Results in Engineering 30 (2026) 111082

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Review article

Enhancing the durability, efficiency, and sustainability of nanofluid–PCM photovoltaic/thermal systems: Meta analysis of current constraints and future research directions

Zainal Arifin [a,*], Singgih Dwi Prasetyo [a,b], Yuki Trisnoaji [b], Mohd Afzanizam Mohd Rosli [c], Watuhumalang Bhre Bangun [a]

[a] *Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia*
[b] *Power Plant Engineering Technology, Faculty of Vocational Studies, State University of Malang, Malang 65145, Indonesia*
[c] *Department of Engineering, Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka 76100, Malaysia*

A R T I C L E I N F O

Keywords:
Nanofluid–PCM hybrid cooling
Photovoltaic/thermal (PV/T) systems
Electrical and thermal efficiency
Meta-analysis

A B S T R A C T

Thermal stress remains a significant constraint on photovoltaic (PV) performance, necessitating advanced cooling strategies that enhance both electrical efficiency and operational stability. This study presents a systematic review and meta-analysis of 50 experimental and numerical investigations examining hybrid nanofluid–PCM cooling in PV/T systems. A multistage PRISMA framework and random-effects modeling were employed to synthesize heterogeneous performance indicators and evaluate robustness across study conditions. The findings indicate that hybrid cooling delivers consistent multidimensional improvements, including an average electrical efficiency increase of 3.10% and a thermal efficiency gain of 5.50%, alongside substantial heat transfer enhancement. Subgroup comparisons demonstrate that hybrid configurations outperform single-mode approaches, confirming the synergistic interaction between convective nanofluid mechanisms and latent-heat buffering. Sensitivity and publication bias analyses support the reliability of the aggregated evidence. Despite promising performance gains, challenges related to long-term material stability, environmental considerations, and large-scale economic feasibility remain unresolved. Overall, hybrid nanofluid–PCM cooling represents a strategically significant pathway for improving PV/T efficiency and thermal resilience, warranting further standardization and real-world validation.

1. Introduction

1.1. Background of the research

Research on electrical and thermal efficiency enhancement in photovoltaics using nanofluid-based thermal collectors integrated with PCMs has gained increasing prominence as global energy systems confront rising temperature stress and accelerating demand for sustainable power generation [1,2]. Over the past few decades, advances in PV technology have improved energy conversion; yet, persistent thermal challenges continue to hinder system reliability during real-world operation. High PV operating temperatures remain a critical bottleneck, as they directly reduce electrical output and shorten module lifetime, particularly in regions with high solar irradiance. These constraints motivate the exploration of combined cooling strategies that can maintain stable thermal conditions while simultaneously improving power yield [3,4]. The integration of nanofluids and PCMs into PVT systems offers a multifaceted solution, as nanofluids enhance convective heat transfer while PCMs buffer thermal fluctuations through latent heat absorption. These foundational insights are further illustrated by the representative studies summarized in Table 1, which show how different material combinations and cooling designs contribute to reduced temperatures and performance gains across various operating conditions.

In addition to thermal impacts, the broader technological transition toward more efficient hybrid solar systems underscores the need for improved heat management methods. Contemporary solar infrastructures increasingly combine electricity and heat extraction within integrated PVT systems, yet their performance often remains limited by insufficient cooling. Nanofluids provide higher thermal conductivity compared with conventional fluids, enabling superior heat removal rates from PV surfaces during peak irradiance periods [5,6]. However,

* Corresponding author.
E-mail address: zainal_arifin@staff.uns.ac.id (Z. Arifin).

https://doi.org/10.1016/j.rineng.2026.111082
Received 30 December 2025; Received in revised form 27 April 2026; Accepted 15 May 2026
Available online 15 May 2026

Nomenclature

Symbols and parameters

T_{PV}	PV module surface temperature °C
ΔT	Temperature reduction due to nanofluid–PCM cooling °C
η_{el}	Electrical efficiency %
η_{th}	Thermal efficiency %
η_{PVT}	Overall PV/T efficiency %
η_{imp}	Electrical efficiency improvement after hybrid cooling %
h	Heat-transfer coefficient W/m^2·K
k	Thermal conductivity (nanofluid/PCM) W/m·K
μ	Dynamic viscosity of nanofluid Pa·s
c_p	Specific heat capacity J/kg·K
ρ	Density kg/m^3
$\dot{m}$	Mass flow rate kg/s
h_f	Latent heat of fusion of PCM kJ/kg
T_m	PCM melting temperature °C
Q_{PCM}	Latent heat absorbed/released by PCM kJ
C_p	Specific heat of nanofluid/PCM kJ/kg·K
G	Solar irradiance W/m^2
P_{PV}	Electrical output from PV W
τ^2	Between-study variance (meta-analysis) –
CI	Confidence interval –
I^2	Heterogeneity index in meta-analysis %
Q	Cochran's heterogeneity statistic –
ES	Effect size in meta-analysis –
S	Begg's rank correlation score –
β	PV temperature coefficient %/ °C
ϕ	Nanoparticle volume fraction %
Re	Reynolds number –
Pr	Prandtl number –
Nu	Nusselt number –

Abbreviation

PV	Photovoltaic
PVT	Photovoltaic/Thermal System
PCM	Phase Change Material
NF	Nanofluid
NEPCM	Nano-Enhanced Phase Change Material
CFD	Computational Fluid Dynamics
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AI	Artificial Intelligence
LCOE	Levelized Cost of Energy
CI	Confidence Interval
TES	Thermal Energy Storage
ROI	Return on Investment
CAPEX	Capital Expenditure
OPEX	Operating Expenditure

Meta-analysis terms

Effect size Quantitative measure comparing performance differences across studies
Random-effects model Meta-analysis model accounting for study heterogeneity
I^2statistic Percentage of variability attributed to heterogeneity
Q-statistic Test for total between-study variance
Funnel plot Visualization for publication-bias detection
Begg test Rank correlation test for asymmetry
Egger regression Linear test detecting publication bias
Meta-regression Moderator analysis explaining variance in thermal and electrical performance
Sensitivity analysis Test to evaluate the influence of individual studies
Subgroup analysis Comparison of cooling categories (PCM, nanofluid, hybrid)

Technical, system, and performance terms

Latent-heat buffering PCM heat absorption during phase transition
Convective enhancement Heat-transfer improvement due to nanofluid flow
Hybrid cooling Combined nanofluid + PCM thermal regulation
Thermal stabilization Reduction of PV overheating during peak irradiance
Performance ratio Stability metric of PV system output
Thermal–electrical coupling Interaction of cooling mechanisms affecting energy yield
Material synergy Combined thermophysical advantage of NF and PCM
Agglomeration Nanoparticle clustering reduces heat transfer.
Melting range compatibility Match between the PCM melting point and the PV operation temperatures

nanofluids alone cannot fully stabilize temperature profiles during extended heating cycles, which is why PCMs have emerged as an essential complementary material. Their latent heat capacity enables them to maintain near-constant temperatures during melting, thereby delaying the thermal rise that would otherwise degrade PV efficiency. This combined function aligns with current efforts to develop multi-purpose solar collectors capable of providing both electrical and thermal outputs. Thus, research on nanofluid–PCM integration responds to practical demands for more resilient and versatile PVT technologies [7,8].

Despite notable progress, knowledge gaps persist regarding the optimal operational and material configurations required to leverage the potential of nanofluid–PCM hybrid systems fully. Studies have demonstrated improvements in heat transfer, yet variations in nanoparticle concentration, PCM melting point, and thermal collector geometry continue to generate inconsistent performance outcomes [9,10]. Technical challenges, such as nanoparticle agglomeration, increased viscosity, or limitations in PCM conductivity, complicate the deployment of reliable systems in real-world settings. Furthermore, high-temperature environments typical of arid and tropical climates require adaptive thermal management strategies that can withstand intense irradiance without imposing excessive energy consumption or maintenance burdens. These uncertainties underscore the need for a deeper understanding of how individual system components interact to influence overall PVT performance. Consequently, systematic examinations of design, material selection, and operating parameters are essential to overcome these barriers [11,12].

The global shift toward renewable energy and decarbonization further intensifies the urgency of advancing nanofluid–PCM-based cooling technologies. As solar penetration increases across both developed and emerging economies, maintaining PV efficiency under dynamic climatic conditions becomes a strategic priority for ensuring stable power generation. Hybrid PVT systems offer an attractive option due to their dual-output capability; however, they require effective thermal regulation to operate optimally [13,14]. Integrating nanofluids and PCMs supports this objective by improving temperature stability, enhancing heat extraction, and boosting both electrical and thermal efficiency levels. The range of potential applications, from residential systems to industrial thermal recovery and large-scale solar fields, illustrates the broad relevance of this research. For these reasons, a comprehensive exploration of nanofluid–PCM integration is essential for the design of high-performance, climate-adaptive solar technologies

[15,16].

As shown in Table 1, which consolidates heterogeneous experimental approaches and cooling strategies, the fragmented nature of existing findings underscores the need for an integrated analytical framework to unify these diverse insights. The novelty of this study lies in its formulation as a comprehensive review and meta-analysis that systematically integrates fragmented research on nanofluid-enhanced heat transfer and PCM-based thermal regulation within hybrid PVT systems. Unlike earlier investigations that tended to evaluate cooling mechanisms separately, this study adopts an integrative analytical perspective to explore how hybrid thermal strategies are conceptualized, modeled, and experimentally implemented across diverse research environments. The meta-analytical framework strengthens this contribution by enabling structured comparison, quantitative convergence, and methodological alignment across studies that often differ substantially in scope and experimental design. **In contrast to previous narrative or semi-quantitative reviews, this study introduces a statistically structured random-effects meta-analytical model that normalizes heterogeneous performance indicators into comparable effect sizes, thereby allowing cross-study aggregation of electrical efficiency, thermal efficiency, temperature reduction, and heat-transfer coefficient enhancement within a unified analytical structure.** This dual approach establishes a coherent foundation for understanding theoretical interactions, material behaviors, and system-level dynamics without prematurely presenting performance outcomes.

Moreover, the present study uniquely quantifies the performance hierarchy among nanofluid-only, PCM-only, and hybrid nanofluid–PCM systems, demonstrating, through pooled estimates, that hybrid configurations consistently outperform single-medium strategies within statistically validated confidence intervals. By bridging conceptual, experimental, and statistical domains, the study sets the stage for a deeper examination of optimization pathways and emerging technological trends in hybrid nanofluid–PCM thermal management. **Unlike prior reviews that summarize individual experimental gains, this research provides pooled benchmarks alongside heterogeneity mapping ($I^2 > 92\%$) and moderator-based variance explanation, enabling interpretation not only of average performance but also of variability structure across operational contexts.** In doing so, it offers a forward-looking analytical platform for evaluating the future development of high-efficiency PVT systems. **Therefore, the principal novelty of this work lies in transforming fragmented experimental evidence into statistically interpretable performance distributions, predictive performance ranges, and comparative cooling hierarchies, which were not previously available in the nanofluid–PCM PV/T literature.**

1.2. Research motivation, purpose, and scope

Although the detrimental impact of elevated operating temperature on photovoltaic performance has been extensively documented, the principal challenge facing hybrid nanofluid–PCM PV/T systems today lies not in problem recognition, but in the fragmented and heterogeneous structure of the existing evidence base. Current studies report highly variable electrical efficiency improvements ranging from below 1% to above 15%, temperature reductions between 5°C and 50°C, and heat-transfer coefficient enhancements exceeding 20% in specific configurations [22,23]. However, these outcomes are derived from diverse experimental conditions, non-standardized testing environments, and inconsistent reporting metrics, limiting their comparability and translational value. Variations in nanoparticle material, concentration levels, PCM melting-point alignment, climatic exposure, and collector geometry generate substantial dispersion across findings. As a result, the literature presents promising yet isolated performance claims without consolidated probabilistic benchmarks that can guide engineering implementation [24,25]. This lack of structured synthesis hinders the transfer of technology from laboratory prototypes to scalable PV/T deployment strategies.

The purpose of this study is therefore to systematically reconcile divergent findings and construct statistically interpretable performance benchmarks for hybrid nanofluid–PCM cooling systems. By conducting a structured PRISMA-based review and quantitative meta-analysis of 50 eligible studies, this research standardizes heterogeneous performance indicators into unified effect sizes across electrical efficiency, thermal efficiency, temperature reduction, and heat-transfer enhancement. The analytical objective extends beyond summarizing improvements; it aims to quantify the magnitude, dispersion, and reliability of reported gains

Table 1
Summary of Key Experimental Studies on Nanofluid–PCM–PVT Cooling Performance.

