specifically-authored peer-reviewed source on biodegradable or bio-based PCM formulations for drying applications was identified in this review; the general expectation that bio-based PCMs are more biodegradable than petroleum-derived paraffins is directionally reasonable but is stated here as an open question rather than attributed to a specific study.

8. Technical Challenges and Limitations

Low thermal conductivity remains the most consistently reported limitation of PCM-assisted solar drying, discussed at length in the foundational PCM reviews [2,1] and addressed in solar-dryer-specific hardware through the fin, foam, nanoparticle, and expanded-graphite strategies of Section 4.4. Subcooling and phase segregation over repeated melt–freeze cycling, particularly in salt hydrates, is the central subject of Rathod and Banerjee's thermal-stability review [8] and means that solar-dryer designs must either select PCMs less prone to this degradation (generally favouring paraffins and fatty acids over salt hydrates, consistent with Section 4.3's finding that paraffins and fatty acids dominate actual dryer prototypes) or plan for periodic PCM replacement.

Leakage of molten PCM drives the near-universal use of macro-encapsulated metal or plastic containment (Section 4.5) [45,7], while direct PCM–metal contact raises a corrosion risk that Ostrý, Bantová, and Struhala [51] quantified directly, finding aluminium the most corrosion-resistant of the container metals they tested. Solid–liquid PCMs also typically undergo 5–15% volumetric expansion on melting, requiring an ullage or expansion allowance in container design [2,1]. Perhaps the most application-specific challenge is matching PCM melting point to the locally achievable collector-outlet temperature and the target crop's drying-temperature requirement: too high a melting point and the PCM never fully melts under the available solar flux; too low, and it discharges its stored heat before drying is complete. This melting-point-matching consideration underlies the design choice in dedicated PCM-dryer studies for specific crops, including El-Sebaii and Shalaby's work on thymus and mint [59,60], and is inherently a site- and crop-specific exercise rather than a one-size-fits-all parameter — directly relevant to selecting a PCM melting point for orange-peel drying in Nagpur's climate (Section 10). Finally, PCM units add container mass, supporting structure, and additional heat-exchange surfaces, a measurable capital-cost and payload increase relative to a plain, no-storage solar dryer that the 3E/4E studies of Section 7 attempt to quantify.

9. Future Perspectives and Research Gaps

Several emerging research directions were identified with verifiable, drying-relevant or closely adjacent citations. Nano-enhanced PCMs, which raise thermal conductivity by dispersing conductive nanofillers, are combined with photovoltaic-thermal (PVT) system optimisation in Javadpour et al. [52], using support-vector-machine modelling — a concrete example of nano-PCM research moving beyond conductivity measurement alone toward system-level, machine-learning-assisted optimisation. PVT-plus-PCM hybrid drying is already an emerging, not purely speculative, direction: Poonia, Singh, and Jain [55] evaluated a PCM-based hybrid photovoltaic/thermal solar dryer for arid fruits, and a bifacial-PVT PCM-integrated greenhouse dryer has also been reported [56]. Machine-learning-based optimisation of drying kinetics and quality, while not yet widely applied specifically to PCM-integrated units in the literature identified here, has a strong general precedent in Khaledifard et al.'s [54] integration of drying kinetics, quality attributes, and machine learning for greenhouse solar drying. Hybrid PCM-plus-desiccant systems, combining thermal and humidity buffering in one unit, appear to be a genuinely underexplored design space: a desiccant-integrated multi-chamber solar dryer has been reported [53], but this specific study does not itself include PCM, and no combined PCM-plus-desiccant drying study was identified during this review — worth stating as a specific, evidence-based future-work recommendation rather than an established finding. Eutectic PCM mixtures are already deployed at larger scale in a Scheffler-dish concentrating solar drying plant [48], demonstrating this is a practically usable, not just theoretical, direction. IoT-enabled monitoring and control of solar dryers has at least one concrete example [57], though it is conference-proceedings literature rather than a peer-reviewed journal article and should be weighted accordingly if cited further.

