

State-of-the-art review on nano enhanced PCMs for solar energy storage applications

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ABSTRACT

Solar thermal energy storage has emerged as a critical component in improving the efficiency and reliability of renewable energy systems. This review examines the role of nano-enhanced phase change materials (NePCMs) in solar thermal energy storage systems, with emphasis on their thermophysical enhancement mechanisms, preparation methods, and performance in applications. The study critically evaluates how nanoparticle incorporation improves thermal conductivity, heat transfer behavior, and thermal stability of conventional phase change materials. In addition, key preparation methods and their influence on material performance and scalability are discussed. The review further analyzes the application of NePCMs in solar thermal systems, including solar cookers, solar dryers, and solar-thermal-assisted power systems, alongside associated engineering challenges. Reported studies indicate that incorporating nanoparticles can enhance thermal conductivity by approximately 5% to 100%, depending on nanoparticle type, dispersion quality, and loading concentration. Overall, NePCMs demonstrate significant potential to improve the efficiency and reliability of solar thermal energy storage, though further research is needed to address costs, stability, and large-scale implementation.

1. Introduction

Since the Industrial Revolution, the primary source of energy has

been fossil fuels. This form of energy has been extensively exploited for various applications such as powering cities, homes, industries, as well as transportations [1]. Aside from its numerous uses and benefits,

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emission of greenhouse gases, carbon dioxides and the rise in the global temperature have remained the side effects of fossil fuels [2]. Demand for energy to run daily activities has increased drastically as a result of population increase and the industrial revolution [3,4]. To meet this exponential energy demand, renewable energy sources provide an alternative solution to the constant energy demand with limited or no environmental impact, such as land degradation, carbon emissions, and destruction of natural resources [5,6]. Renewable energies such as Biomass, Wind, Geothermal, and Solar can be exploited to meet the energy demands of an overpopulated world. Of all these renewable energy sources available, solar energy is the cleanest, cost-effective, easily accessible, and readily available [7]. Solar energy has numerous uses, including cooking, drying, heating, power generation, industrial uses, and transportation [8–10].

Harnessing solar energy effectively to replace fossil fuels has led to several research studies aimed at engineering systems that can store solar thermal energy and release it for later use during off-sunshine hours or cloudy days, due to unpredictable weather [11–13]. Due to the intermittent nature of solar radiation, using solar energy at night or on cloudy days is highly impractical without appropriate engineering to store it and convert it into thermal energy for sustainable use and applications [14]. Thermal energy storage (TES) is a key technology for solar energy storage applications [15]. These systems can store large amounts of solar energy to ensure long-term thermal energy availability using Phase Change Materials (PCMs) [16]. TES are classified into various types depending on their unique characteristics. They can store heat for a longer period using sensible, latent, or thermochemical heat storage. Sensible heat storage systems store heat by raising the temperature of materials. Latent heat storage systems store heat through phase change materials that undergo melting or solidification. Thermochemical heat storage systems store heat energy through chemical processes involving bond-breaking or bond-formation. TES systems are used for space heating and cooling, industrial processes, and power generation [17,18]. The choice of TES system depends on factors such as the specific application, desired operating temperature, storage duration, and efficiency. Fig. 1 illustrates the general classification of energy

storage technologies, highlighting the position of thermal energy storage, which forms the primary focus of this review. Amongst the various types, thermal energy storage is the most efficient. TES systems utilize the solar energy stored throughout the day into excess thermal energy for short or long term uses [20].

1.1. Phase change materials (PCMs)

Phase change materials are substances that undergo reversible phase transition, typically from solid to liquid and vice versa, while absorbing or releasing latent heat. Depending on the phase transition, PCMs are categorized as solid-to-solid, solid-to-liquid, solid-to-gas, or liquid-to-gas. Among the above, solid-to-liquid PCMs offer excellent potential for thermal energy storage and thermal regulation due to their high energy storage capacity, wide temperature range, and small volume change rate [21,22]. This unique behavior allows PCMs to store and release thermal energy over a narrow temperature range, making them ideal for applications that require efficient heat storage and transfer [23, 24]. These materials have been studied for their good thermal conductivity (though most have low thermal conductivity), low heat capacity, and high energy storage capacity [25]. There are three types of PCMs: Organic PCMs, Inorganic PCMs, and Eutectic PCMs, as shown in Fig. 2. These types have specific thermophysical properties depending on their makeup [27]. Organic PCMs are typically fatty acids and paraffin waxes. They are known by their ability to melt and solidify without undergoing supercooling under constant temperature. Paraffin wax is a hydrocarbon that is derived from petroleum with straight-chain or branched alkanes. They have moderate thermal conductivity, are non-corrosive, and have stable chemical compositions [28]. Inorganic PCMs, composed of salt hydrates [29], metals, and alloys, have a higher latent heat of fusion than organic PCMs; they are inexpensive and have high thermal conductivity. Hydrated inorganic salts have been used in various applications, such as solar energy storage systems, buildings, and solar water heating systems, due to their low phase-change temperature range [30]. Eutectic PCMs, on the other hand, have been used to enhance the capacity of thermal energy storage systems for sustainable energy

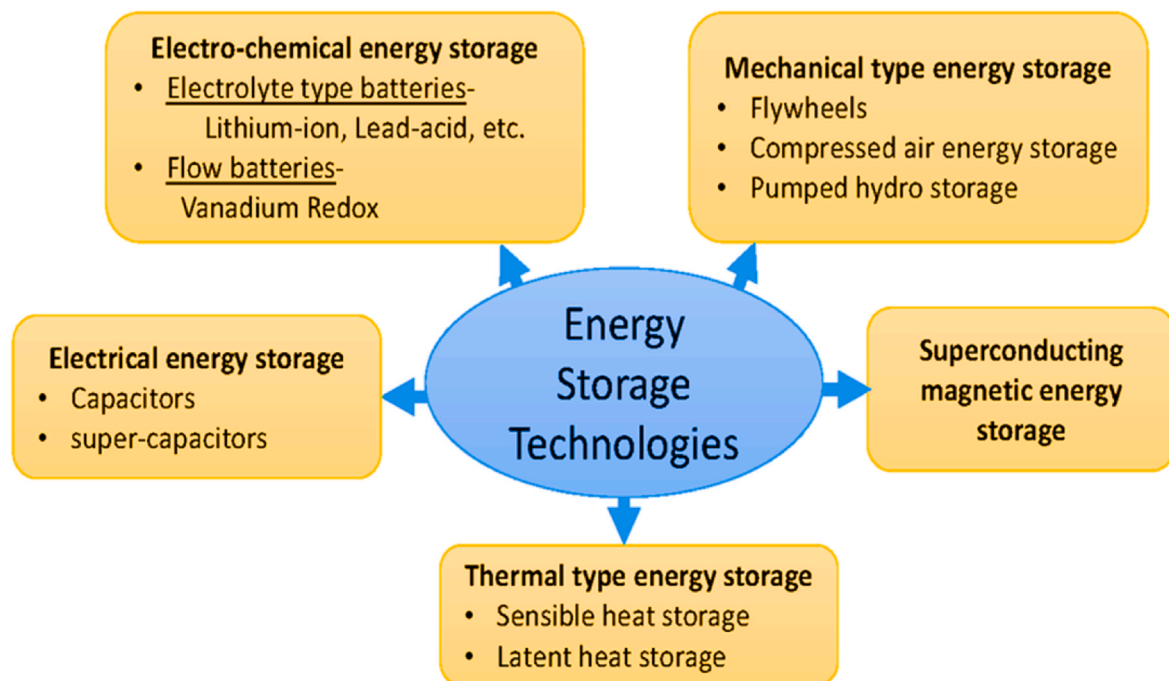


Fig. 1. Classification of energy storage technologies, including electrochemical, mechanical, electrical, thermal, and superconducting magnetic energy storage systems. Thermal energy storage is further categorized into sensible and latent storage, which forms the basis for phase change material (PCM) applications discussed in this review. Reproduced with permission from Datta et al. [19] Copyright 2021, John Wiley and Sons.