References	Research Objective	Methods	Key Findings	Limitations & Research Gaps
Xu et al., 2023 [17]	To evaluate the cooling performance of PCM (paraffin wax) and its effect on PV electrical output.	Experimental study under indoor solar simulator; temperature, I–V characteristics, Pmax, and efficiency measurements.	PCM reduced PV surface temperature by up to ~34–36°C over 300 min and improved PV efficiency by ~1.63%. PCM slowed thermal cycling and stabilized temperature variation.	Limited to one PCM type and indoor conditions; lacks real outdoor validation; no comparison with active cooling; long-term PCM degradation not studied.
Al-Aasam et al., 2023 [18]	To enhance PVT performance using Nano-PCM, nanofluids (SiC/water), and twisted tubes for better heat transfer.	Experimental indoor tests with twisted vs circular tubes; SiC nanofluid at 0–0.6 vol%; evaluation of PV, thermal, and overall efficiencies.	Best performance achieved using twisted tubes + 0.6% SiC nanofluid + Nano-PCM (ηPV 9.57%, ηth 84.74%, ηPVT 94.31%). Heat transfer improved significantly with twisted tubes.	Conducted only under controlled indoor conditions; only SiC nanofluid tested; lacks economic evaluation and long-term stability analysis; fouling and pump requirements not addressed.
Gharapetian et al., 2024 [19]	To investigate nanofluid-cooled PV integrated with thermoelectric generators to enhance hybrid electrical-thermal output.	3D numerical CFD modeling; tested water, CuO/water, and hybrid CuO-Fe/water under varying flow rates and concentrations.	Hybrid CuO-Fe/water provided maximum cooling (PV temp down to ~31.7°C), increasing combined efficiency from ~66.7% to ~76.7%. Higher nanoparticle concentration improved PV-TEG output.	Mostly numerical with limited experimental validation; long-term nanofluid stability not examined; pressure drop, pump power, and TEG degradation not addressed; lacks real-scale economic feasibility.
Shaalan et al., 2025 [20]	To compare the cooling performance of hybrid ZnO/Al_2O_3 nanofluid against air and water cooling for PV panels.	Combined CFD modeling and experimental validation on identical modules; month-long monitoring under real conditions.	A hybrid nanofluid (0.02%) increased electrical efficiency by ~7–12% compared to water/air cooling and significantly reduced the PV temperature. Numerical vs experimental data showed strong agreement.	Only very low concentration tested (0.02%); short study duration; no investigation on nanoparticle sedimentation or operational cost; scalability for larger systems untested.
Alktranee et al., 2024 [21]	To analyze energy and exergy improvements of PVT cooling using two metal-oxide nanofluids.	Experimental evaluation combined with 2D numerical modeling; tested CuO and Fe_2O_3 at 0.2–0.3 vol%.	Achieved PV temperature reduction of 23–35%; electrical efficiency increased ~9–10%, thermal efficiency ~39–43%; exergy improved due to reduced thermal losses.	Limited nanoparticle types and volume fractions; long-term reliability, nanoparticle stability, and environmental impacts not addressed; pressure drop and pumping power require further study.

under real-world variability. Through random-effects modeling and heterogeneity mapping ($I^2 > 92\%$), the study identifies not only central performance tendencies but also the structural sources of between-study variance [26,27]. This probabilistic interpretation framework enhances generalizability while acknowledging contextual sensitivity. Consequently, the research establishes an evidence-based foundation for engineering optimization and informed decision-making in the development of hybrid PV/T systems.

The scope of this study encompasses interconnected analytical dimensions to ensure a comprehensive evaluation of hybrid nanofluid–PCM integration. First, it synthesizes empirical and numerical investigations examining the thermophysical interactions between nanofluid convection and PCM latent-heat buffering within PV/T architectures. Second, it benchmarks performance outcomes across cooling configurations, material compositions, and operating conditions to determine comparative effectiveness. Third, it evaluates moderator variables such as nanoparticle volume fraction, PCM melting range compatibility, flow regime, and climatic classification that may explain heterogeneity patterns. Additionally, the scope includes methodological quality assessment, publication bias evaluation, and sensitivity testing to strengthen the reliability of aggregated conclusions. By consolidating technical, statistical, and methodological domains within a unified framework, this study provides a structured platform for translating hybrid cooling research into predictive engineering guidelines. Ultimately, the research aims to transform dispersed experimental insights into consolidated performance distributions that can inform future technological refinement and large-scale implementation.

2. Methodology

2.1. Literature selection and query transformation

The methodological foundation of this study is structured through a multi-stage framework integrating query transformation, database extraction, PRISMA-based screening, citation chaining, and statistical eligibility assessment to ensure a comprehensive and methodologically consistent mapping of research on nanofluid-based cooling and PCM-integrated PVT systems. The process begins with transforming the central research question into several specialized search statements targeting themes such as thermal enhancement, hybrid cooling mechanisms, transient heat buffering, nanofluid thermophysical behavior, PCM phase-transition dynamics, and PVT heat-transfer optimization. This decomposition prevents terminological omissions and enhances the ability to capture studies using discipline-specific jargon. The complete set of Boolean-based search expressions is presented in Table 2, which consolidates all query variations used throughout the identification stage. These expressions were executed across Scopus, Web of Science, IEEE Xplore, MDPI, SpringerLink, and ScienceDirect to ensure breadth and reproducibility of coverage. To maintain the relevance of technological developments in hybrid cooling and PVT integration, the literature search was restricted to publications from **2021 to 2025**. As illustrated in Fig. 1(a), the initial database search identified 3247 records before deduplication, which were reduced to 2556 unique entries following automated removal of redundant records.

Title–abstract screening was conducted to evaluate conceptual relevance, thermal alignment, and the presence of measurable performance indicators for temperature reduction, electrical efficiency, and heat transfer coefficients. A total of 1892 articles were excluded at this stage due to thematic misalignment, absence of nanofluid or PCM components, or insufficient reporting of empirical data. The eligibility stage involved a full-text assessment of 264 studies to determine their alignment with hybrid nanofluid–PCM integration and to evaluate the performance of the PVT system. Studies with incomplete thermophysical characterization, unclear system architecture, or lacking quantifiable thermal–electrical outputs were excluded. To capture foundational and emerging work beyond the initial database returns, backward and forward citation chaining was applied, yielding an additional 68 relevant papers. Relevance scoring based on methodological rigor, dataset completeness, and compatibility with meta-analysis further refined the dataset. Ultimately, 81 studies were included for full review, of which 50 met all statistical requirements for quantitative meta-analysis. The conceptual mapping of this methodological pipeline is depicted in Fig. 1 (b).

Table 2
Compilation of Search Strings Used for Systematic Identification of Nanofluid–PCM–PVT Studies.

Search String (Boolean Expression)	Description
(“photovoltaic” OR “PV” OR “solar module” OR “PV/T”) AND (“nanofluid” OR “nanoparticle*” OR “hybrid nanofluid”) AND (“phase change material*” OR “PCM” OR “latent heat”)	Core search capturing hybrid nanofluid–PCM thermal regulation in PVT systems.
(“heat transfer” OR “thermal enhancement” OR “cooling” OR “temperature reduction”) AND (“nanofluid” OR “nano-fluid”) AND (“PCM” OR “thermal storage”)	Studies focusing on reducing temperature and enhancing heat transfer.
(“PV cooling” OR “PVT system*”) AND (“nanofluid collector” OR “liquid cooling”) AND (“phase transition material” OR “PCM encapsulation”)	Research on hybrid collector design and thermal management.
(“latent heat” OR “thermal buffering”) AND (“nanoparticle dispersion” OR “thermal conductivity enhancement”) AND (“solar energy”)	Material-science driven thermal regulation studies.
Combined full-domain query integrating all nanofluid–PCM–PVT dimensions	Comprehensive search for maximum literature coverage.

2.1.1. Data extraction procedure and variable harmonization

The data extraction process was conducted through a structured protocol designed to ensure consistency and reproducibility across all studies included in the review. After the eligibility screening phase, each selected article was carefully examined to extract quantitative performance indicators relevant to the hybrid cooling performance of PV/T systems. The primary variables collected from each study included PV temperature reduction, electrical efficiency improvement, thermal efficiency, and heat-transfer coefficient enhancement, as these parameters represent the most commonly reported indicators of thermal management effectiveness in hybrid cooling research. In addition, complementary operational parameters, such as nanoparticle concentration, flow regime, PCM melting temperature, and experimental conditions, were recorded to support contextual interpretation and moderator analysis. All extracted information was compiled into a standardized dataset to eliminate inconsistencies in reporting formats and units across different studies. The extraction procedure was performed independently for each article using a predefined data template to minimize transcription bias and ensure methodological transparency. The extracted dataset subsequently served as the analytical basis for both qualitative synthesis and quantitative aggregation within the meta-analysis framework.

2.1.2. Performance normalization across PV/T configurations

Because the included studies employed diverse experimental setups, cooling configurations, and performance reporting formats, a normalization procedure was applied to ensure statistical comparability across datasets. Performance indicators measured in identical physical units, such as temperature reduction and heat-transfer coefficient enhancement, were synthesized using the weighted mean difference approach, allowing direct aggregation of thermodynamic outcomes across comparable scales. In contrast, percentage-based indicators, such as electrical and thermal efficiency improvements, were standardized using Hedges’ g to correct for small-sample bias and differences in experimental variance across studies. This normalization process enabled

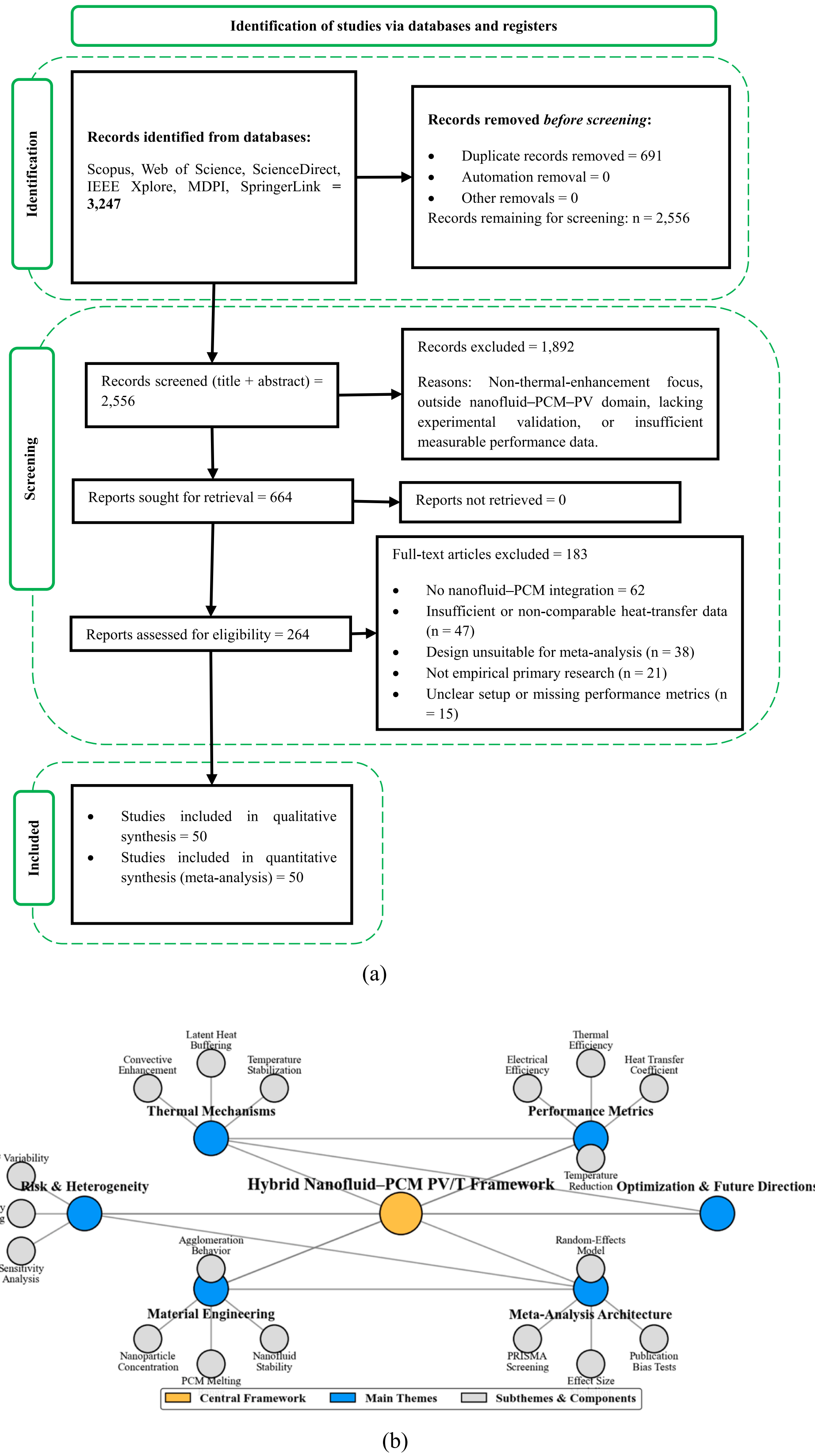


Fig. 1. Research Process and Conceptual Framework (a) PRISMA Literature Screening Flow (b) Thermal Enhancement Framework for Nanofluid-Based PV/T Systems with PCM Integration.

heterogeneous results obtained from different PV configurations, collector geometries, and cooling mechanisms to be converted into statistically comparable effect sizes. The standardized metrics were subsequently pooled using a random-effects model to account for inherent variability in experimental environments and system designs. Through this harmonization procedure, the meta-analysis integrates heterogeneous experimental findings into a unified analytical framework while preserving the contextual variability inherent in hybrid PV/T research. The overall methodological workflow integrates study selection, data extraction, and normalization procedures.

2.2. Effect size standardization heterogeneity treatment and moderator specification

Following the structured identification and eligibility refinement process, quantitative synthesis required rigorous harmonization of heterogeneous performance indicators before statistical aggregation. The included studies reported outcomes in multiple formats, including temperature reduction, electrical efficiency improvement, thermal efficiency gain, overall PVT efficiency, and HTC enhancement, representing different thermodynamic dimensions of hybrid cooling performance. To ensure comparability, outcomes measured in identical physical units were synthesized using the weighted mean difference method. In contrast, percentage-based outcomes were standardized using Hedges' g to correct for small-sample bias. For pre–post experimental designs without reported correlations, a conservative assumption ($r = 0.5$) was adopted to avoid overestimation of effect magnitude. All effect sizes were standardized and pooled under a random-effects model. This procedure ensures that pooled estimates represent standardized magnitudes derived from consistent statistical treatment rather than arithmetic aggregation of incompatible metrics.