Several gaps recur across the review-type sources consulted [26,27,28] and across the individual case studies synthesised in Section 6. First, inconsistent reporting metrics — studies use varying, not always comparable, definitions of drying and exergy efficiency and economic payback — make cross-study comparison difficult, reinforcing the case for a standardised PCM-solar-dryer testing and reporting protocol; the closest identified source addressing PCM thermal characterisation methods generally, rather than a drying-specific testing standard, is a 2024 book chapter [58]. Second, essentially all PCM solar-dryer studies identified in this review report short-duration experimental campaigns (single drying seasons or a handful of batch runs) rather than multi-year field-deployment data; even the most detailed techno-economic model identified [30] projects over a 35-year assumed lifetime as a modelling assumption, not measured field longevity. Third, dedicated techno-economic modelling for smallholder or rural developing-country contexts is essentially absent (Section 7) — a gap of direct relevance to the orange-peel-drying case study addressed in Section 10. Fourth, LCA coverage of PCM-integrated (as opposed to PCM-free) solar drying systems specifically is sparse, with only one directly on-topic comparative study identified and its PCM-specific scope unconfirmed [49]. Fifth, no verifiable citation-quality source on bio-based or biodegradable PCM formulations for drying applications, and no verifiable source on second-life or recycled PCM sourcing, was located during this review; both should be treated as open areas rather than supported with an invented citation.

10. Implications for Orange-Peel Drying in Nagpur, Maharashtra

The energy-storage-based indirect solar dryer under development for orange peel drying in Nagpur, Maharashtra (approximately 21.15° N, 79.09° E) operates in a hot semi-arid to tropical wet-and-dry climate, with summer ambient temperatures of 45–47°C and a measured collector stagnation (no-load) temperature of approximately 90°C, as documented in the companion AHP material-selection study for this same dryer's absorber, glazing, and insulation subsystems. Read against Section 4.2's melting-point-matching criterion, this climate points toward a PCM with a melting point at the higher end of the 45–70°C window — plausibly a fatty acid such as stearic or palmitic acid (melting point ≈55–65°C, Table 1) or a mid-to-high-melting paraffin grade — rather than a low-melting salt hydrate, so that the PCM reliably fully melts under Nagpur's high solar flux while still discharging at a temperature useful for maintaining effective drying-air conditions into the evening. Consistent with Section 5's finding that heat-transfer-enhanced (finned, tubed, or expanded-graphite-composite) PCM configurations are associated with the largest reported efficiency gains, and with Section 4.4's conclusion that the optimal conductivity-enhancement method depends on cost and complexity tolerance, a simple finned aluminium can or tray configuration is the most literature-consistent, lowest-fabrication-complexity starting point for a farmer-deployable design — aluminium being independently supported by Section 4.5's corrosion-resistance evidence [51] and by the companion AHP study's own material-selection analysis for this dryer's absorber plate, which likewise favours aluminium's corrosion resistance under humid, outdoor, low-maintenance operating conditions.

Two research gaps identified in Sections 7 and 9 are directly actionable for this project rather than purely general observations. First, the near-total absence of dedicated techno-economic modelling for smallholder or rural Indian PCM-solar-dryer adoption means that even the most favourable payback figures identified in this review (0.74–1.29 years, Senthil Kumar et al. [30]) cannot be assumed to transfer directly to a Nagpur-region farmer-deployment context without a dedicated local costing exercise — an analysis this project, or a follow-on study, could usefully contribute to the literature. Second, because no PCM-assisted indirect solar dryer study specifically targeting citrus or orange-peel drying was identified anywhere in this review's source material, any PCM melting-point and configuration recommendation for this application necessarily rests on general indirect-solar-drying and PCM-property evidence (Sections 4–6) rather than a directly analogous prior study, reinforcing — consistent with the companion AHP paper's own conclusion regarding its absorber, glazing, and insulation material selection — that the recommendations in this section should be treated as a literature-grounded starting hypothesis for experimental validation, not a validated regional precedent.

11. Conclusion

This review synthesised 61 independently verified references on PCM-assisted indirect solar drying, covering PCM classification and selection criteria, indirect-dryer design fundamentals, PCM integration configurations, and quantitative performance evidence from thirteen studies published between 2014 and 2025. Reported efficiency gains from PCM integration range from 6–8% to 77% relative to each study's own baseline, and reported drying-time reductions range from 5.3% to 50%, with the largest gains consistently associated with heat-transfer-enhanced (finned or tubed) PCM configurations and with combined sensible-plus-latent storage rather than bulk PCM alone. Techno-economic assessments report simple payback periods as short as 0.74–1.29 years for a PCM-integrated active indirect dryer, but dedicated economic modelling for smallholder or rural-farmer adoption is essentially absent from the literature, as is multi-year field validation, a standardised testing protocol, and life-cycle assessment specifically comparing PCM-integrated against PCM-free configurations. With 46% of the reviewed literature published in 2023–2026, PCM-assisted indirect solar drying is a rapidly maturing but still young research field, and the gaps identified here — rural techno-economics, standardised reporting, long-duration field data, and crop-specific (including citrus/orange-peel) PCM configuration studies — represent concrete, evidence-grounded directions for future work, including for the orange-peel-drying application in Nagpur, Maharashtra, discussed in Section 10.

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