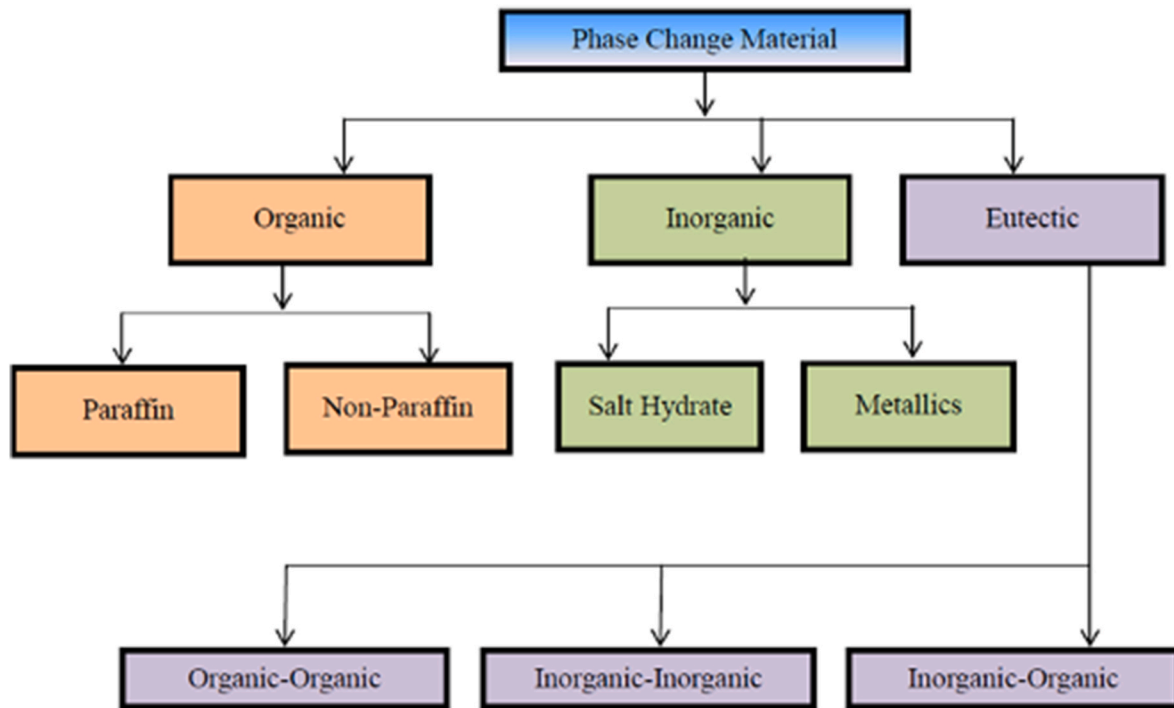


Fig. 2. Classification of phase change materials into organic, inorganic, and eutectic categories. Organic PCMs include paraffin and non-paraffin materials, while inorganic PCMs consist of salt hydrates and metallics. Eutectic PCMs are further categorized into organic–organic, inorganic–inorganic, and organic–inorganic combinations. This classification provides the fundamental basis for selecting suitable PCMs for nano-enhanced solar thermal energy storage applications. Reproduced from Ref. [26] licensed under a Creative Commons Attribution 4.0 International License.

applications [31]. These materials consist of two or more substances that melt or solidify at temperatures different from those of the individual components. They are a combination of organic–organic, organic–inorganic, and inorganic–inorganic PCMs. They have a high melting point and a high latent heat. However, their thermophysical properties depend on the exact composition of the mixture in question [32]. PCMs have been widely employed in thermal energy storage systems due to their moderate thermal conductivity and stability over a wide temperature range [33]. In recent years, their applications have expanded significantly across various engineering domains, including building thermal management, solar thermal energy storage, waste heat recovery, and photovoltaic–thermal hybrid systems, where efficient heat storage and temperature regulation are essential [34]. Recent studies have demonstrated that PCMs can enhance system efficiency, reduce energy consumption, and improve thermal stability under dynamic operating conditions [35,36].

Additionally, advancements in PCM integration techniques have shown promising results in improving heat transfer performance and long-term reliability in practical applications [37,38]. Despite their benefits and wide-ranging applications, conventional PCMs still face several limitations, such as low thermal conductivity, phase segregation, supercooling, and volume expansion during phase transitions, which can negatively affect system performance and long-term stability [39]. To overcome the limitation of low thermal conductivity, several enhancement strategies have been explored beyond nanoparticle dispersion [40]. These include the incorporation of extended surfaces such as fins, the use of high-conductivity porous structures such as metal foams and graphite matrices, encapsulation techniques, and hybrid thermal systems [41,42]. These approaches enhance heat transfer by increasing effective thermal pathways, improving surface area contact, and promoting uniform heat distribution within the PCM matrix. Recent studies have demonstrated that such methods can significantly improve charging and discharging rates, thermal response, and overall system

efficiency [43,44]. However, these methods often introduce additional design complexity, increased system weight, and higher fabrication costs, which limit their scalability and practical implementation. As a result, nanoparticle-based enhancement has emerged as a more practical and efficient solution for improving PCM performance [45]. These limitations have motivated extensive research into nano-enhanced phase change materials (NePCMs), in which nanoparticles are incorporated to overcome these challenges and improve thermophysical properties [46]. Fig. 2 presents the general classification of phase change materials, which serves as a basis for selecting appropriate PCM types for nano-enhancement and solar thermal applications discussed in this review.

1.2. Nano-enhanced phase change materials (NePCMs)

NePCMs are PCMs that have been enhanced with nano conductive particles. These materials have emerged as a promising, innovative class with a wide range of applications across diverse fields. Due to the conductive nature of these nanomaterials, NePCM materials combine the advantageous properties of both nanoparticles and PCMs, resulting in enhanced thermal performance, improved energy efficiency, and novel functionalities [45]. NEPCMs have attracted significant interest from researchers and industry alike due to their potential to address critical challenges across applications, ranging from energy storage and thermal management to electronic cooling and beyond [47,48]. Enhancing PCMs by incorporating nanoparticles into the material matrix increases thermal conductivity, storage capacity, melting temperature, density, and thermal stability during successive cycles of heating and cooling [49]. Misawo et al. [50] employed a numerical approach to study the temperature–energy relationship and spatial distribution analysis of NePCMs via thermal energy. Their analysis focused on understanding the relationships between energy, temperature, and nanoparticle distribution within PCMs, using 3D surface and scatter plots to

illustrate how energy storage characteristics vary with temperature and spatial variables. They concluded that this visualization guides PCMs' optimization for improved thermal conductivity and heat capacity. Farsijani et al. [51] enhanced the performance and stability of a solar pond using an external heat exchanger with NePCM. They used energy and exergy analyses to assess the effects of nanoparticles and their concentration on overall solar performance. Their findings were compared with the performance of water and pure paraffin wax as phase change materials. They concluded that the system energy was efficiently increased from 10.72% (51.83%) for water to 14.7% (70.1%), 22.77% (82.13%), and 25.93% (87.58%) for PCM, PCMs with 1 wt% nanoparticles, and PCMs with 2 wt% nanoparticles, respectively. The integration of nanoparticles into PCMs within an external heat exchanger enhances the stability and performance of solar pond systems.

Said et al. [52] did a comprehensive study on nano-enhanced PCMs and their fundamental applications in energy storage systems. They concluded that adding nanoparticles into PCMs enhanced thermal conductivity and heat storage enthalpy of the resulting NePCMs. Graphene-based PCM composite has been used to enhance the thermal conductivity of solar-thermal conversion storage systems. Graphene-based PCMs exhibit a high thermal conductivity of 9.87 W/m·K and an electrical conductivity of 68.08 S/cm, along with excellent shape stability [53]. Öztöp et al. [54] investigated the structural, morphological, thermal energy storage, and stability characteristics of B₄C nanoparticle-enhanced RT35HC. The addition of B₄C nanoparticles improves both the thermal conductivity and specific heat capacity of the NePCM in solid and liquid phases. Investigation into the latent heat thermal storage (LHTS) for concentrated solar energy using numerical studies reveals that integrating nanoparticles into the storage medium presents viable ways to boost the efficiency and stability of concentrated solar storage systems [55]. Bharathiraja et al. [56] synthesized hybrid PCMs (HPCMs) by dispersing varying weight fractions of multiwalled carbon nanotubes (MWCNTs) and SiO₂ nanoparticles into paraffin wax. Increasing nanoparticle loading enhanced thermal conductivity from 0.24 W/m·K to 0.45 W/m·K. Notably, MWCNTs and CuO nanoparticles contributed to conductivity enhancements of 82.6% and 49.6%, respectively. This confirms NePCMs as potential materials for thermal energy storage in various applications [57]. Challenges such as corrosion, leakage, supercooling, and phase segregation or separation can hinder the performance and applications of PCMs energy storage systems [58–60]. To address some of these challenges, a phase-change micro-nanoencapsulation approach has been developed to mitigate the problems listed above for NePCMs [61]. The melting performance of PCMs can be enhanced in thermal energy storage systems by employing rectangular fins with a combination of CuO and TiO₂ nanoparticles. Using this hybrid approach improves heat transfer rates in conjunction with nanoparticles [62].