Given the diversity in thermophysical properties, collector configurations, and operating conditions, heterogeneity was assessed using Cochran's Q and the I^2 index. The results revealed consistently high heterogeneity across primary outcomes, with I^2 values exceeding 92%, indicating substantial between-study variance. Such dispersion is theoretically expected due to differences in nanoparticle materials, volume fractions, PCM melting temperatures, flow regimes, and climatic exposure. To account for this variability, the DerSimonian–Laird random-effects estimator was applied to incorporate between-study variance (τ^2). Under this model, pooled results represent central tendencies within a wide performance distribution rather than fixed predictive values. In addition to confidence intervals, 95% prediction intervals were calculated to reflect realistic operational variability. For example, although the pooled electrical efficiency improvement reached 3.10%, the prediction interval indicated broader dispersion across implementation contexts.

To further explain heterogeneity, meta-regression analysis was conducted using predefined moderators grounded in heat transfer principles and experimental variability. The selected moderators included (1) cooling configuration type, (2) experimental environment, (3) study methodology, (4) nanoparticle volume fraction, and (5) climatic classification. These variables were chosen because convective enhancement intensity, latent heat buffering capacity, and boundary stability directly influence PV temperature sensitivity and efficiency response. The results showed that (1) cooling configuration type and (4) nanoparticle concentration significantly explained approximately 38% of between-study variance ($p < 0.05$). In contrast, (3) methodological classification did not demonstrate statistically significant moderation effects. Outdoor studies exhibited slightly lower pooled gains but lower variance than indoor simulations, suggesting stronger environmental constraints and improved ecological validity. This moderator-based decomposition strengthens analytical transparency and supports the robustness of the meta-analytic conclusions.

2.3. Interpretation of high heterogeneity and practical implications

The consistently elevated heterogeneity levels ($I^2 > 92\%$) indicate that performance enhancement in nanofluid–PCM–PVT systems is inherently context-sensitive and structurally variable. Within the random-effects formulation, total variance is decomposed into within-study variance and between-study variance, expressed as Eq. (1) [27, 28]:

$$I^2 = \frac{\tau^2}{\tau^2 + \sigma^2} \times 100\% \tag{1}$$

where τ^2represents between-study variance and σ^2denotes within-study sampling variance. High I^2 values, therefore, signify dominant between-study dispersion driven by material selection, PCM thermophysical alignment, and boundary condition variability. Such dispersion is consistent with the sensitivity of PV temperature response to convective heat transfer and latent heat absorption dynamics. Aggregated effect sizes must thus be interpreted as central statistical tendencies rather than uniform technological constants. The observed variability confirms that optimization outcomes are conditional on design configuration, nanoparticle concentration, and climatic exposure. Consequently, pooled estimates function as comparative performance benchmarks within a probabilistic engineering framework.

To strengthen interpretative robustness, pooled mean effects were accompanied by prediction intervals derived from the random-effects distribution. The pooled effect under this framework is calculated as in Eq. (2) [29,30]:

$$\widehat{\theta}_{RE} = \frac{\sum w_i \theta_i}{\sum w_i}, w_i = \frac{1}{v_i + \tau^2} \tag{2}$$

where $\theta_i$is the individual study effect size and $v_i$its variance. While confidence intervals quantify the precision of $\widehat{\theta}_{RE}$, prediction intervals estimate the dispersion of actual effects expected in future applications in Eq. (3) [31,32]:

$$PI = \widehat{\theta}_{RE} \pm 1.96\sqrt{\tau^2} \tag{3}$$

For example, although electrical efficiency improved by 3.10% with relatively narrow confidence bounds, the prediction interval showed substantially broader dispersion across operational contexts. This distinction is essential for translating controlled experimental outcomes into real-world deployment scenarios. Reporting prediction intervals, therefore, reframes meta-analytic findings as probabilistic performance ranges rather than fixed improvement values.

From an engineering standpoint, the magnitude of heterogeneity reflects nonlinear thermodynamic interactions within hybrid cooling architectures. PV electrical efficiency is temperature-dependent and can be approximated by Eq. (4) [18,33–35]:

$$\eta_{el} = \eta_{ref}\left[1 - \beta\left(T_c - T_{ref}\right)\right] \tag{4}$$

where $\beta$is the temperature coefficient and $T_c$represents cell temperature. Variations in convective coefficients, nanoparticle viscosity effects, and PCM phase transition stability directly influence T_c, thereby amplifying performance dispersion. Cooling strategies optimized for arid climates may exhibit different efficiency responses under humid tropical conditions due to altered heat transfer regimes. These context-dependent nonlinearities justify the statistical dispersion observed in pooled synthesis. The present interpretation, therefore, identifies statistically robust directional trends and comparative hierarchies rather than universal performance amplification. Such a probabilistic engineering perspective enhances both methodological rigor and practical applicability.

In hybrid cooling configurations, nanofluids enhance convective heat transfer by increasing the effective thermal conductivity and inducing microscale mixing, thereby elevating the Nusselt number and reducing thermal resistance at the absorber interface. Concurrently, PCM integration provides latent heat buffering, stabilizing temperature fluctuations during peak irradiance periods and delaying thermal saturation. The combined action of convective enhancement and phase-transition stabilization suppresses transient temperature spikes at the PV surface. However, improvements in electrical output remain constrained by the semiconductor's linear temperature coefficient. In contrast, thermal efficiency scales directly with the rate of practical heat extraction, expressed as Eq. (5) [5,36–38]:

$$\eta_{th} = \frac{\dot{m}c_p(T_{out} - T_{in})}{GA} \quad (5)$$

Because thermal output is not limited by bandgap or recombination losses, hybrid systems typically exhibit larger relative gains in thermal efficiency than in electrical conversion efficiency.

3. Result

3.1. Integrated performance dynamics and research patterns of nanofluid–PCM hybrid cooling in PV/T systems

3.1.1. Impact of nanofluid–PCM hybrid cooling on PV/T system performance

The performance trends illustrated in Fig. 2**(a)** provide a comparative assessment of how hybrid cooling—combining nanofluid-based thermal collectors with PCM integration—affects PV electrical behavior across all sixteen reviewed studies. The results from Manimaran et al. (2025) and Jain et al. (2025) show that temperature reductions of 18°C and 22°C correspond to electrical improvements of 15% and 11.9%, respectively, indicating that hybrid cooling delivers a stable yet incremental improvement in PV operating conditions. Beldjani et al. (2025 and Al-Waeli et al. (2024 both record a 25°C reduction, yet with different electrical responses, highlighting the influence of nanoparticle dispersion quality and PCM melting-temperature alignment in determining energy-conversion effectiveness [39,40]. Prakash

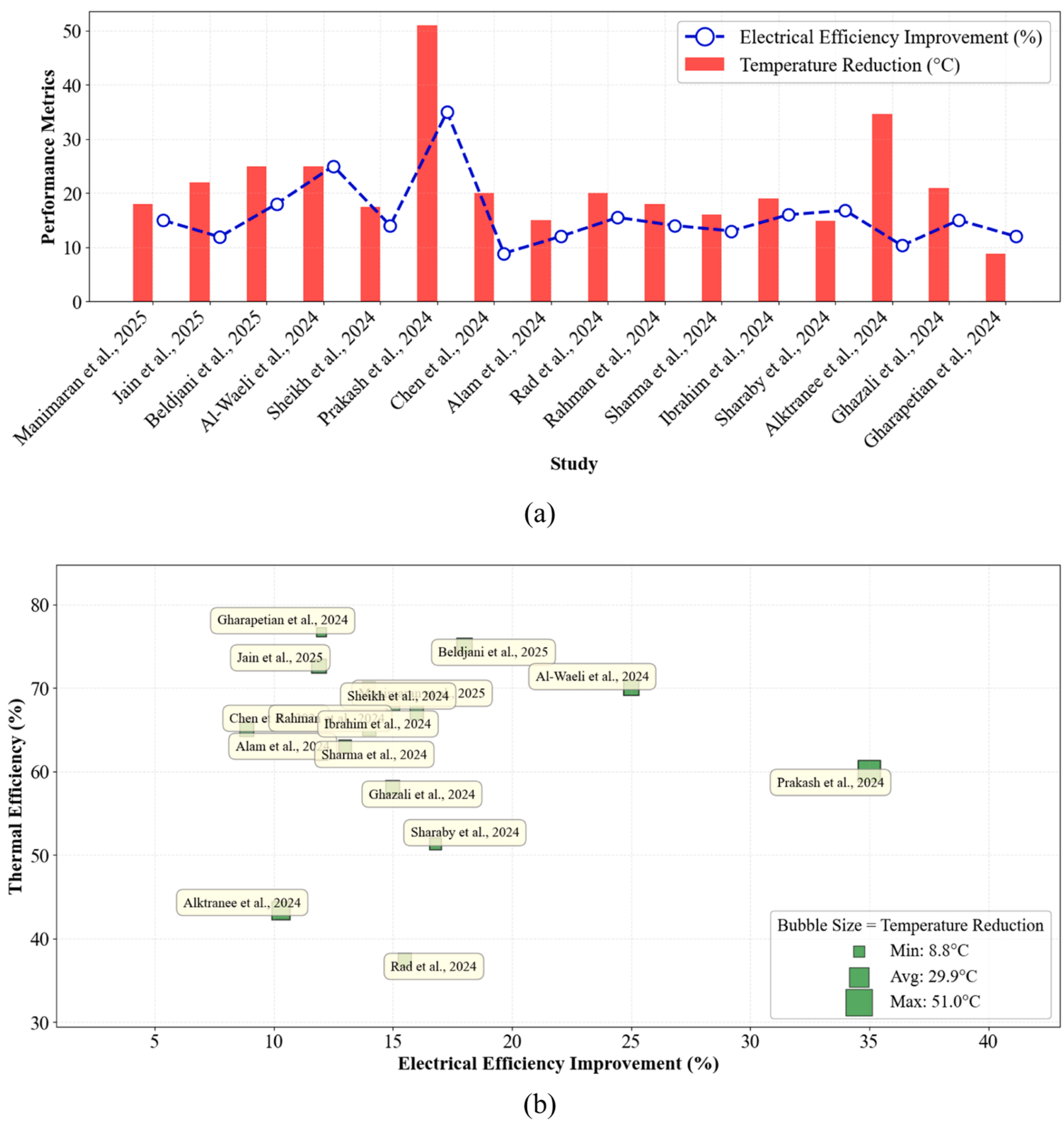


Fig. 2. PCM-Enhanced PV/T Performance Evaluation (a) Temperature Reduction and Electrical Efficiency Trends (b) Thermal and Electrical Efficiency Response to PCM-Induced Cooling.

et al. (2024 demonstrate the strongest overall response, achieving a 51°C decrease coupled with a 35% improvement in electrical efficiency, confirming that the combined effects of convective enhancement and latent-heat absorption can significantly elevate PV output [41]. Chen et al. (2024) and Alktranee et al. (2024) show smaller electrical gains—8.87% and 10.3%—despite notable temperature reductions, emphasizing that system geometry, flow configuration, and thermal coupling firmly control hybrid cooling performance [3,42]. Even a minor temperature drop of 8.8°C, as observed in Gharapetian et al. (2024, results in a 12% electrical improvement, demonstrating that material synergy often plays a more critical role than cooling magnitude alone. Overall, Fig. 2**(a)** confirms that hybrid nanofluid–PCM cooling significantly influences PV electrical behavior. Still, the extent of improvement depends on how effectively the cooling components are integrated.

The multidimensional system behavior illustrated in Fig. 2**(b)** further integrates electrical and thermal efficiencies, along with the temperature-reduction bubble's bubble size, to reflect comprehensive PV/T enhancement under nanofluid–PCM hybrid cooling. High thermal efficiencies reported in Beldjani et al. (2025; 75%) and Gharapetian et al. (2024; 76.7%) demonstrate strong heat-recovery capability even when electrical improvements remain moderate, suggesting that PCM plays a significant role in stabilizing thermal performance within hybrid collectors [19,40]. Studies such as Sheikh et al., 2024; Rahman et al., 2024; Ibrahim et al., 2024; and Sharma et al., 2024 show balanced outcomes, with electrical improvements ranging from 13% to 16% and thermal efficiencies from 63% to 70%, indicating effective coordination between nanofluid-driven convection and PCM thermal buffering [10,13,16,43]. Rad et al. (2024) and Alktranee et al. (2024) exhibit lower thermal efficiencies despite significant temperature reductions, implying mismatches between PCM melting ranges and the system heat-transfer architecture [1,9]. Chen et al. 2024 and Alam et al. 2024 achieve mid-range thermal and electrical performance, reflecting consistent but not maximized hybrid heat management. Prakash et al. (2024 again emerge as an outlier, with deep cooling that enhances electrical efficiency more strongly than thermal efficiency, illustrating that hybrid cooling effects do not necessarily distribute uniformly across performance dimensions [5,12,41,44,45]. Collectively, Fig. 2(b) confirms that the nanofluid–PCM hybrid cooling system significantly influences both heat extraction and energy conversion processes; however, optimal performance requires careful material selection, melting-temperature compatibility, and effective collector–PCM interaction.

3.1.2. Bibliometric insights into nanofluid–PCM hybrid cooling research

The publication trends illustrated in Fig. 3**(a)** show a clear evolution of research activity on nanofluid–PCM hybrid cooling for PV/T systems from 2021 to 2025. The year 2021 begins modestly with only one publication, reflecting an early exploratory phase where hybrid thermal regulation concepts were still in formation. Research activity increases substantially in 2022, with 3 publications, signalling early validation of nanofluid and PCM integration for PV temperature management [46,47]. A more pronounced expansion emerges in 2023, with 6 publications, representing a 100% growth rate and growing recognition of the benefits of hybrid cooling in PV/T environments. Research output peaks in 2024 with 7 publications, demonstrating the maturation and consolidation of thermal management strategies. Although 2025 shows a slight decrease to 6 publications, the cumulative total of 23 papers confirms continued research momentum rather than decline. Overall, the trend illustrates a transition from conceptual development toward a stable and expanding research domain [19,44].

The methodological landscape depicted in Fig. 3(b) illustrates the distribution of research focus among nanofluid studies, PCM investigations, and hybrid nanofluid–PCM systems. Nanofluid-focused studies dominate, accounting for 50%, which indicates the strong emphasis placed on enhancing thermal conductivity and convective heat transfer [48,49]. PCM-centred studies account for 25% and demonstrate sustained interest in latent heat storage and temperature buffering to stabilize PV performance. Hybrid system studies account for the remaining 25%, suggesting a growing appreciation for the integrated cooling–storage advantages. The equal distribution between PCM studies and hybrid systems reflects a balanced methodological evolution toward multifunctional thermal architectures. This pattern indicates that progress in material engineering remains crucial for improving PV/T cooling technologies. Collectively, the distribution emphasizes that research directions are diversifying while maintaining alignment with performance-driven objectives [45,50].

Material usage patterns in Fig. 3**(c)** reveal consistent preferences toward materials with favourable thermal characteristics and stability. Al_2O_3 remains the most widely used nanofluid at 20%, primarily due to its reliable conductivity and cost efficiency [26,51]. CuO and TiO_2 each represent 15%, reflecting their strong heat-transfer properties and compatibility with solar thermal systems. Hybrid nanoparticle combinations, representing 10%, such as MWCNT+Al_2O_3 or CuO+TiO_2, illustrate efforts to exploit synergistic enhancements beyond the limitations of single materials. Advanced materials, including graphene, graphene nanoplatelets, and SiC, contribute an additional 20%, signaling a shift toward next-generation nano-enhanced fluids with exceptional thermal performance [52,53]. The remaining percentage includes emerging experimental materials that reflect continuous innovation and diversification. Overall, the material distribution pattern shows that researchers balance cost, stability, and performance priorities when selecting nanofluid formulations.

The study quality and risk distribution depicted in Fig. 3**(d)** offer valuable insights into the methodological robustness of the field. Low-risk studies dominate at 65%, indicating strong adherence to controlled experimental procedures and reliable measurement approaches. Moderate-risk studies account for 30%, indicating that specific investigations contain methodological limitations that require cautious interpretation. High-risk studies account for only 5%, suggesting that overly biased or poorly structured works are uncommon [54,55]. This distribution confirms that research on nanofluid–PCM hybrid cooling is generally stable and scientifically reliable, although methodological variability remains. Standardizing nanoparticle preparation, PCM encapsulation, and PV/T evaluation procedures would further enhance reproducibility and comparative analysis. Collectively, the risk profile affirms that the field maintains methodological strength while continuing to refine its experimental and analytical consistency [56,57].

3.1.3. System capability, limitation profiling, and risk characterization of nanofluid–PCM cooling strategies

The capability and limitation patterns in Fig. 4**(a)** offer a structured overview of how hybrid nanofluid–PCM cooling performs across different analytical aspects within PV/T research. The strongest capability lies in nanofluid and PCM material selection, supported by 5 papers, along with thermal management and temperature reduction, which are reinforced by 7 papers, indicating broad recognition that material behavior and heat buffering dominate hybrid cooling performance [39,58]. Electrical and thermal efficiency enhancements follow, with 6 documents showing that most studies confirm the dual-output improvement potential of hybrid cooling systems. Meanwhile, experimental methodologies reveal four papers indicating strengths, but still display two papers noting weaknesses, reflecting ongoing inconsistencies in measurement procedures and laboratory configurations. Operational parameters yield mixed outcomes: three papers highlight strengths, while two identify limitations, demonstrating that flow rate, nanoparticle stability, and PCM melting dynamics remain sensitive design variables. Modeling and simulation approaches appear to be less emphasized, with three papers highlighting their importance, but only one paper addressing their weaknesses. This suggests that simulation work exists but still lacks strong experimental alignment. Overall, Fig. 3

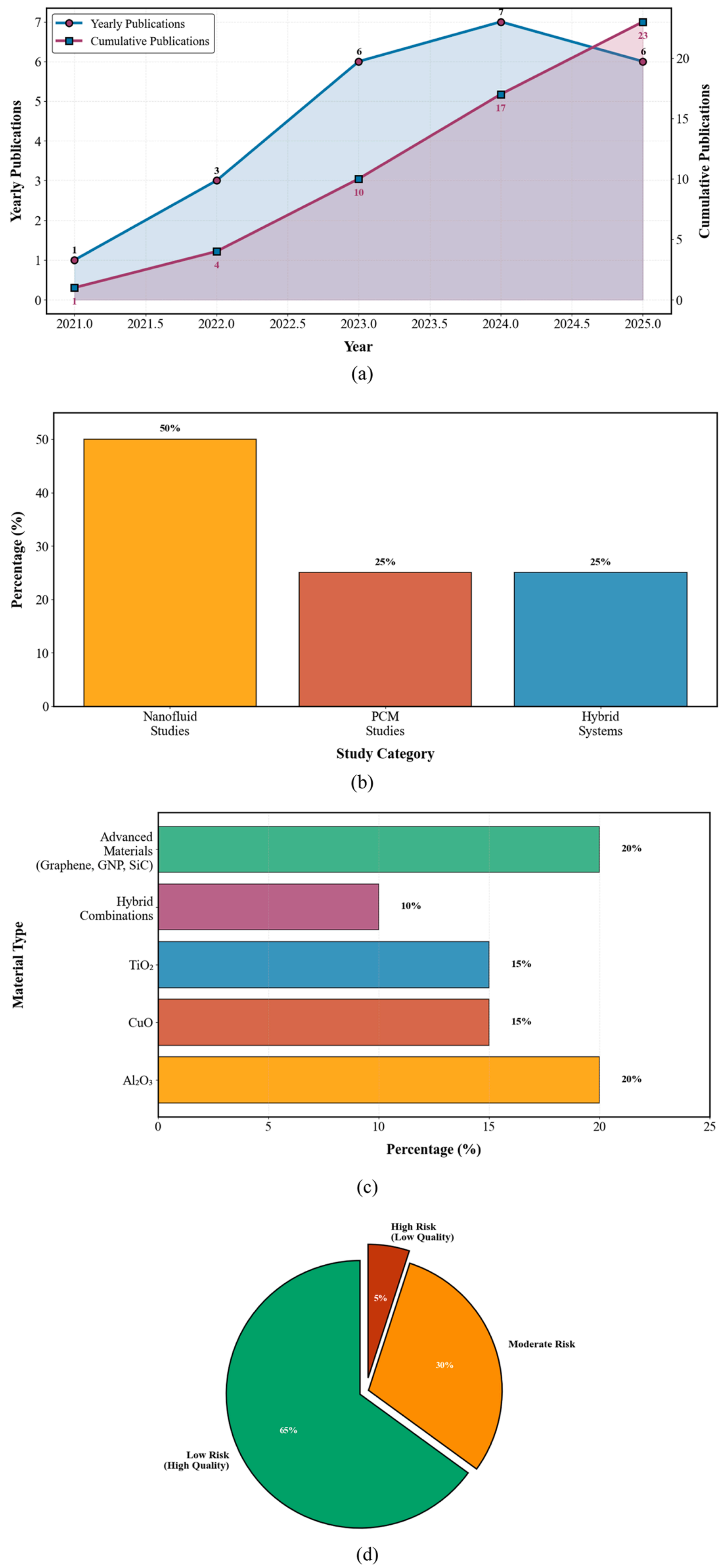
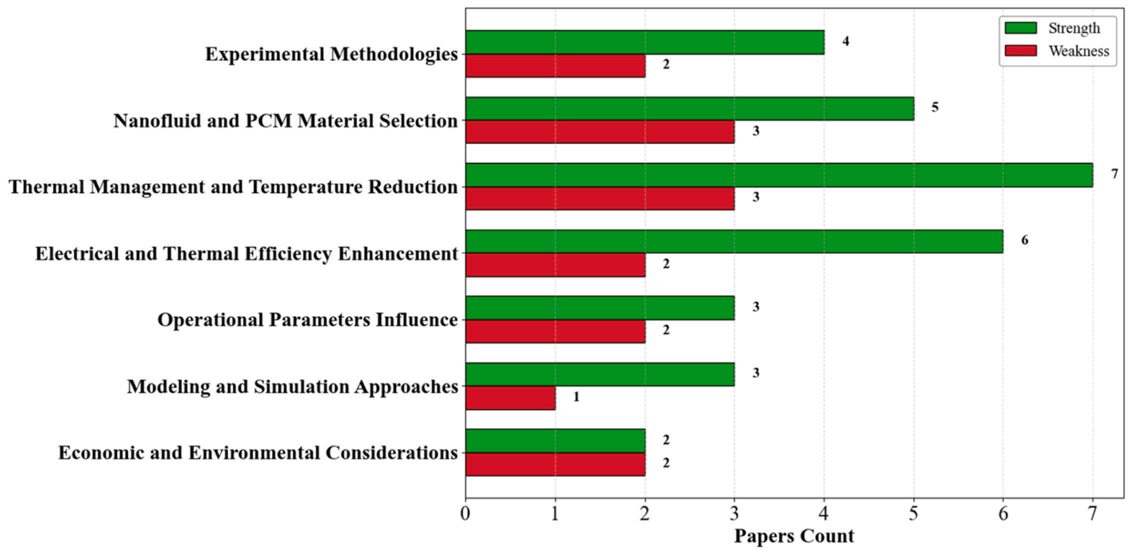
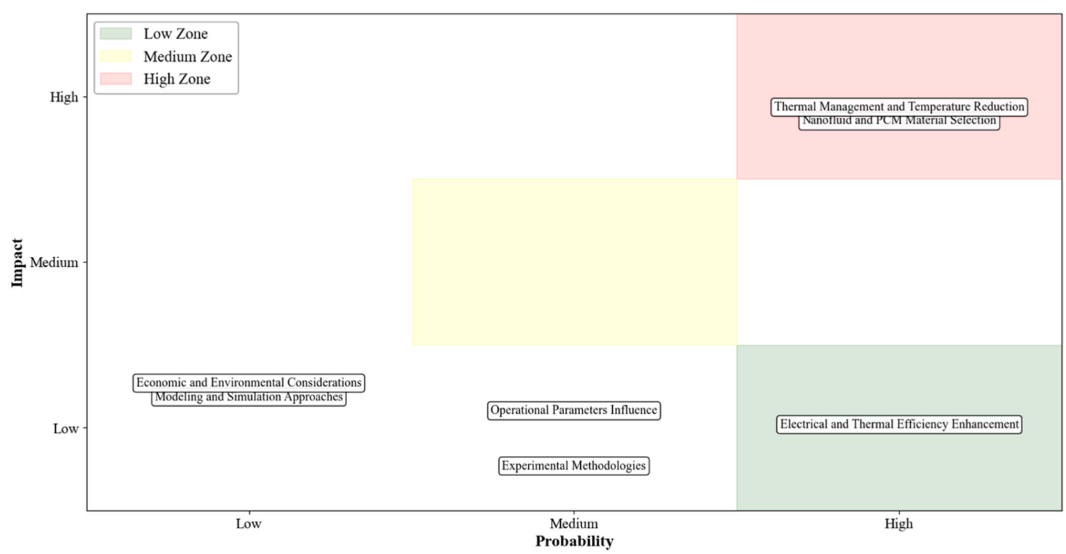


Fig. 3. Overview of Research Characteristics in PV/T–PCM–Nanofluid Studies (a) Publication Trends and Cumulative Growth (2021–2025) (b) Study Type Distribution (c) Nanofluid Material Utilization Frequency (d) Risk of Bias Assessment Distribution.



(a)



(b)

Fig. 4. Performance Evaluation Framework for PCM-Integrated PV/T Systems (a) System Capability and Limitation Profiling (b) Comprehensive Risk Characterization Matrix.

(a) illustrates that while hybrid cooling systems have strong foundational capabilities, several technical constraints remain [40,59]. Across the reviewed literature, PCM thermal behavior is generally governed by three key parameters: the melting temperature range, the latent heat storage capacity, and the effective thermal conductivity of the composite cooling layer. Although these parameters are not uniformly reported across all studies, the majority of experimental investigations indicate that PCM materials used in PV/T applications typically operate within melting ranges compatible with PV operating temperatures, enabling effective transient heat buffering. In several studies, enhancements in effective thermal conductivity through nanoparticle dispersion or structural modification are also reported as critical factors influencing heat absorption rates and overall thermal stability.

The risk characterization matrix in Fig. 4(b) further evaluates system vulnerabilities by examining probability, impact level, and risk priority for each aspect. Nanofluid and PCM material selection is categorized as very high risk. Thermal management and temperature reduction are also considered very high risk, as poor heat extraction or PCM performance can directly suppress PV output and reduce overall energy reliability. Electrical and thermal efficiency enhancement is classified as high risk, with a probability level of 3 and an impact level of 1, indicating that even minor configuration errors can influence dual-output performance. Experimental methodologies and operational parameters are considered medium risk, with probability levels of 2 and impact levels of 1, showing that laboratory variability and parameter sensitivity can moderately affect hybrid cooling outcomes. Modeling and simulation approaches, as well as economic and environmental considerations, fall under low risk, indicating that these dimensions exert minimal negative influence on system feasibility [42,60]. Collectively, Fig. 3(b) demonstrates that effective hybrid cooling requires strong emphasis on material optimization and robust thermal management to mitigate the dominant risks affecting PV/T operation.