Integration of nanoparticles into paraffin wax enhances the performance of the thermal energy storage system, thereby improving the thermal conductivity of NePCMs for solar energy storage applications [63]. A comprehensive review by Aziz et al. [64] revealed that incorporating nanoparticles into PCM matrix enhances the thermal conductivity, heat capacity as well as the stability of the NePCMs storage systems. TES enhanced with NePCMs has improved thermal conductivity and reduced supercooling across multiple phase-change temperatures by up to 32%. Shape-stabilized PCMs can increase heat transfer rates by up to 10-fold, making them suitable for solar PV-based heat recovery systems [65]. Microencapsulation has been exploited to reduce supercooling by using hydrated salts as nanoparticles for TES applications [66]. Paraffin wax is recognized as a promising PCM for energy storage applications. However, the material's low thermal conductivity limits its performance in thermal storage applications. The addition of copper (Cu) nanoparticles improves the thermal and chemical stability of paraffin-based PCMs, thereby delaying thermal degradation and enhancing their suitability for solar thermal storage applications [67]. The main limitations of traditional PCMs are their low thermal

conductivity and their low response to heat transfer rates. Enhancing the heat transfer rate in nano-PCMs reduces charging and discharging times, making them useful for solar thermal storage applications [68]. Eutectic PCMs have attracted considerable attention as solar storage materials due to their binary, ternary, and multi-component PCMs that melt at temperatures lower than the melting points of their constituent components. Compared with single-component PCMs, NePCMs have shown superior performance in TES applications, with a wide phase-change temperature range and improved phase stability [69,70]. Enhancing PCMs with nanoparticles such as CuO, Al₂O₃, C, and graphene improves the phase segregation, long-term stability, and supercooling of the resulting NePCM, making them highly conductive for solar thermal storage applications [71]. To present comprehensive information about the thermophysical properties of nano-enhanced PCMs, their density, thermal conductivity, and stability, including successive cycles of heating and cooling over a wide range of temperatures, needs to be studied. Organic PCMs (such as paraffin wax, fatty acids) [72,73], inorganic PCMs (such as salt hydrates) [74–76] as well as mixtures of their eutectic counterpart have low melting temperature, while other nanoparticles like chlorides, carbonates, and fluorides require high melting temperature [77–79]. Fig. 3 illustrates the relationship between melting temperature and heat of fusion for different PCM categories, highlighting the trade-offs in selecting materials for specific solar thermal applications. It can be observed that fatty acids, paraffin wax, and salt hydrates require lower temperatures than chlorides and fluorides [81]. NePCMs exhibit superior performance compared to conventional PCMs, primarily due to the improved thermal conductivity introduced by nanoparticle incorporation.

In this review, the term solar energy storage refers specifically to solar thermal energy storage, where absorbed solar radiation is stored as heat and later released for useful thermal applications. Accordingly, this article focuses on the role of NePCMs in latent heat storage, heat retention, temperature regulation, and in thermally driven solar systems such as solar cookers, solar dryers, solar water-heating units, and solar-thermal-assisted power systems. Photovoltaic systems are considered only when NePCMs serve a thermal management or heat recovery function, rather than as electrical energy storage media. This distinction avoids conflating thermal energy storage with photovoltaic electricity generation or electrochemical storage technologies.

Despite the growing body of research on NePCMs, existing reviews often focus on isolated aspects, such as thermophysical property enhancement or specific application domains, without providing an integrated perspective that links nanoparticle selection, preparation methods, microscopic mechanisms, and engineering applications. In addition, limited attention has been given to the relationships among nanoparticle characteristics, dispersion behavior, and large-scale system performance, as well as to practical challenges related to scalability, stability, and cost. Therefore, this review provides a comprehensive and structured analysis that bridges material-level mechanisms with application-level performance, while also identifying key research gaps and future development directions for effective implementation of NePCMs in solar thermal energy storage systems.

2. Role of nanoparticles in enhancing the performance of PCMs

Incorporating nanoparticles into conventional PCMs improves stability, reliability, density, heat transfer performance, melting temperature, and thermal conductivity [82,83]. These desired properties are the reason behind the race to engineer PCMs that can store solar energy for a longer duration with maximum thermal storage efficiency during low solar radiation or for use during night time [84,85]. Various experimental and numerical studies have been done to elucidate the effect of nanoparticles in NePCMs [86–90]. Table 1 summarizes the effects of various nanoparticles on the thermophysical performance of phase change materials, highlighting key improvements in thermal conductivity, energy storage capacity, and system stability under different

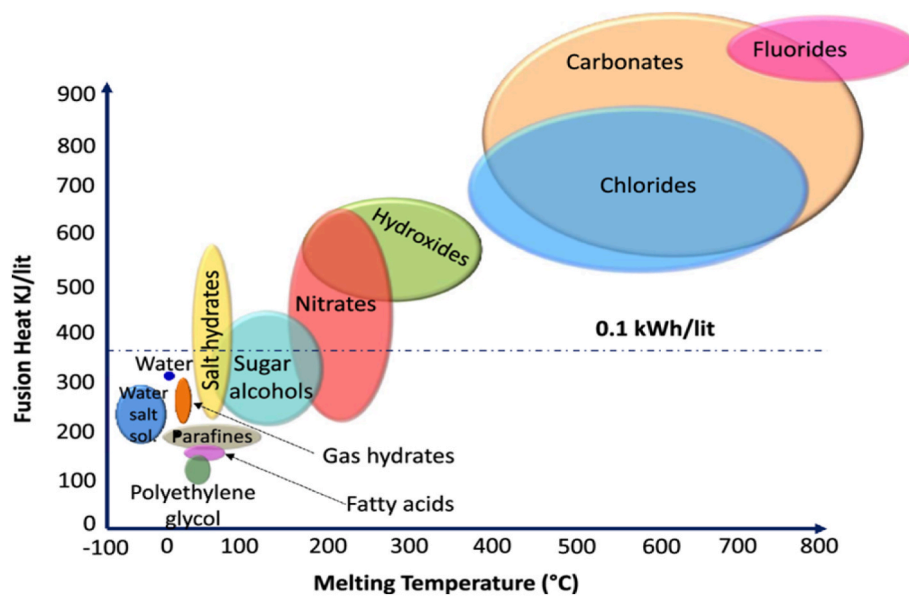


Fig. 3. Comparison of melting temperature and heat of fusion for various phase change materials, including organic compounds (paraffins, fatty acids, sugar alcohols), inorganic materials (salt hydrates, nitrates, hydroxides), and high-temperature salts (chlorides, carbonates, fluorides). The x-axis represents melting temperature (°C), while the y-axis indicates volumetric heat of fusion (kJ/L). The figure highlights the trade-off between operating temperature range and thermal storage capacity, which is critical for selecting suitable PCMs in solar thermal energy storage applications. The dashed line indicates an approximate energy storage density of 0.1 kWh/L for comparison purposes. Reproduced from Khan et al. [80] licensed under the Creative Commons CC-BY license.

concentrations and conditions.