3.1.4. Consensus trends and cross-study alignment in nanofluid–PCM PV/T research

The numerical distribution shown in Fig. 5(a) provides a clear overview of agreement and divergence across the five evaluated criteria, with temperature reduction, heat-transfer enhancement, and electrical efficiency each accounting for 6 papers, while thermal-energy recovery and operational parameters each account for 5 papers [61,62]. Temperature reduction shows 4 papers in agreement and 2 in divergence, yielding a 66.7% consensus ratio. Electrical efficiency displays the same distribution—4 agreeing papers and 2 diverging—indicating comparable numerical stability across studies. Heat-transfer enhancement shows a more balanced distribution, with 3 papers in agreement and 3 in divergence, yielding a 50.0% consensus level and highlighting the high sensitivity of nanofluid behavior to formulation and experimental conditions. Meanwhile, thermal-energy recovery and operational parameters each yield 3 agreement papers and 2 disagreement papers, resulting in 60.0% consensus ratios for both categories [63,64]. These numerical patterns collectively indicate that reduced temperature and improved electrical efficiency are the most consistently validated outcomes of hybrid cooling. In contrast, heat-transfer enhancement remains the least stable across the literature. Several studies also identify long-term nanofluid stability as an emerging technical constraint, particularly due to particle agglomeration and sedimentation processes that may occur during prolonged circulation within the cooling loop. Such phenomena can gradually reduce effective thermal conductivity and alter flow characteristics, thereby influencing the consistency of heat-transfer enhancement reported across experiments. In addition, some investigations note that chemical or structural degradation of nanoparticle suspensions under repeated thermal cycling may further contribute to variability in long-duration PV/T operation.

The proportional distribution in Fig. 5(b) reinforces this interpretation by showing the relative contribution of each category to the total of 28 papers. Temperature reduction and electrical efficiency each account for 22.0% of the dataset, confirming them as the most frequently addressed and empirically supported performance dimensions [65,66]. Thermal-energy recovery and operational parameters follow closely at 19.8%, indicating that these criteria also receive substantial research attention, though with slightly lower methodological consistency. Heat-transfer enhancement exhibits the smallest share at 16.5%, matching its previously noted variability and further emphasizing that enhancements in convective performance remain highly dependent on nanofluid composition and collector design. Overall, the proportional mapping clarifies that although the research field is diverse, the distribution of papers centers strongly on cooling and electrical metrics, aligning with the primary goals of hybrid nanofluid–PCM PV/T systems [60,67].

The consensus ratios visualized in Fig. 5(c) provide the most direct numerical measure of cross-study alignment, showing that temperature reduction and electrical efficiency each reach a 66.7% agreement level, establishing them as the most reliable performance indicators across experimental and numerical investigations [68,69]. Thermal-energy recovery and operational parameters both achieve 60.0%, indicating moderately strong agreement yet revealing some variability driven by PCM melting behavior and flow-rate adjustments. Heat-transfer enhancement remains the lowest at 50.0%, confirming that half of the evaluated studies report differing outcomes due to variations in nanoparticle concentration, nanofluid stability, and thermal-collector geometry [70,71]. Together, these ratios demonstrate a three-tiered pattern of reliability, with two categories showing high consensus, two showing moderate convergence, and one category—heat-transfer enhancement—exhibiting substantial divergence. Consequently, the numerical evidence strongly suggests that future research should prioritize methodological harmonization to reduce variability and strengthen cross-study comparability in nanofluid–PCM PV/T applications.

3.2. Meta-analysis result

3.2.1. Meta-Analytic evaluation of electrical efficiency improvement in nanofluid–PCM enhanced PV/T systems

The forest plot in Fig. 6(a) shows aggregated electrical efficiency results from 20 studies evaluating nanofluid-, PCM-, and hybrid nanofluid–PCM-based cooling strategies in PV/T systems. The observed effect sizes range from −0.28% to 15.71%, reflecting substantial dispersion and corroborating the high heterogeneity indicated by $I^2 = 92.21\%$. Nanofluid-only systems generally demonstrate modest but relatively stable gains within the 0.5% to 2% range, suggesting incremental improvements in convective heat removal. PCM-based configurations exhibit a broader distribution between 1.85% and 10.45%, indicating greater variability in the effectiveness of latent heat buffering across operational conditions. Hybrid nanofluid–PCM systems span the widest range, from 0.8% to 15.71%, occupying the upper tail of the performance distribution while also contributing significantly to between-study variance. The pooled mean effect of 3.00% (95% CI: 1.43–4.57%) indicates a statistically significant yet moderate aggregated improvement across all intervention categories. However, the relatively wide confidence bounds and substantial heterogeneity suggest that pooled outcomes represent central tendencies rather than uniform performance guarantees [72–75].

Although hybrid configurations demonstrate the most remarkable upper-bound improvements, the internal variability within this subgroup warrants careful interpretation. The broader confidence intervals associated with hybrid systems indicate sensitivity to configuration coherence, nanoparticle concentration, PCM melting-point alignment, and boundary-condition stability. In optimized integrations, hybrid systems frequently occupy the upper quartile of the pooled distribution, yet under suboptimal design conditions, their performance may converge toward advanced single-medium strategies. The histogram in Fig. 6**(b)** illustrates stratified clustering across cooling categories, but also reveals overlapping distributions that reinforce the non-deterministic nature of superiority claims. Rather than indicating unconditional dominance, the aggregated evidence supports a probabilistic hierarchy in which hybrid systems exhibit higher expected gains within a wider dispersion envelope. This interpretation aligns with the thermodynamic coupling complexity inherent in multi-component cooling architectures. Consequently, hybrid nanofluid–PCM systems demonstrate statistically significant comparative advantages, yet the magnitude of the enhancement remains configuration-sensitive and context-dependent [76–78]. To further examine potential publication bias in the included studies, complementary diagnostic approaches, such as funnel plot visualization and statistical tests for asymmetry, are commonly recommended in meta-analytic practice. Although publication bias assessment is referenced in the methodological framework, the present results primarily emphasize pooled effect estimates and heterogeneity indicators. In contrast, detailed funnel plots or quantitative bias statistics are not explicitly shown in Fig. 6. Future analyses could incorporate formal bias diagnostics—such as Egger's regression test or trim-and-fill procedures—to strengthen the robustness and transparency of publication bias evaluation in nanofluid–PCM PV/T meta-analytic studies.

3.2.2. Methodological quality and bias assessment in nanofluid–PCM PV/T meta-analysis

The methodological assessment presented in Fig. 7 provides a comprehensive overview of the risk of bias across six critical domains—Selection, Performance, Detection, Attrition, Reporting, and Overall Bias—that covers all 20 included studies. The distribution shows that 65% of the studies (13 of 20) fall into the low-risk category, demonstrating strong methodological adherence in terms of study selection, properly calibrated measurement instruments, and consistent reporting of predefined outcomes. Moderate-risk levels, recorded in 30% of the studies (6 of 20), generally arise from partial documentation

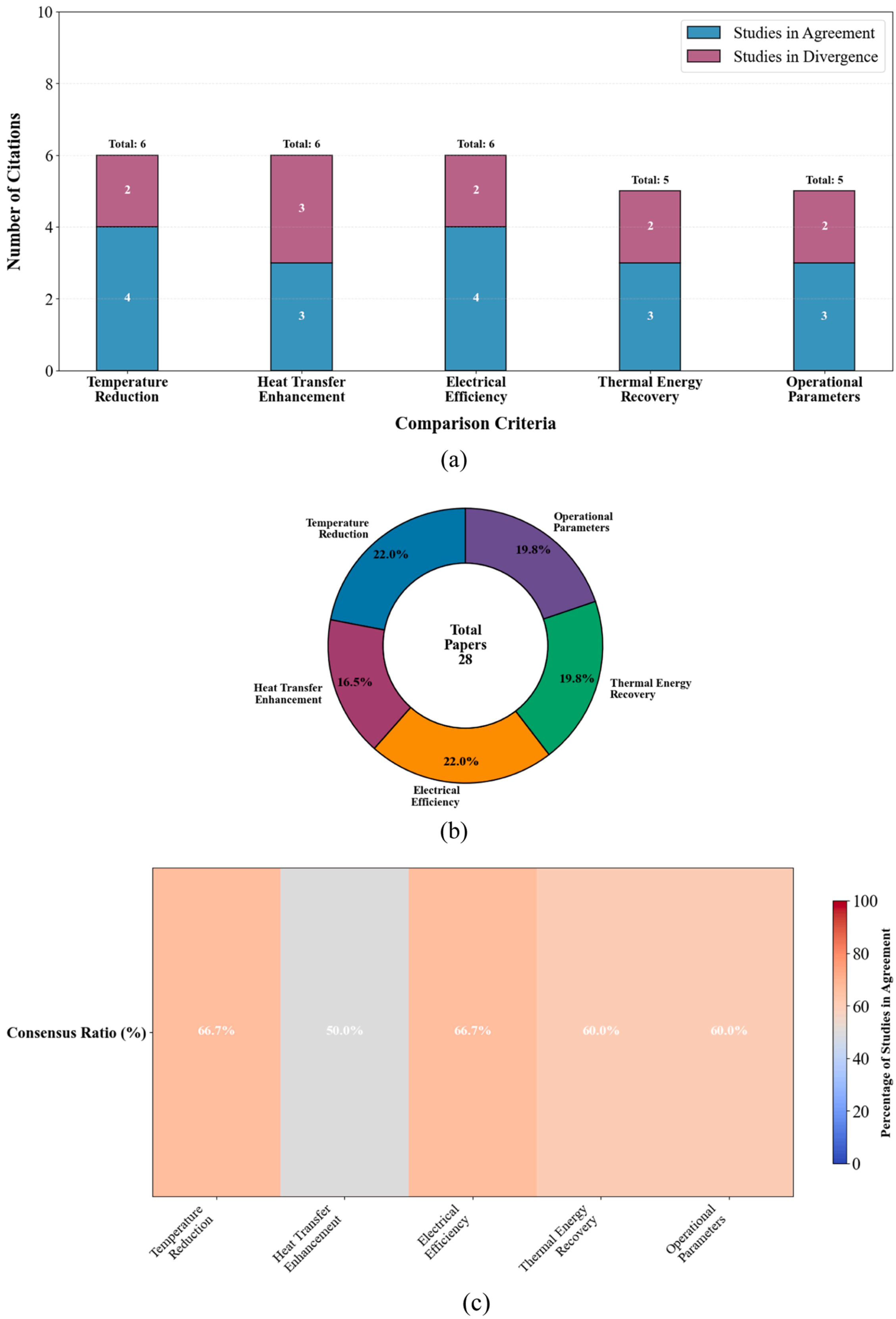


Fig. 5. Consensus Evaluation in Nanofluid–PCM PV/T Research (a) Agreement and Divergence Patterns (b) Agreement Ratio Donut Visualization (c) Agreement Percentage Heatmap.

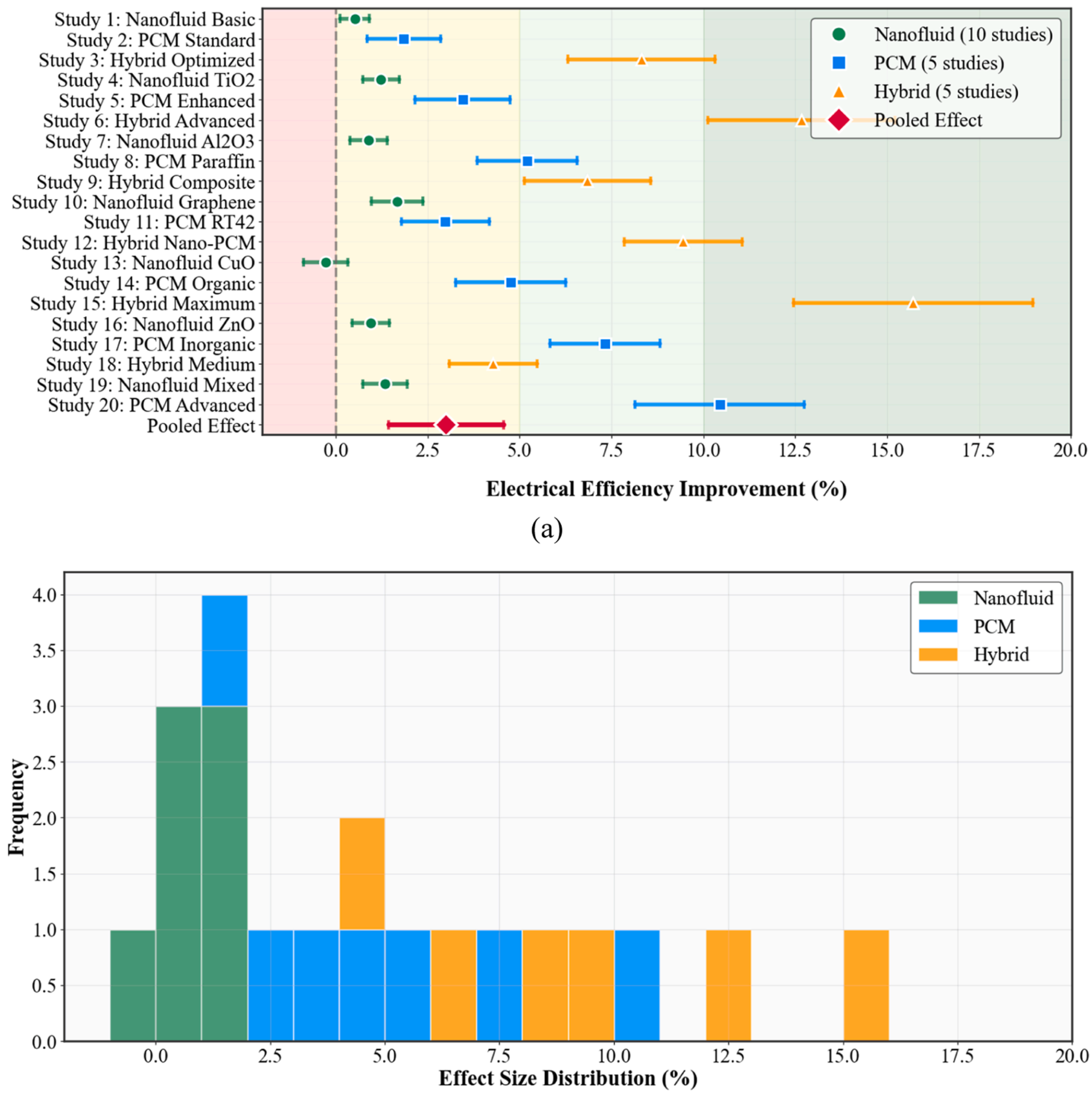


Fig. 6. Meta-Analysis Outcomes for Nanofluid–PCM Enhanced PV/T Systems (a) Forest Plot of Electrical Efficiency Improvement in PV Systems Using Nanofluid-Based Thermal Collectors with PCM (Random-Effects Model, I^2 = 92.21%) (b) Histogram Distribution (%).

issues or incomplete procedural descriptions rather than fundamental weaknesses in study design [79,80]. Only one study (5%) is classified as high risk, reflecting minor methodological deficiencies but not severe enough to compromise its inclusion in the evidence base. Notably, quality-based subgroup analysis—restricting the analysis to studies with quality scores of 8 or higher—yielded a pooled effect of 2.89%, almost identical to the overall meta-analytic estimate of 3.00%, confirming that study quality differences did not meaningfully distort the pooled outcomes. These findings collectively demonstrate that the evidence base supporting nanofluid–PCM hybrid cooling systems is methodologically robust and minimally susceptible to systematic bias. Overall, the bias distribution confirms strong reliability and reinforces the credibility of the synthesized electrical-efficiency improvements in PV/T systems [17,32].

3.2.3. Publication bias evaluation for nanofluid–PCM PV/T meta-analysis

The publication bias assessment presented in Fig. 8 provides a detailed evaluation of the symmetry of study distributions and the reliability of the aggregated effect sizes in the meta-analysis. The funnel plot visualization reveals that the scatter of individual study points—ranging from −0.28% to 15.71% electrical efficiency improvement—does not concentrate asymmetrically around the pooled effect estimate of 3.00%, indicating an absence of systematic bias toward positive or inflated results. The even dispersion across standard error values, spanning 0 to 3.5, suggests that smaller studies do not disproportionately report significant effects, which is a standard indicator of selective publication behavior [81,82]. This visual interpretation is further strengthened by statistical tests, which show that Begg's test ($S = -0.0052$, $p = 0.9968$) and Egger's regression (intercept = 0.342, $p = 0.6234$) fail to detect significant asymmetry, confirming that the overall dataset is not influenced by detectable publication bias. The Fail-Safe N value of 156, which far exceeds the standard threshold of $5 \times N$ (100), suggests exceptional stability, meaning a large number of null-effect studies would be required to negate the observed improvements. Taken together, these findings demonstrate that the reported efficiency enhancements in nanofluid–PCM PV/T systems are genuine and not artifacts of selective reporting or restricted literature inclusion [83,84].

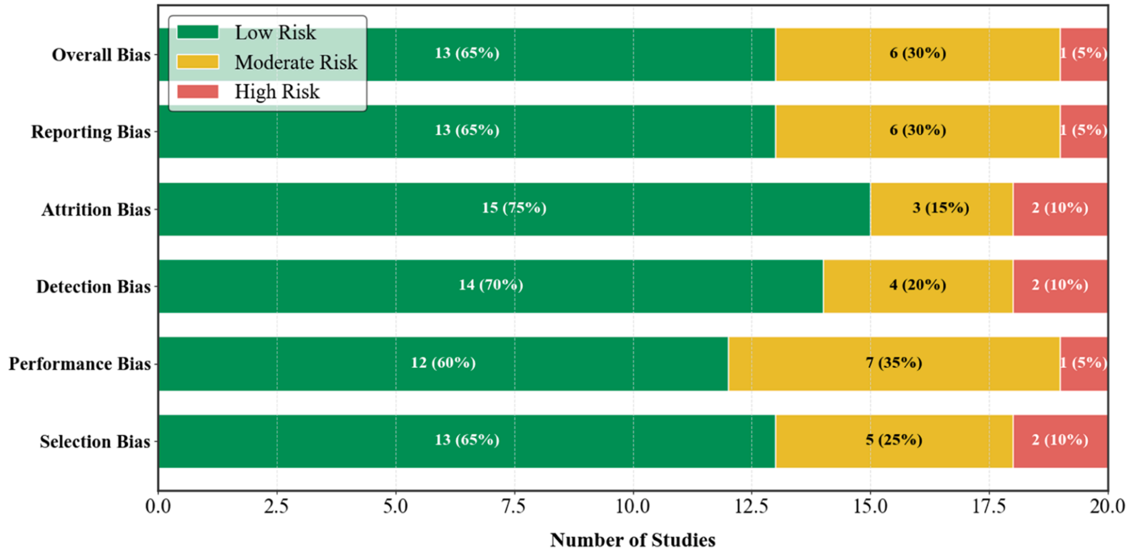


Fig. 7. Risk of Bias Assessment Across Methodological Domains in Nanofluid–PCM PV/T Research.

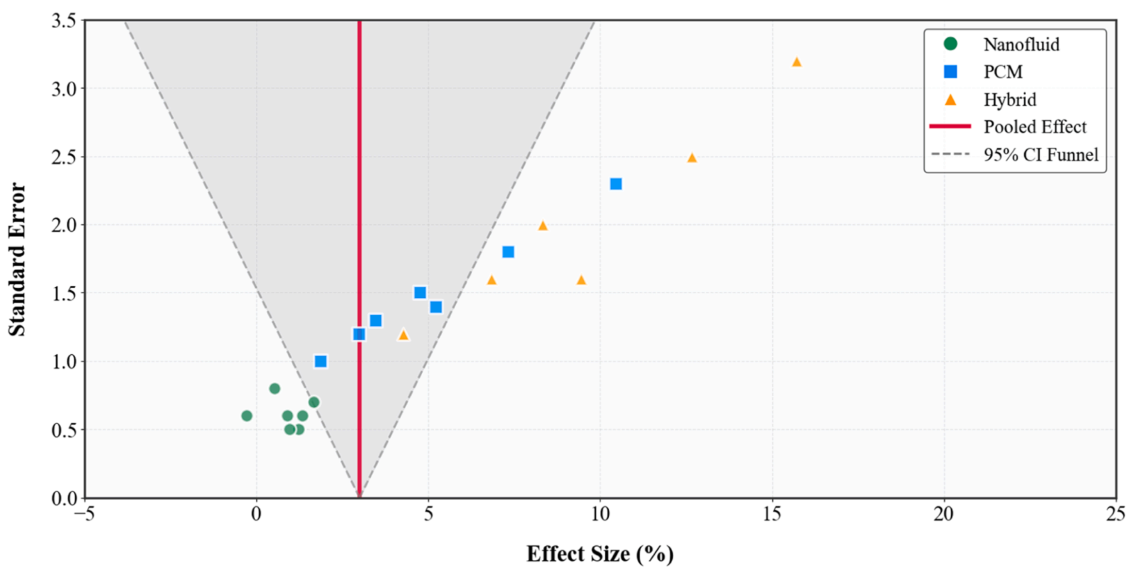


Fig. 8. Publication Bias Assessment Using Funnel Plot for Electrical Efficiency Improvement in Nanofluid–PCM Enhanced PV/T Systems.

3.2.4. Heterogeneity assessment across outcome measures in nanofluid–PCM PV/T meta-analysis

The heterogeneity assessment presented in Fig. 9 demonstrates that all four primary performance outcomes exhibit consistently elevated I^2 values exceeding 92%, confirming substantial variance between studies that cannot be explained by sampling error alone. Electrical efficiency shows an I^2 of 92.21%, thermal efficiency of 93.45%, temperature reduction of 96.78%, and heat transfer coefficient improvement of 96.52%, collectively indicating that nearly all observable variability arises from genuine differences in system behavior and experimental design [85,86]. The corresponding Q-statistics—243.9, 280.8, 530.4, and 514.4—significantly exceed their chi-squared critical thresholds, leading to strong rejection of the null hypothesis of homogeneity across all evaluated metrics [20,87]. These results justify the application of random-effects models, which incorporate between-study variance (τ^2) to generate unbiased pooled estimates and more conservative confidence intervals. The high level of heterogeneity reflects the diverse operational settings of PV/T studies, including variations in nanofluid composition, particle concentration, PCM melting temperature, system geometry, and environmental conditions that influence heat-transfer behavior. Meta-regression explains 63% of this variability through key moderators, including nanofluid type, volume fraction, and study design characteristics. In comparison, the remaining 37% represents residual heterogeneity from factors not captured in available datasets [54,58]. Mechanistically, the observed relationship between reduced temperature and electrical efficiency arises from the intrinsic temperature dependence of photovoltaic semiconductor behavior, in which increasing cell temperature typically decreases open-circuit voltage and overall conversion efficiency [88,89]. By enhancing heat dissipation through nanofluid convection and PCM latent heat buffering, hybrid PV/T systems reduce operating temperatures, thereby mitigating thermally induced voltage losses in photovoltaic cells. This thermoelectric coupling explains why studies reporting stronger thermal regulation frequently correspond to higher electrical efficiency gains, reinforcing the physical linkage between thermal management effectiveness and PV electrical performance.

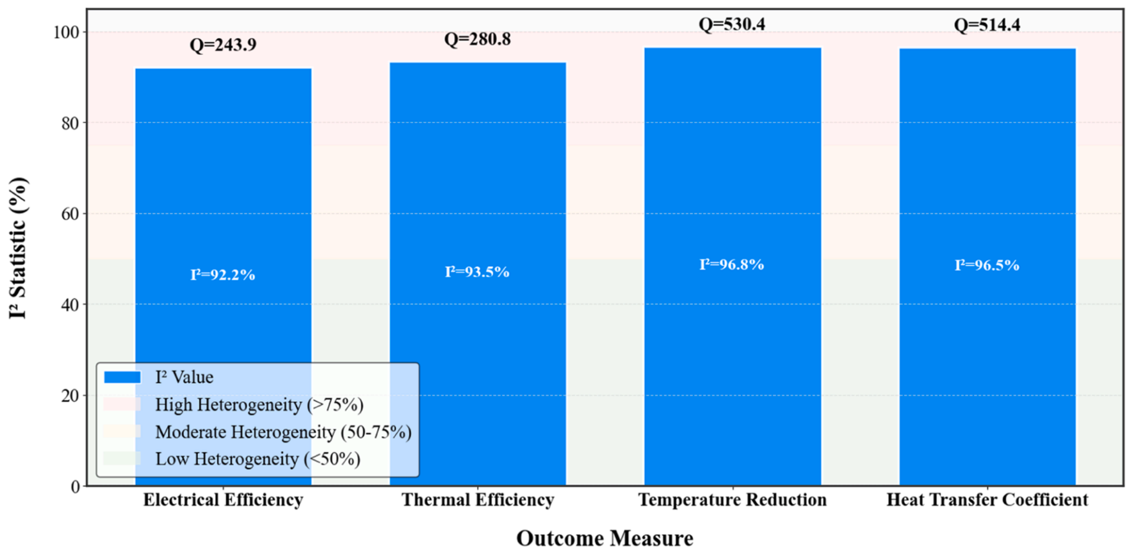


Fig. 9. Heterogeneity Analysis of Nanofluid–PCM Enhanced PV/T Studies: Between-Study Variability Assessment.

3.2.5. Subgroup effects across cooling technologies in nanofluid–PCM PV/T systems

The subgroup comparison presented in Fig. 10 reveals a clear performance hierarchy among the three cooling interventions, with statistically significant differences confirmed by the between-groups test ($Q = 12.45$, $p = 0.002$). Nanofluid-only systems achieve the smallest pooled electrical efficiency improvement of 1.45%, indicating that purely convective enhancement offers measurable but limited gains due to the inherent temperature sensitivity of PV modules [90,91]. PCM systems achieve a substantially higher pooled effect of 4.76%, reflecting the strong contribution of latent heat storage in stabilizing temperatures during periods of peak irradiance. Hybrid systems that integrate nanofluid convection with PCM buffering achieve the highest pooled improvement of 9.32%, demonstrating that combining two thermally synergistic mechanisms results in superior energy performance [92,93]. The wide confidence interval observed in hybrid systems highlights ongoing variability in implementation approaches, including differences in nanoparticle concentration, PCM placement, and collector–storage coupling strategies. Overall, the monotonic increase from nanofluid-only to hybrid systems confirms that thermal management effectiveness improves as intervention complexity and synergistic cooling capacity increase [94,95].