A systematic analysis of the reported studies reveals several consistent trends in the modification of phase change materials using nanoparticles [106,107]. Carbon-based nanomaterials, such as graphene and carbon nanotubes, exhibit the greatest enhancement in thermal conductivity due to their high intrinsic thermal transport properties and effective phonon transfer mechanisms [108]. Metal oxide nanoparticles, including Al_2O_3 , CuO , and TiO_2 , offer moderate thermal conductivity improvements while providing better dispersion stability and cost-effectiveness, making them more suitable for large-scale applications. In terms of optimal loading, most studies indicate that nanoparticle concentrations between 0.5 wt% and 5 wt% achieve a balance between enhanced thermal performance and minimal reduction in latent heat capacity [109–111]. Higher concentrations tend to improve conductivity but may also lead to agglomeration and a decrease in energy storage density. Furthermore, the effectiveness of nanoparticle incorporation depends on the type of PCM: organic PCMs show better compatibility with carbon-based nanomaterials, while inorganic and eutectic PCMs demonstrate improved stability with metal oxide additives. These observations highlight the importance of nanoparticle selection and formulation strategy in achieving optimized thermophysical performance of NePCMs for solar thermal energy storage applications.

2.1. Microscopic mechanisms of NePCM modification

The enhancement of thermophysical properties in NePCMs is governed not only by the presence of nanoparticles but also by the underlying microscopic interaction mechanisms between nanoparticles and the PCM matrix [33]. At the nanoscale, improvements in thermal conductivity are primarily attributed to phonon transport and the formation of conductive pathways within the PCM. High-conductivity nanoparticles such as carbon-based materials (e.g., graphene, carbon nanotubes) and metal oxides (e.g., CuO , Al_2O_3) facilitate phonon propagation, thereby reducing thermal resistance within the composite system [112,113]. In addition, interfacial interactions between nanoparticles and PCM molecules significantly influence the overall performance of NePCMs. Strong interfacial bonding and surface compatibility enhance heat transfer across the particle–matrix interface, while poor

dispersion or weak interfacial adhesion may lead to increased thermal resistance and agglomeration [114]. Surface modification and functionalization of nanoparticles have been widely explored to improve dispersion stability and interfacial heat transfer efficiency [115].

Furthermore, nanoparticles can influence the crystallization behavior and phase transition characteristics of PCMs. The presence of nanoparticles acts as nucleation sites, reducing supercooling and promoting uniform crystal growth during solidification [116]. However, excessive nanoparticle loading may disrupt the crystal structure of the base PCM, thereby reducing its latent heat storage capacity. The modification mechanisms also vary depending on the type of nanoparticle used. Carbon-based nanoparticles typically enhance thermal conductivity by forming percolation networks, whereas metal oxide nanoparticles enhance thermal conductivity through particle–matrix interactions and improved heat-diffusion pathways [117]. Recent studies employing molecular dynamics simulations and interfacial engineering approaches have further revealed that nanoscale interactions significantly affect the thermal transport behavior and stability of NePCMs, highlighting the importance of optimizing nanoparticle type, concentration, and dispersion techniques to improve performance [118].

2.2. Material selection, performance evaluation, and engineering considerations of NePCMs

Although numerous studies have demonstrated the effectiveness of nanoparticles in enhancing the thermophysical properties of PCMs, selecting suitable nanoparticles and determining their optimal loading concentration remains highly dependent on the type of PCM and the intended application [119]. A systematic comparison indicates that carbon-based nanoparticles, such as graphene and multi-walled carbon nanotubes (MWCNTs), generally exhibit superior thermal-conductivity enhancement due to the formation of percolation networks and their high intrinsic conductivity [120]. However, these materials may suffer from dispersion challenges and increased viscosity at higher concentrations.

Metal oxide nanoparticles, such as Al_2O_3 and CuO , are widely used due to their chemical stability, cost-effectiveness, and relatively easy

Table 1

Summary of nanoparticle-enhanced phase change materials and their thermo-physical performance improvements.

Author	Nanoparticles	Key Findings
Papade and Kanase-Patil [91]	NaNO ₃ , KNO ₃ , Al ₂ O ₃	The addition of 1.5 wt% Al ₂ O ₃ enhanced energy storage capacity due to improved nanoparticle dispersion within the PCM matrix.
Awad and Muayad [92]	NaNO ₃ , Fe ₂ O ₃	The incorporation of 0.75 wt% Fe ₂ O ₃ improved charging and discharging rates by 25.6% and 23.92%, respectively, while increasing the specific heat capacity and latent heat by 17.86% and 9.97%, respectively.
Pirouzmand and Ahmadi [93]	Al ₂ O ₃ , Graphene (GNP)	The addition of 10 wt% Al ₂ O ₃ reduced melting time, while 2.5 wt% GNP enhanced system energy and exergy, improving overall thermal storage performance.
Deepak and Behura [94]	MWCNTs	The addition of 0.5–1.5 wt% MWCNTs improved chemical stability, optical properties, and thermal stability of eutectic PCMs.
Kalbande et al. [95]	CuO, MWCNTs	Hybrid CuO–MWCNT NePCMs showed a 6.2% increase in thermal conductivity and a 66.6% reduction in melting time compared to pure paraffin.
Lu et al. [96]	Fe ₂ O ₃	The incorporation of Fe ₂ O ₃ enhanced thermal conductivity by 53% (solid) and 79% (liquid), while reducing latent heat.
Pandya et al. [97]	Cu	Increasing Cu nanoparticle concentration improved thermal conductivity, with 3 wt% identified as optimal for thermal storage performance.
Masoumi and Haghighi [98]	TiO ₂	The addition of 0.39 wt% TiO ₂ increased thermal conductivity by 7% (liquid phase) and 15% (solid phase).
Singh et al. [70]	GNP	Functionalized GNP (1–5 wt%) increased thermal conductivity by up to 104% and improved specific heat capacity.
Sharshir et al. [99]	CuO, Co ₃ O ₄	Metal oxide nanoparticles and their composites enhanced overall thermal storage system performance compared to pure PCM.
Alshukri et al. [100]	ZnO, CuO	The addition of 5 wt% CuO and ZnO improved thermal storage efficiency by 50% and 41.4%, respectively.
Maher et al. [101]	SiC, Ag	The addition of 15 wt% SiC and Ag increased thermal conductivity by 58.2% and 31.2%, respectively.
Manoj Kumar et al. [102]	SiO ₂	Increasing SiO ₂ concentration (up to 2 wt%) enhanced thermal conductivity by 33.34%, while lower concentrations improved latent heat.
Nedjem et al. [103]	GNPs	The addition of 1 wt% GNP showed optimal thermal performance compared to higher concentrations (3 wt%).
Wu et al. [104]	MWCNTs, Ca(OH) ₂ , CaCl ₂	The incorporation of nanoparticles improved latent heat, thermal conductivity, and stability while reducing supercooling.
Ouikhalfan et al. [105]	ZnO, CuO, Al ₂ O ₃ , TiO ₂	Dispersion of metal oxide nanoparticles improved thermal conductivity and cycling stability, with 2 wt% identified as optimal.

dispersion in both organic and inorganic PCMs [121]. These nanoparticles typically provide moderate improvements in thermal conductivity while maintaining acceptable latent heat storage capacity. For organic PCMs, which are prone to low thermal conductivity, carbon-based nanoparticles are often preferred for high-performance

applications, whereas metal oxides are suitable for cost-sensitive and stability-oriented systems [122]. In inorganic and eutectic PCMs, compatibility and stability at high temperatures are critical factors. Metal oxide nanoparticles are generally more suitable in such systems due to their thermal stability and resistance to degradation [123]. The optimal nanoparticle loading is typically reported to be 0.1–5 wt%, beyond which issues such as agglomeration, sedimentation, and reduced latent heat storage capacity become significant [124].

Furthermore, the selection of nanoparticles must consider trade-offs between thermal conductivity enhancement and other properties such as viscosity, phase change enthalpy, and long-term cycling stability. Therefore, a balanced formulation strategy is required, in which nanoparticle type, concentration, and dispersion technique are optimized for specific application requirements, including solar thermal storage systems, heat recovery units, and temperature regulation applications [125]. To facilitate clearer comparison and practical material selection, a summary of commonly used nanoparticles is presented in Table 2. Table 2 provides a systematic comparison of commonly used nanoparticles in NePCMs, highlighting their compatibility with different PCM types, optimal loading ranges, key advantages, and associated limitations to guide material selection and formulation.

Beyond material selection and formulation, evaluating the overall performance and long-term reliability of NePCMs is essential for practical applications. Therefore, a broader perspective that includes quantitative performance comparison, cycle stability, and encapsulation strategies is presented in the following discussion.

While numerous studies have reported improvements in the thermophysical properties of NePCMs, a direct quantitative comparison with conventional PCMs is essential to evaluate the magnitude of these enhancements. In general, incorporating nanoparticles significantly improves thermal conductivity, accelerates heat transfer rates, and enhances thermal cycling stability, though it may slightly reduce latent heat storage capacity at higher nanoparticle concentrations [133,134]. Table 3 presents a normalized comparison of key performance metrics between conventional PCMs and NePCMs based on representative values reported in the literature.

Cycle stability is a critical factor in evaluating the long-term reliability of NePCMs, particularly for applications involving repeated thermal charging and discharging [144]. While many studies report enhanced thermal conductivity and improved heat transfer performance, the long-term cycling behavior of NePCMs is less consistently documented [145]. In general, NePCMs exhibit improved cycle stability compared to conventional PCMs due to reduced supercooling and enhanced thermal transport; however, performance may still degrade over extended cycles due to nanoparticle agglomeration, phase segregation, and structural changes within the material [146,147].

Experimental evaluation of cycle stability is typically conducted

Table 2

Comparative selection guidelines for nanoparticles in nano-enhanced phase change materials based on PCM type, performance, and limitations [122, 126–132].

Nanoparticle	Suitable PCM Type	Main Advantage	Limitation	Typical Loading
Graphene/CNTs	Organic PCMs	High thermal conductivity (percolation network)	Agglomeration, high viscosity	0.1–3 wt %
Al ₂ O ₃	Organic/Inorganic	Good stability, easy dispersion	Moderate conductivity enhancement	0.5–5 wt %
CuO	Organic/Inorganic	High thermal conductivity, cost-effective	Possible sedimentation	0.5–5 wt %
SiO ₂	Organic PCMs	Improves stability, reduces leakage	Lower conductivity enhancement	0.5–3 wt %

Table 3

Quantitative comparison of thermophysical properties between conventional PCMs and NePCMs [33,135–143].

Property	Conventional PCM	NePCM	Typical Improvement
Thermal Conductivity	0.2 – 0.5 W/m-K	0.5 – 5 W/m-K	More than 50% – 300%
Latent Heat Storage	High	Slightly reduced	Reduce 5% – 15%
Heat Transfer Rate	Moderate	High	Higher 30% – 100%
Charging/Discharging Time	Longer	Shorter	Shorter 20% – 50%
Thermal Stability (Cycles)	Moderate	Improved	Up to 500+ cycles
Supercooling	Present	Reduced	Significant reduction

through repeated melting–solidification cycles, often ranging from 100 to over 1000 cycles, using techniques such as differential scanning calorimetry (DSC) and thermal conductivity measurements [142,148]. Key performance indicators include latent heat retention, phase change temperature stability, variation in thermal conductivity, and degree of supercooling across repeated cycles. To mitigate degradation and enhance long-term stability, several modification strategies have been proposed, including surface functionalization of nanoparticles to improve dispersion, encapsulation techniques to prevent leakage and structural degradation, and the development of hybrid composite systems to enhance compatibility between nanoparticles and PCM matrices [149,150]. However, a major limitation in current research is the lack of standardized testing protocols and evaluation criteria, which makes direct comparison across studies challenging [151]. Establishing consistent testing methodologies is therefore essential for advancing the practical application and industrialization of NePCMs.

In addition to material performance and stability, encapsulation and system integration are crucial for enabling the practical deployment of NePCMs. Encapsulation plays a crucial role in enabling the practical application of NePCMs in solar thermal energy storage systems, addressing key challenges such as leakage, structural degradation, and long-term stability [152]. Several encapsulation techniques have been developed, including microencapsulation, macroencapsulation, and shape-stabilized composite structures [153]. Microencapsulation involves enclosing PCM particles within polymeric or inorganic shells, thereby enhancing heat transfer surface area, preventing leakage during phase transitions, and improving thermal cycling stability [154]. Macroencapsulation, on the other hand, uses larger containment systems, such as tubes, spheres, or panels, allowing easier integration into solar collectors and storage units, though it may suffer from lower heat transfer efficiency due to greater thermal resistance [155]. Shape-stabilized NePCMs represent another effective approach, in which the PCM is embedded within a supporting matrix, such as porous materials, polymers, or carbon-based structures, eliminating leakage without the need for external encapsulation [156]. The selection of encapsulation materials, including polymers, metals, and carbon-based materials, significantly influences the system's thermal conductivity, mechanical strength, and chemical compatibility.

From a system-integration perspective, encapsulated NePCMs are incorporated into solar thermal devices such as solar cookers, dryers, and thermal storage tanks, where their performance depends on factors including heat-transfer configuration, container geometry, and compatibility with existing system designs [130]. Despite significant progress, challenges remain in terms of large-scale manufacturing, the cost of encapsulation materials, and maintaining long-term reliability under repeated thermal cycling. Therefore, optimizing encapsulation techniques and integration design is essential for improving the practical applicability and industrial deployment of NePCMs in solar energy storage systems.

3. Performance enhancement and preparation of NePCMs

To achieve the desired performance of solar thermal storage systems enhanced with NePCMs, various experimental and numerical methodologies have been adopted in the study of NePCMs. Preparational methods like Solgel, hydrothermal have been experimentally exploited to yield unique thermophysical properties such as thermal conductivity, density, discharging and discharging rates of NePCMs [157–160]. Experimentally, NePCMs have been synthesized using one-step, two-step, three-step, or even four-step methods, depending on the desired property. In the one-step technique, both the PCM and nanoparticles are synthesized simultaneously, whereas in the two-step technique, they are synthesized separately in two distinct steps. The two-step technique is widely used to prepare nano PCM [161,162]. Moreover, three-step techniques involve impregnation, compression, and sintering processes to prepare the NePCM. Similar to the three-step synthesis, a four-step synthesis involves four distinct stages. This include synthesizing the PCM and the nanoparticles separately, then later modifying the nanoparticles or PCM surface, and then dispersing the modified nanoparticles into the PCM [163].

Various preparation methods have been developed for synthesizing NePCMs, each with distinct advantages and limitations in terms of process complexity, cost, modification effectiveness, and scalability [164]. The one-step method offers superior nanoparticle dispersion and reduced agglomeration by simultaneously synthesizing and integrating nanoparticles into the PCM matrix [150]. However, this method is generally associated with higher process complexity, stricter control requirements, and limited scalability for large-scale applications. In contrast, the two-step method is the most widely adopted approach due to its simplicity, cost-effectiveness, and suitability for large-scale production [165]. Despite these advantages, challenges such as nanoparticle agglomeration, sedimentation, and long-term stability remain significant concerns.

Advanced preparation techniques such as sol–gel and hydrothermal methods provide enhanced control over nanoparticle morphology, distribution, and interfacial interactions, resulting in improved modification effectiveness and thermal performance [166]. However, these methods typically involve higher processing costs, longer synthesis durations, and more complex operational conditions, which may limit their industrial scalability. Overall, the two-step method is considered the most practical and scalable technique for industrial applications, while one-step, sol–gel, and hydrothermal methods are more suitable for research-level optimization and high-performance material development [167]. Key bottlenecks across all preparation methods include nanoparticle dispersion stability, prevention of agglomeration, the cost of nanomaterials, and maintaining long-term thermal reliability under repeated phase-change cycles. Table 4 summarizes the comparative analysis of preparation methods for nano-enhanced phase change materials (NePCMs).