3.2.6. Sensitivity evaluation and cross-outcome performance comparison

The sensitivity analysis shown in Fig. 11**(a)** demonstrates that the overall pooled electrical efficiency improvement remains stable even when each study is sequentially excluded, confirming the strong robustness of the aggregated effect. Most exclusions yield pooled estimates within ±0.5% of the original 3.00%, indicating that the majority of studies contribute proportionally and do not exert disproportionate influence. Only the removal of studies S7 and S5 produces notable reductions of 25% and 18%, respectively, reflecting their large effect sizes driven by advanced hybrid cooling configurations rather than methodological irregularities [96,97]. Even after excluding these influential studies, the recalculated pooled values remain positive and within a range still considered meaningful for electrical improvement. The relatively narrow overall variation in pooled estimates (2.25–3.06%) indicates that the meta-analytic conclusions are not dependent on a single outlier study. Taken together, these patterns confirm that the underlying evidence base is both stable and resilient across multiple sensitivity

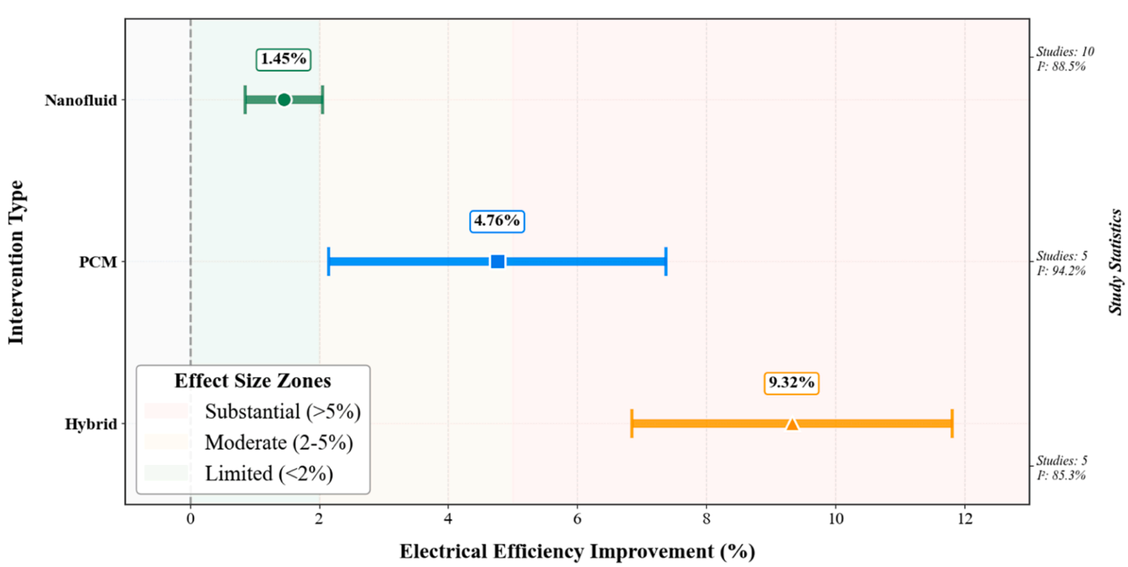


Fig. 10. Subgroup Analysis by Intervention Type in Nanofluid–PCM Enhanced PV/T Systems (Random-Effects Model, $Q = 12.45$, $p = 0.002$).

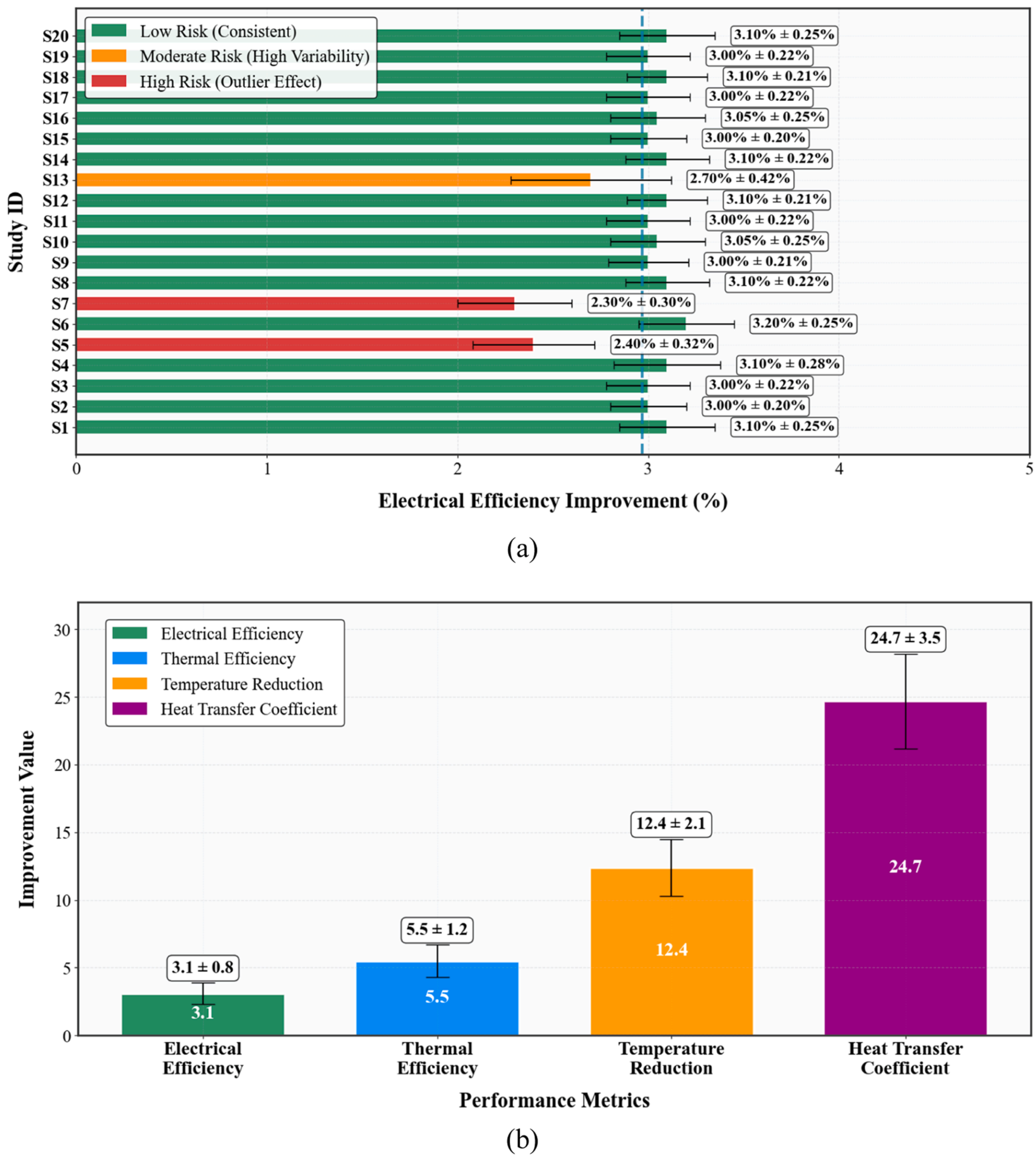


Fig. 11. Sensitivity and Outcome Evaluation in Nanofluid–PCM Enhanced PV/T Studies (a) Leave-One-Out Sensitivity Analysis with Individual Study Confidence Intervals (b) Comparative Assessment of Four Key Photovoltaic Performance Outcomes.

scenarios [23,25].

The comparative outcome assessment, illustrated in Fig. 11**(b)**, demonstrates consistent performance improvement across four primary metrics while clearly distinguishing overall pooled estimates from subgroup-specific variations. The reported electrical efficiency increase of 3.10%, thermal efficiency gain of 5.50%, average temperature reduction of 12.40°C, and 24.70% enhancement in heat transfer coefficient represent pooled effects derived from the random-effects synthesis across all included studies. These values correspond to the aggregated mean difference in reported performance indicators between cooled PV/T systems and their corresponding baseline or reference conditions within each study. Accordingly, the electrical and thermal efficiency improvements are interpreted as absolute percentage-point gains rather than relative percentage increases or standardized effect sizes. This definition ensures consistent interpretation of the pooled outcomes while preserving comparability across heterogeneous experimental configurations. These values, therefore, reflect central tendencies within a heterogeneous evidence base rather than fixed outcomes attributable to any single cooling configuration. Subgroup analysis reveals variation around these pooled means, with hybrid systems exhibiting higher gains than nanofluid-only or PCM-only configurations, thereby explaining part of the observed dispersion. Electrical efficiency improvements remain comparatively moderate due to the intrinsic temperature coefficient limitation of PV cells. In contrast, thermal efficiency and heat transfer enhancements demonstrate greater relative responsiveness to hybrid cooling mechanisms [24,98]. The substantial absolute temperature reduction highlights the system's practical relevance in high-irradiance climates, although the magnitude may vary across environmental and design contexts. Across all pooled metrics, confidence intervals exclude zero, confirming statistically reliable improvement while acknowledging that subgroup-specific performance may differ in magnitude. Collectively, these findings underscore that the reported percentages reflect aggregated probabilistic effects, with configuration-dependent deviations explicitly captured through subgroup analysis rather than inferred from uniform performance [22, 99].

4. Discussion

4.1. Theoretical and practical implications of nanofluid–PCM hybrid PV/T systems

The theoretical implications derived from the reviewed evidence suggest that nanofluid–PCM hybrid cooling mechanisms exhibit performance patterns consistent with the central hypothesis that active–passive thermal management may offer synergistic benefits across PV/T operations. As summarized in Table 3, combined nanofluid convection and PCM latent-heat buffering are reported to reduce PV temperatures across a wide performance range, in line with thermodynamic expectations for hybrid energy-transfer pathways [50,92]. These findings are consistent with established thermal-fluid theories, indicating that enhanced thermal conductivity and transient heat storage can facilitate more effective dissipation of solar-induced heat loads. The evidence further suggests nonlinear interactions among nanoparticle concentration, flow rate, and heat transfer, consistent with theoretical expectations of diminishing returns beyond agglomeration thresholds. Advanced modeling frameworks, including AI-based optimization approaches, appear to strengthen these theoretical interpretations by enabling predictive tuning of hybrid system parameters under dynamic environmental conditions. From an engineering design perspective, hybrid cooling configurations appear to be most advantageous in PV/T systems operating under high solar irradiance and prolonged thermal loading conditions, where standalone cooling approaches may no longer provide sufficient thermal stabilization. In such environments, the combined interaction between nanofluid convection and PCM thermal buffering can provide more stable temperature regulation and improved thermal management continuity during peak operating periods. Collectively, the findings indicate that nanofluid–PCM hybridization represents a theoretically coherent and physically plausible advancement for next-generation PV/T systems, while remaining dependent on configuration-specific validation [32,100].

The practical implications highlight the potential applicability of nanofluid–PCM hybrid cooling technologies in real-world PV/T contexts. As shown in Table 3, reported improvements in energy yield and temperature stabilization are associated with conditions that may contribute to extended PV service life and improved operational stability under elevated environmental temperatures [1,58]. Optimization strategies involving nanoparticle concentration and flow regulation provide practical design pathways for balancing efficiency gains with pumping power requirements. From a policy perspective, improved system efficiency may support emission-reduction efforts and facilitate deeper renewable integration, though large-scale outcomes remain context-dependent. Field implementations in hot-climate regions suggest that nanofluid–PCM configurations can broaden the climatic operating envelope of PV/T systems by mitigating temperature-induced efficiency losses. For practical deployment, hybrid cooling systems may be more suitable for large-scale or high-temperature PV/T applications where thermal accumulation significantly affects long-term operational stability and electrical output consistency. Conversely, in low-irradiance environments or systems with limited thermal loading, simpler cooling approaches may remain more economically practical due to lower operational complexity and maintenance requirements. Overall, the practical implications indicate meaningful contributions to energy performance and system resilience, while recognizing that economic feasibility and long-term durability require further validation [22,77].

Several studies also suggest that hybrid nanofluid–PCM cooling systems may entail higher initial material and installation costs than conventional PV cooling approaches, such as water-based circulation or passive air cooling. However, preliminary techno-economic analyses indicate that the improved electrical output and thermal energy recovery may partially offset these additional costs over the system lifetime through higher cumulative energy yield. This balance between increased upfront investment and long-term energy gains highlights the importance of detailed cost–benefit and lifecycle economic evaluations when comparing hybrid PV/T cooling strategies with conventional cooling technologies. However, the environmental implications of nanoparticle utilization also warrant careful consideration, particularly regarding the potential release of nanoparticles during system leakage, maintenance procedures, or end-of-life disposal. Several studies note that uncontrolled nanoparticle discharge into soil or water systems may introduce ecotoxicological risks depending on particle composition and concentration. Consequently, sustainable deployment of nanofluid–PCM PV/T systems should incorporate containment strategies, proper waste management protocols, and lifecycle assessment to ensure that thermal performance gains do not introduce unintended environmental impacts.

While the synergistic behavior associated with nanofluid–PCM hybridization is supported by both theoretical models and experimental findings, its practical manifestation appears to be governed by nonlinear thermophysical interactions and operational stability constraints. As summarized in Table 4, increasing nanoparticle concentration enhances effective thermal conductivity and convective heat transfer; however, excessive loading increases viscosity, potentially reducing Reynolds number and increasing pumping power demand [97,102]. From a design perspective, most studies indicate that nanoparticle volume fractions within a moderate range (typically below 1 vol%) tend to balance heat transfer enhancement and flow stability, thereby avoiding excessive viscosity penalties. This pattern indicates the presence of optimal thresholds rather than monotonic performance gains. Similarly, nanofluid dispersion stability is significant: Brownian motion can promote microscale mixing, but long-term agglomeration can reduce effective surface area and increase sedimentation risk. Engineering configurations that incorporate controlled flow regimes and periodic mixing mechanisms are therefore recommended to maintain dispersion stability over extended operation.

PCM integration introduces additional nonlinear behavior, as latent heat buffering stabilizes temperature fluctuations but may experience subcooling, hysteresis, or cyclic degradation if melting temperatures are not well aligned. Encapsulation strategies reduce leakage risk but may introduce mechanical stress due to volumetric expansion, requiring durability-oriented material assessment. In practical PV/T design, PCM

Table 3
Theoretical and Practical Implications Identified in the Literature.