Several studies have demonstrated the effectiveness of nanoparticle-enhanced PCMs across different preparation approaches. Ghafari et al. [173] examined the melting temperature of NePCMs inside a sphere using image processing and the volume shrinkage method. They concluded that increasing the ZnO nanoparticle concentration from 0.0 wt% to 0.2 wt% in NePCMs increases the melting time and significantly improves the material's thermal conductivity. Al-Jethelah et al. [174] employed experimental, scale, and numerical simulation approaches to investigate the effect of CuO nanoparticles in NePCMs, demonstrating enhanced thermal conductivity and improved melting behavior. Wu et al. [175] studied the thermophysical properties of paraffin and carbon nanotube composites of NePCM by analyzing their findings with a laser thermal conductivity meter and a differential scanning calorimeter. They found that increasing the mass fraction of CNTs by 3% increases the thermal conductivity of the solid and liquid phase by 30.3% and 28.5%, respectively. This reduces the latent heat of melting and solidification of the NePCM composite by 8.9% and 9.3%,

Table 4

Comparative analysis of preparation methods for nano-enhanced phase change materials [33,164,168–172].

Method	Process Complexity	Cost	Effectiveness	Scalability	Advantage	Limitation
One-step	High	High	Excellent	Low-Medium	Good dispersion	Complex, expensive
Two-step	Low	Low	Moderate	High	Simple, scalable	Agglomeration
Sol-gel	High	High	High	Low	Controlled structure	Costly, slow
Hydrothermal	Medium-High	Medium-High	High	Medium	Strong bonding	Equipment cost

respectively. Jacob et al. [176] synthesized nano eutectic PCM dispersed with TiO₂ nano fillers for thermal storage applications. Analysis of their digital scanning calorimetry showed no phase segregation, no supercooling, and a stable phase transition temperature. They concluded that the addition of TiO₂ The nanoparticle demonstrated excellent thermal stability beyond 500 thermal cycles, making it a suitable candidate for thermal management applications in PVTs. An experimental and numerical investigation of a tube-in-tank latent thermal storage system using composite PCM was conducted by Meng and Zhang [177]. They concluded that the LTES unit with composite PCMs shows good heat transfer performance. Hybrid systems employing graphene-based NePCM composites were experimentally evaluated under periodic pulse heat-transfer loads for electronic thermal management, demonstrating improved thermal performance. The sintering method was used to investigate the stability of the erythritol-graphite (EG) composite NePCM for thermal energy storage. The findings showed that increasing the EG content up 10 wt% increases the thermal conductivity and the freezing temperature with a reduction in the latent heat, supercooling, and the melting temperature of the resulting NePCM. These studies have demonstrated experimental and numerical approaches to integrating nanoparticles into PCMs.

The selection of preparation methods plays a critical role in determining the thermophysical performance and long-term reliability of NePCMs in practical applications [171]. Parameters such as

nanoparticle dispersion, interfacial bonding, and structural stability directly influence heat transfer efficiency, thermal cycling behavior, and overall system performance. Therefore, understanding the advantages and limitations of different synthesis techniques is essential for optimizing NePCMs for specific solar thermal applications. The following section discusses how these material characteristics translate into performance improvements across various solar energy storage systems.

4. Application of NePCMs in solar thermal systems

Recent studies indicate that nano-enhancers significantly enhance the performance of NePCMs, supporting their application in a wide range of thermal energy storage systems [178]. This has resulted in financial savings, time savings and environmentally friendly storage systems with no limited hazardous effects [179]. The use of NePCMs has recently been focused on two main areas, which is thermal energy storage systems and thermal management systems [180]. Thermal storage systems range from solar thermal regulation and storage with the use of solar collectors for industrial and most importantly domestic uses which is the main motivation behind the search of for NePCM [181]. Fig. 4 presents a simplified schematic of the key application areas of NePCMs in solar thermal systems, highlighting their role in enhancing thermal storage, stability, and system efficiency.

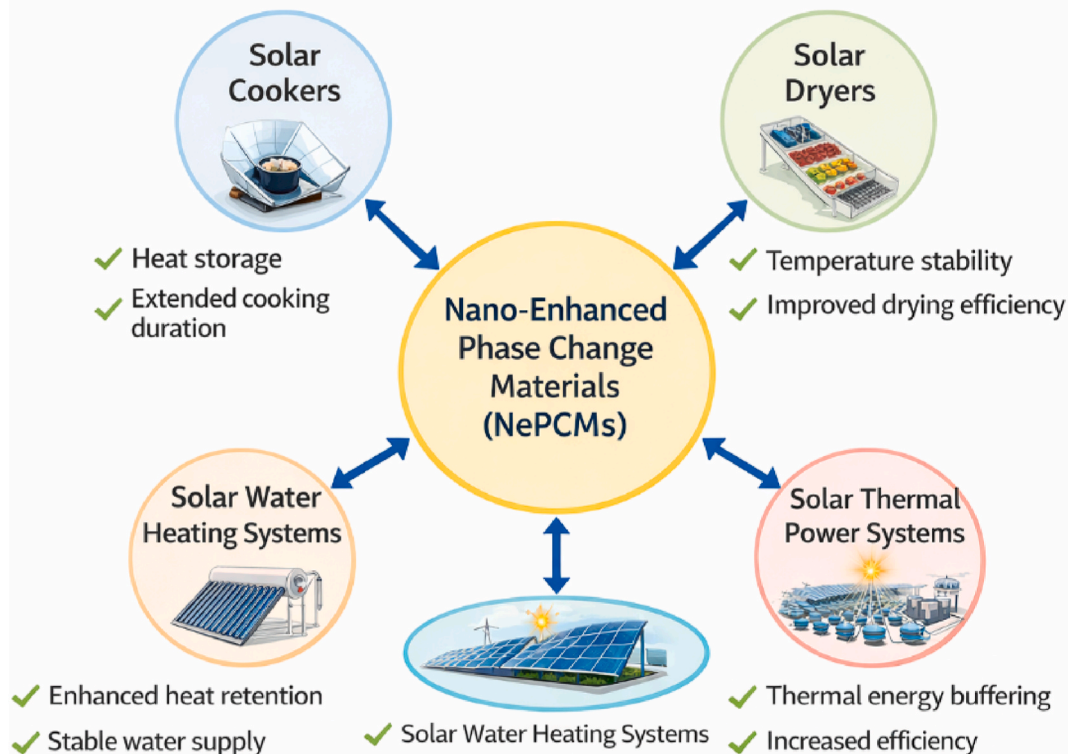


Fig. 4. Schematic illustration of the major application areas of NePCMs in solar thermal energy systems, including solar cookers, solar dryers, solar water heating systems, and solar thermal power systems. NePCMs enhance heat storage, temperature regulation, thermal buffering, and overall system efficiency across these applications. The arrows indicate the integration of NePCMs into different thermal systems for improved performance. Adapted from Ibrahim, R. et al. [182].

4.1. NePCM solar cookers

Due to the constant depletion of fossil fuels as a result of the exponential increase in population growth. Switching to cheap and accessible energy like solar can help mitigate the emission of carbon dioxide into the atmosphere. Large number of the overall population from developing countries such as Africa still use traditional methods like charcoal, kerosine, firewood for cooking and heating of their homes [183]. This has called for the need to look for materials that can store solar energy and release for use during low or off sunshine times. PCMs over the years have been exploited for this purpose, however, due to their low thermal conductivity, supercooling, low density and low heat of fusion has results in the integration of nano conductive particles to enhance the thermophysical properties of the above-mentioned materials which are significant for the operation performance of solar storage systems. Solar cookers have the potential to resolve some of the global energy demand and the over dependence of fossil fuels which have affected the climatic state of the world [184,185]. In order to fully commercialized the use of solar cookers as alternative source to renewable energy, factors such as cost of the material used, long-term stability and improvements of thermal efficiency needs to be realized for the overall acceptance of these kind of cookers [186]. Enhancing NePCMs with nano conductive material such salt hydrates, enhanced paraffin wax, carbon nanotubes can improve the temperature performance up to 125 °C for longer duration during off sunshine hours [187]. Conventional solar cookers work during higher sun radiation and are limited during off sunshine hours. They lack the ability to store solar energy for longer period during peak sun hours due to their low thermal storage capabilities. However, with integrated with nano-enhanced PCMs, they outperform the traditional solar cookers with longer cooking hours, high thermal efficiency and excellent operational performance during night times or off sunshine hours. Papade and Kanase-Patil [188] designed a cooker with a parabolic solar collector, which supplies heat energy during sunshine hours and is limited in operation during night time. With the addition of NePCM, the system delivered the stored energy for cooking up to 4 h after sunset. The addition of salt hydrates to PCMs enhances thermal storage capacity, thereby improving the overall cooking performance of the system. The solar box cooker was shown to deliver excellent cooking performance with longer cooking duration when integrated with doped $(\text{MgAl}_2\text{O}_4)\text{Fe}_2\text{O}_3$ nanoparticles. Enhanced PCM raises the box cooker's internal temperature to 164.12 °C. Compared with the conventional PCM solar box cooker, the Ni-enhanced NePCM delivered excellent thermal performance of 56.21%, while the conventional cooker achieved 33.90% [189]. Santhi Rekha and Sukchai [190] fabricated two solar cookers with parabolic solar collectors. With the design equal, the cooker with enhanced NePCM performed better than the cooker without PCM, with cooking powers of 125.3 W and 65.6 W, respectively. Their findings concluded that a cooker with NePCM can be used for indoor and outdoor cooking applications.

Enhanced evacuated tube solar collector cooker with NePCM has been examined to deliver outstanding cooking performance by Hebbar et al. [191]. A feasibility study done in India using solar box cooker (SBC) with integrated NePCM was shown to deliver excellent cooking rate with improved thermal efficiency of 52.2%, 301 W/m²°C heat transfer rate, 53.21 W cooking power unit and 4.11 W/m²°C heat loss than its counterpart with no enhanced PCM integration [192]. Factoring cost benefit analysis in the commercialization of NePCM cookers can help reduce the overdependence of traditional cooking methods and bring about sustainable development [193]. NePCM-based solar cookers exhibit superior thermal performance compared to conventional systems with or without PCMs. The integration of latent heat storage further enhances thermal efficiency due to the improved heat transfer properties of nanoparticle additives [194]. A portable solar cooker incorporating erythritol-based thermal energy storage (TES) demonstrates effective cooking performance in the absence of solar radiation, maintaining temperatures between 100 °C and 125 °C and achieving an

improvement of approximately 351.16% in cooking performance [195]. Cookers with parabolic solar collector cookers enhanced with NePCMs have shown an improvement in stability, thermal conductivity, latent heat, longer cooking duration, quicker heat transfer, and outstanding thermal efficiency [196]. Fig. 5 illustrates a typical solar cooker configuration, where concentrated solar radiation is used for cooking, and the incorporation of NePCMs can significantly enhance heat retention and cooking continuity.

Despite the promising laboratory-scale performance of NePCMs in solar cooking applications, several engineering challenges must be addressed for practical deployment. One of the primary concerns is the increased cost associated with nanoparticle incorporation, which may limit affordability for large-scale or household use [121]. In addition, effective encapsulation techniques are required to prevent leakage of PCM, enhance thermal stability, and maintain consistent heat release during repeated cooking cycles. Long-term operational stability is also a critical issue, as nanoparticle agglomeration and phase segregation can reduce system efficiency over time [144]. Furthermore, challenges related to large-scale manufacturing, uniform dispersion of nanoparticles, and integration into conventional solar cooker designs must be considered. Recent developments in microencapsulation, composite PCM structures, and surface modification of nanoparticles offer potential solutions to improve durability and performance, thereby supporting the practical application of NePCMs in solar cooking systems.

While solar cookers demonstrate the effectiveness of NePCMs in low-to medium-temperature applications, similar thermal storage principles can be extended to more complex systems, including solar-thermal power generation and heat recovery systems, where higher operational temperatures and system integration challenges are involved.

4.2. NePCMs in solar power generation systems

NePCMs can contribute to power generation systems when they are employed as thermal storage or thermal buffering media within solar-thermal-assisted energy conversion routes [198]. The discussion in this section is restricted to solar-thermal and hybrid thermal-coupling applications in which NePCMs enhance heat management, extend

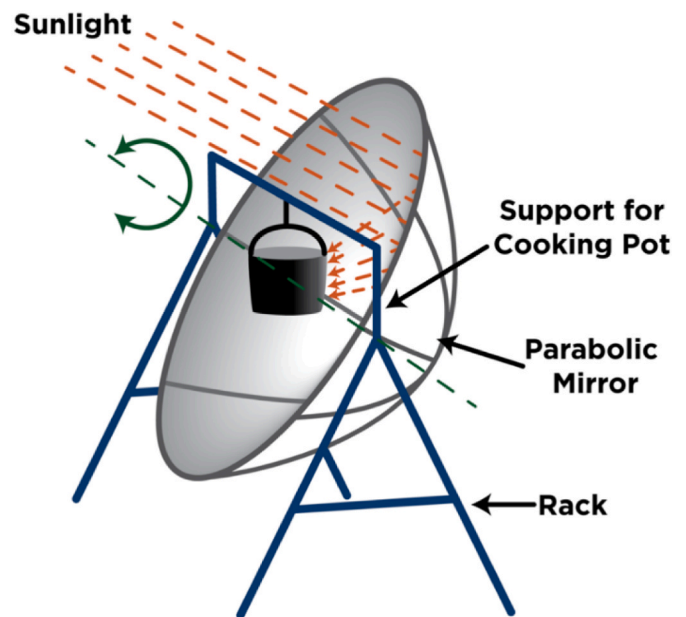


Fig. 5. Schematic representation of a solar cooker system utilizing a parabolic reflector to concentrate solar radiation onto the cooking vessel. The integration of NePCMs into such systems enables effective heat storage, extended cooking time, and improved thermal stability under intermittent solar radiation conditions. Reproduced from Ahmed A.S. et al. [197].

operation during low-radiation periods, or improve thermal stability of the overall system. In photovoltaic or photovoltaic-thermal configurations, NePCMs are relevant only when they act as passive thermal control or heat recovery materials [144]. Their function in such systems is to reduce temperature fluctuations, recover excess heat, or improve thermal uniformity, rather than to store electrical energy.

Shao et al. [199] generated electricity from the phase transition between liquid and gaseous water using evaporation-induced and moisture-induced generators to direct the current output. They concluded that, exploiting phase change transition can enhance the possibility of generating electricity from natural water cycles. Thus, the technology can help rural areas with no access to electricity [199]. Integrating optimizing NePCMs into TES with waste heat recovery has the potential to improve the efficiency in many industrial processes [200]. A thermoelectric energy generator-based harvesting block incorporated with NePCM can generate electricity up to 24 h using solar radiation [201]. A heat sink filled with NePCM can store thermal energy and enable continuous solar power generation at night using a thermoelectric generator. It operates by storing the heat rejected by the TES with the help of the PCM, which is utilized as a heat source for power generation during cooling, using a reversible process [202].

Direct solar Rankine cycle system with NePCM can generate electricity with net power output of 26.8 KW annually. The incorporated PCM enhances the overall performance of the system during charging and discharging modes [203]. However, maintaining the operational temperature of solar power generating systems is very crucial in ensuring the efficiency and performance of this systems. Phase change materials have been used to moderate the temperature fluctuations to boost the performance of power delivered to sensors or environmental monitoring device at remote locations through microbial fuel cell applications [204]. Rea et al. [205] used prototype latent heat storage system with aluminium-silicon enhanced PCM to drive Stirling engine for electricity generation. The systems demonstrated a maximum energy efficiency of 18.5% in converting the heat to electricity at maximum power output above 1 KW representing advancement in establishing efficiency for any system that employs latent heat storage for electricity generation [205].