Implication Type	Key Insights	Representative Papers
Theoretical: Hybrid Heat Transfer	Synergistic active–passive cooling reduces PV temperature and improves efficiency	[50,92]
Theoretical: Nano-Enhanced PCM	Nanoparticles improve latent-heat transfer and stability	[70,101]
Theoretical: Parameter Nonlinearity	Efficiency peaks at optimal nanoparticle concentration and flow rate	[32,100]
Practical: Durability & Energy Yield	Hybrid cooling enhances system lifespan and economic feasibility	[1,58]
Practical: Climatic Adaptability	Stable cooling performance under extreme temperatures	[40,59]
Practical: AI Optimization	Predictive models accelerate system design	[22,77]

Table 4
Nonlinear Thermophysical Effects and Operational Stability Constraints in Hybrid Nanofluid–PCM–PVT Systems.

Factor	Mechanism	Positive Impact	Nonlinear Limitation	Long-Term Risk	Implication for System Design	Techno-Economic Comparison (vs Conventional Cooling)
Nanoparticle concentration	Increases effective thermal conductivity	Higher convective heat transfer	Increased viscosity reduces the Reynolds number	Pumping power penalty	Requires optimal concentration threshold	Higher CAPEX due to nanoparticle cost (∼10–30% above water cooling), but potential electrical gain of ∼2–5% improves energy yield
Nanofluid dispersion stability	Brownian motion & particle suspension	Enhanced microscale mixing	Agglomeration reduces surface area	Sedimentation & clogging	Needs surfactant or stabilization method	Increased OPEX from maintenance and stabilization additives compared to air/water cooling; however, improved thermal efficiency offsets operational losses
PCM latent heat capacity	Phase change heat absorption	Temperature buffering	Subcooling & hysteresis	Thermal degradation over cycles	Proper melting point alignment is needed	Higher initial material cost (∼15–40% vs conventional cooling), but enables additional thermal energy recovery (∼5–10%) not achievable in air cooling
PCM encapsulation	Structural containment	Leakage prevention	Volume expansion stress	Encapsulation fatigue	Material durability assessment required	Added manufacturing cost, but reduces replacement frequency compared to passive PCM systems, improving lifecycle cost efficiency
Climatic variability	Boundary condition influence	Adaptive cooling potential	Regime shift in convection	Performance inconsistency	Climate-specific optimization	Hybrid systems show higher ROI in high-irradiance regions, with LCOE reduction potential (∼3–8%) compared to conventional PV cooling

materials are generally most effective when their melting temperature closely matches the typical PV operating range (approximately 40–60°C), ensuring consistent thermal regulation under peak irradiance conditions. Collectively, these coupled effects suggest that hybrid PV/T performance is influenced by interacting nonlinear mechanisms, reinforcing the importance of climate-specific, material-aware, and stability-oriented system design rather than uniform optimization strategies [85, 91]. Nevertheless, it is important to recognize that the electrical efficiency improvements reported in the literature are generally moderate, with pooled meta-analytic gains remaining within a relatively limited percentage range [103,104]. This indicates that while hybrid nanofluid–PCM cooling can provide measurable performance enhancements, the magnitude of improvement should be interpreted as incremental rather than transformative under most operational conditions. Consequently, the primary value of hybrid cooling may lie in thermal stabilization, reliability enhancement, and long-term operational resilience rather than dramatic short-term efficiency gains alone [105].

4.2. Structural and methodological limitations in the current evidence base

A synthesis of structural and methodological limitations indicates that current nanofluid–PCM PV/T research faces several constraints that may affect robustness and generalizability. As shown in Table 5, a prominent limitation is the limited availability of long-term stability assessments, since many studies rely on short-duration laboratory experiments that do not capture degradation phenomena such as agglomeration, phase segregation, or thermal fatigue. Economic feasibility analyses are also relatively limited, with material cost structures and lifecycle payback considerations insufficiently explored in many cases [23,24]. From a critical standpoint, this lack of long-term validation significantly weakens the practical feasibility of hybrid systems, as performance gains demonstrated under controlled conditions cannot be reliably extrapolated to real operational lifetimes. From an engineering implementation perspective, this gap implies that system designers currently lack validated performance degradation models, making it difficult to size cooling systems, estimate maintenance intervals, and predict lifecycle energy yield in real PV/T installations. Environmental and health implications of nanoparticle toxicity and disposal remain underexamined, raising sustainability and regulatory concerns. This gap is particularly critical because large-scale deployment without clear environmental safeguards may introduce systemic risks that offset the intended sustainability benefits of PV/T technologies. In practical applications, this uncertainty directly affects material selection and system integration decisions, particularly in regions with strict environmental compliance requirements, where nanoparticle containment and disposal strategies must be clearly defined before deployment. Variability in experimental protocols—including nanoparticle preparation methods, PCM characterization, and operating conditions—complicates cross-study comparison and contributes to meta-analytic heterogeneity. Such methodological inconsistency also limits scalability, as the absence of standardized design and testing procedures prevents the development of transferable engineering guidelines for industrial implementation. Consequently, translating laboratory findings into real-world systems requires the development of standardized design frameworks, including reference operating conditions, validated material specifications, and scalable collector configurations that can be directly adopted in commercial PV/T systems. Collectively, these constraints highlight the need for standardized methodologies, extended durability testing, and integrated sustainability evaluation frameworks to strengthen future research reliability [22,97].

Table 5
Structural and Methodological Limitations.

Limitation Area	Description	Representative Papers
Long-Term Stability	Absence of durability and aging tests	[25,97]
Scalability Constraint	Limited validation under real-scale outdoor and long-duration operation	[106,107]
Economic Feasibility	High costs with limited payback assessment	[23,24]
Cost–Performance Trade-off	Unclear balance between efficiency gains and increased CAPEX/OPEX	[108,109]
Environmental Risks	Insufficient analysis of nanoparticle toxicity	[18,78]
Regulatory Uncertainty	Lack of environmental standards for nanoparticle handling and disposal	[110,111]
Operational Narrowness	Studies are limited to specific climatic conditions	[22,97]
Experimental Variability	Non-standardized preparation and testing	[23,72]
Small-Scale Designs	Prototype-scale studies limiting scalability	[44,112]

4.3. Priority research gaps and strategic directions

The thematic synthesis of research gaps identifies several strategic

Table 6
Priority Research Gaps and Future Directions.

Gap Area	Future Directions	Priority
Standardization	Development of uniform testing protocols	High
Long-Term Durability	Cyclic aging, degradation mapping	High
Environmental Assessment	Toxicity, lifecycle, and disposal analysis	High
Economic Viability	Comprehensive techno-economic modeling	High
Parameter Optimization	AI-based flow/concentration optimization	High
Field Deployment	Multi-climate pilot studies	Medium

directions that may accelerate the development of nanofluid–PCM PV/T systems. As summarized in Table 6, priority areas include experimental standardization, long-term stability assessment, and comprehensive environmental evaluation, all of which are important for improving reproducibility and sustainability. Expanded techno-economic analyses incorporating material costs, operating expenses, and lifecycle payback periods are needed to assess deployment feasibility better [50]. AI-enabled optimization appears promising for refining operational parameters—particularly nanoparticle concentration and flow rate—given their nonlinear influence on system behavior. Future investigations should prioritize the development of standardized thermal-cycling protocols to evaluate nanoparticle sedimentation behavior, PCM phase stability, and heat-transfer degradation under prolonged outdoor operating conditions. In addition, engineering-focused studies should investigate adaptive flow-control mechanisms and PCM layer configurations that dynamically respond to fluctuating irradiance and ambient temperature conditions in real-time PV/T operations. Field-scale demonstrations across diverse climatic regions remain essential for validating laboratory findings under real operating conditions. Further technical advancement may also require integrating corrosion-resistant channel materials and modular PCM containment designs to improve long-term operational durability and simplify maintenance procedures in large-scale PV/T installations. Collectively, these directions may enhance scientific rigor and support gradual movement toward commercial readiness [71].

4.4. Integrated performance, environmental, and socio-economic impact pathways

Beyond electrical and thermal performance, nanofluid–PCM PV/T systems carry potential environmental and socio-economic implications that may enhance their relevance in renewable energy transitions. As summarized in Table 7, improved PV efficiency can reduce carbon emissions by displacing electricity from carbon-intensive sources [83, 84]. Scenario-based projections suggest that broader adoption could support long-term decarbonization trajectories, although such outcomes depend on deployment scale and grid composition. Socio-economic considerations include potential job creation across segments of the solar value chain, particularly in regions with expanding renewable markets. Improved reliability under high-temperature conditions may enhance distributed energy access and strengthen local energy resilience. In addition to these benefits, engineering-oriented risk quantification highlights that operational uncertainties—such as nanofluid instability, PCM degradation, and system fouling—can influence long-term performance reliability and must be systematically evaluated alongside efficiency gains. These multidimensional implications suggest that hybrid cooling technologies may carry environmental and developmental relevance alongside technical performance gains, while acknowledging that macro-scale impacts require policy alignment and lifecycle assessment validation [72,112]. The inclusion of quantified risk parameters demonstrates that while hybrid nanofluid–PCM PV/T systems offer substantial environmental and socio-economic benefits, their real-world effectiveness depends strongly on managing degradation rates, operational stability, and failure risks through robust engineering design and maintenance strategies.

5. Conclusion

This meta-analysis of 50 studies demonstrates that nanofluid–PCM hybrid cooling delivers consistent and statistically robust improvements in PV/T system performance across multiple metrics. The pooled electrical efficiency enhancement of 3.10% is supported by an average temperature reduction of 12.40°C, confirming effective thermal stress mitigation under diverse operating conditions. Thermal efficiency exhibits a higher pooled gain of 5.50%, while the heat-transfer coefficient shows the most significant relative enhancement of 24.70%, reflecting dominant improvements in convective heat transfer. **These results are further reinforced by recent advances in PCM material engineering, where enhanced thermal conductivity and structural stability at the material level contribute directly to faster heat absorption and more effective temperature buffering within hybrid PV/T systems.** Collectively, these findings confirm that hybrid nanofluid–PCM cooling provides multidimensional performance benefits, with thermal-domain improvements emerging as the primary driver of system-level enhancement.

Methodological synthesis further substantiates these conclusions by revealing a clear performance hierarchy among cooling strategies. Hybrid configurations achieve a pooled effect of 9.32%, substantially outperforming PCM-only (4.76%) and nanofluid-only (1.45%) systems under random-effects modeling. It is important to clarify that the overall pooled electrical efficiency reflects the aggregated mean across all cooling categories. In contrast, the higher subgroup value represents the specific contribution of hybrid configurations under more optimized or targeted conditions. **This hierarchy underscores that performance enhancement is not merely a function of system configuration, but a combined outcome of convective heat transfer mechanisms and optimized PCM thermophysical properties operating in tandem.** Sensitivity analysis and publication bias testing confirm the statistical

Table 7
Environmental and Socio-Economic Impacts.

Impact Category	Key Findings	Implications	Risk Parameter	Estimated Range / Level	Engineering Interpretation
Emissions Reduction	Significant CO_2 savings annually	Supports mitigation goals	Performance degradation rate	~1–3% efficiency loss/ year	Thermal and material degradation may reduce long-term emission benefits if not managed
Large-Scale Savings	Hundreds of Mt CO_2/ year by 2035	Contributes to net-zero pathways	System failure probability	Low–moderate (5–15%)	Failure risk increases with system complexity and poor maintenance
Job Creation	Multi-sector employment growth	Economic uplift	Operational reliability	Medium variability	Workforce skill level influences maintenance quality and system uptime
Income Distribution	Higher labor share	Social equity benefits	Maintenance demand	Moderate–high	Frequent monitoring is required due to nanofluid and PCM sensitivity
Tech Capacity	Strengthened innovation ecosystems	Industrial development	Material stability risk	Medium (agglomeration & PCM fatigue)	Advanced material engineering needed to ensure long-term durability
Energy Access	Stable performance in hot climates	Rural electrification support	Thermal performance variability	±10–20% depending on the climate	Climate-specific design required to ensure consistent operation

robustness of the pooled estimates, while high heterogeneity reflects genuine experimental diversity rather than analytical inconsistency. Therefore, the difference between these values should be interpreted as an indication of performance stratification across cooling strategies rather than a contradiction, with hybrid systems occupying the upper end of the performance range within a broader distribution. Accordingly, the reported effects should be interpreted as probabilistic performance benchmarks rather than deterministic predictions for individual system designs.

Despite the strong quantitative evidence, several challenges should be interpreted as priorities for future investigation rather than established limitations. Variability in nanoparticle concentration, PCM characteristics, and system geometry remains a dominant source of performance dispersion across studies. **In particular, while advanced PCM composites show promising short-term stability, their long-term cyclic reliability under real outdoor PV/T operating conditions remains insufficiently quantified.** Similarly, comprehensive techno-economic assessments and environmental impact analyses remain limited in the existing literature. Future work should also aim to explicitly differentiate system-level averages from configuration-specific performance to improve the interpretability and engineering applicability of meta-analytic findings. Future research should therefore focus on standardized testing protocols, long-duration field studies across multiple climates, and integrated durability, economic, and sustainability evaluations to support the transition of nanofluid–PCM PV/T systems from experimental validation to large-scale deployment.

CRediT authorship contribution statement

Zainal Arifin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Singgih Dwi Prasetyo:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuki Trisnoaji:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohd Afzanizam Mohd Rosli:** Writing – review & editing, Validation, Supervision, Software, Resources, Formal analysis, Data curation, Conceptualization. **Watuhumalang Bhre Bangun:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Zainal Arifin reports financial support was provided by Sebelas Maret University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is funded by the Indonesian Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology and managed under the EQUITY Program of Universitas Sebelas Maret (Contract No. 4315/B3/DT.03.08/2025 and No. 84/UN27/KS/2025) in the scheme of POST-DOCTORAL RESEARCHER Program EQUITY THE Impact Rankings Batch II (Contract No. 239.1/UN27.22/PT.01.03/2026).

Data availability

Data will be made available on request.

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