Energy conversion technologies integrated with PCMs (NePCMs) have gained popularity despite the associated challenges. However, nanocomposite PCMs with enhanced thermal conductivity can significantly improve the efficiency of thermoelectric energy conversion. This system can produce long-term stable power generation with output voltage of 287 mV achieving effective conversion from solar energy to electricity [206]. Liu et al. [207] created state-of-the art alternative energy generation solar thermal material device using biomass-based phase change material gel for solar energy conversion using thermoelectric generator. Their proposed system delivered high thermal energy storage capacity up to 183.04 Jg^{-1} , high thermal absorbance of 95.68% with high cell availability of 117.9% [207]. Mortazavi et al. [208] employed an experimental approach to generate electricity using organic PCM with a thermoelectric generator. Edible oils such as ostrich, coconut, mutton, and beef were used as PCMs. Among them, coconut oil combined with Fe_2O_3 nanoparticles and carbonized sawdust exhibited the highest thermal energy efficiency, reaching 62% and 53%, respectively [208]. The energy efficiency and its associated thermal storage capacity in photovoltaic systems can be enhanced with NePCMs. The system can store up to 324 KJ/m^2 of thermal energy during charging with optimized PCM. Incorporating NePCMs into photovoltaic systems can generate 1.8 to 2 times more thermal energy compared with standalone photovoltaic systems [209]. The thermoelectric generator plays a significant role in electricity generation. The system can be enhanced continuously by using heat stored in PCMs to generate electricity, increasing average output by 31.6% [210].

Nano-enhanced PCMs can be used to absorb heat from a heat-harvesting block via a thermoelectric generator. The PCM acts as a

heat sink to convert sensible heat into latent heat, which increases the electricity generated by this system [211]. Solar thermal steam electricity generation can be enhanced with NePCM to boost the energy efficiency of this system within a high temperature range due to the high thermal capacity of these materials to store and deliver energy at different temperature ranges [212]. Electricity generated by a solar thermal system can be efficient with nano-enhanced PCMs for domestic and industrial use. Fig. 6 demonstrates the integration of NePCMs into photovoltaic-thermal (PVT) systems, where improved thermal management enhances electrical and thermal efficiency.

Although NePCMs demonstrate enhanced thermal performance in laboratory-scale solar-thermal power systems, several engineering challenges remain for large-scale implementation. The cost of nanoparticles and complex preparation methods can significantly increase system investment, particularly for utility-scale applications [214]. In addition, maintaining long-term thermal stability under continuous high-temperature cycling is essential to ensure reliable operation. Effective encapsulation and containment strategies are required to prevent leakage and degradation of PCM materials under harsh operating conditions [215]. Furthermore, issues such as nanoparticle agglomeration, uneven heat distribution, and integration with existing solar-thermal infrastructure present additional challenges. To address these limitations, current research focuses on advanced encapsulation techniques, hybrid composite materials, and improved dispersion methods to enhance durability and efficiency. Overcoming these challenges is crucial for the successful industrialization of NePCMs in solar-thermal power generation systems.

In contrast to power generation systems, which operate at higher temperatures and require complex energy conversion mechanisms, solar drying systems represent a more direct thermal application of NePCMs, where temperature stability and prolonged heat availability are critical for maintaining product quality.

4.3. NePCM in solar dryers

Solar dryers have played a significant role in domestic, industrial, and agricultural use for drying and preserving crops and food products [216–218]. These systems have significantly reduced post-harvest losses, offering significant benefits to small-scale farmers in remote regions with limited access to electricity [219,220]. Solar drying technologies are economically viable which has enhanced food security, access to thermal energy for household use and industrial processes, ensuring economic stability and contributes to environmental preservation [221]. However, solar dryers face significant challenges related to their dependence on weather conditions, insufficient sunlight, cloud cover, and seasonal fluctuations which hinder their thermal performance, leading to extended drying durations. The unpredictable weather fluctuations call for additional heat sources which affects operational costs. Aside these challenges, the operational cost for technology and infrastructure development poses a barrier for small-scale farmers and consumers in resource-constrained areas [222].

Addressing these challenges may involve incorporating energy storage systems to ensure reliable operation and broader adoption, particularly in regions with inconsistent or limited sunlight availability. Integrating NePCM into solar drying systems significantly improves their efficiency and reliability. This system efficiently accumulates heat during sunny hours, storing it for later use to facilitate continuous drying during nighttime or cloudy weather, making it an optimal solution for seamless, energy-efficient drying processes. Majeed et al. [223] evaluated the performance of an indirect mode solar dryer augmented with phase change material for food dehydration using potato slides under controlled conditions. They recorded a temperature of 63°C with 40% drop in relative humidity. The sample attained the targeted moisture content of 10 wt% in a span of 24 h when compared with conventional sun drying methods with no PCM which took 38 h to reduce the moisture content [223]. The use of PCM in conventional indirect solar dryers

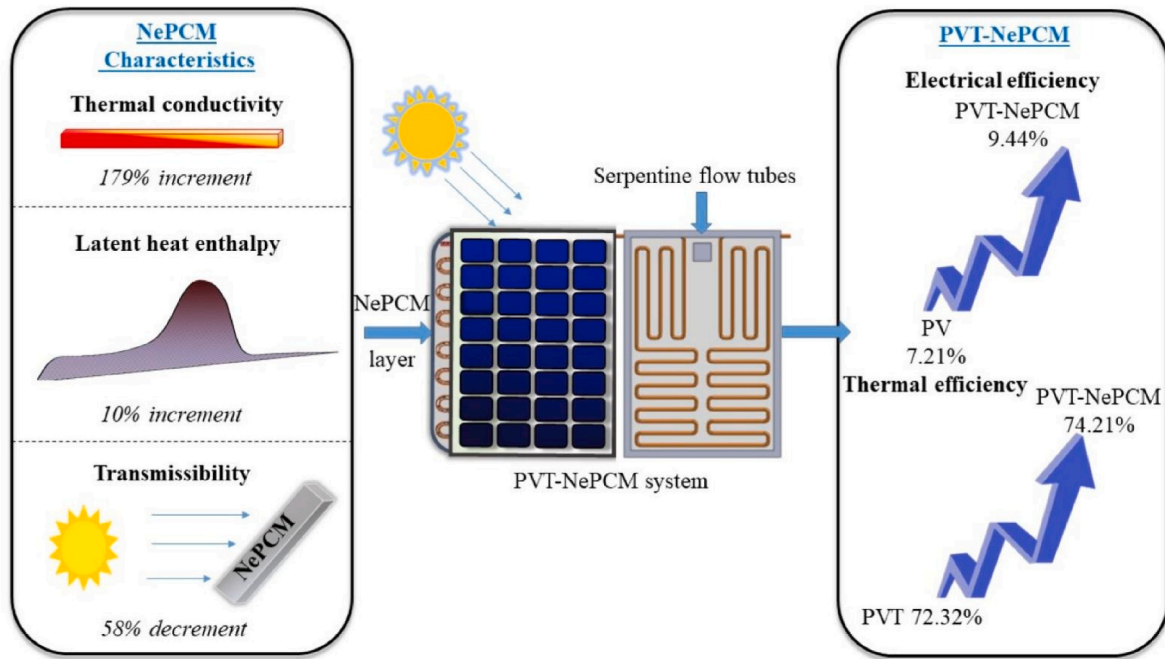


Fig. 6. Schematic illustration of a photovoltaic-thermal system integrated with nano-enhanced phase change materials (PVT-NePCM), highlighting the enhancement in thermal conductivity, latent heat storage, and overall system performance. The incorporation of NePCMs improves both electrical and thermal efficiency through enhanced heat dissipation and temperature regulation. Reproduced with permission from Laghari et al. [213] Copyright 2024, Elsevier.

(ISD) can significantly enhance the drying of agricultural produce during sunny days and off sunshine hours [224]. One of the main limitations of solar drying systems is the low thermal efficiency and inhomogeneous distribution of temperature in the drying chamber. This limitation is overcome with nano-enhanced PCM which improves temperature uniformity and the drying efficiency of the solar chamber up to 43.42% [225]. To obtain dried products with good taste and quality as the original food crop. It is imperative to dry the products under strictly controlled conditions. Indirect solar drying techniques are the most advantageous ones among all the drying methods. The enhanced PCM

integration into solar dryers significantly improves drying efficiency, resulting in shorter drying duration than open-sun drying with conventional or no PCM. This preserves the quality, color, and scent of the food product [226]. It can be used to dry a wide range of agricultural produce, such as tomatoes and potatoes [227]. Malakar and Arora [228] developed a PCM-assisted evacuated tube solar dryer to evaluate its thermal performance and drying characteristics of pumpkin slices. The PCM-integrated system maintained temperatures between 50.78 °C and 61.29 °C beyond sunshine hours and achieved an additional 4–8% reduction in moisture content compared to a system without PCM.

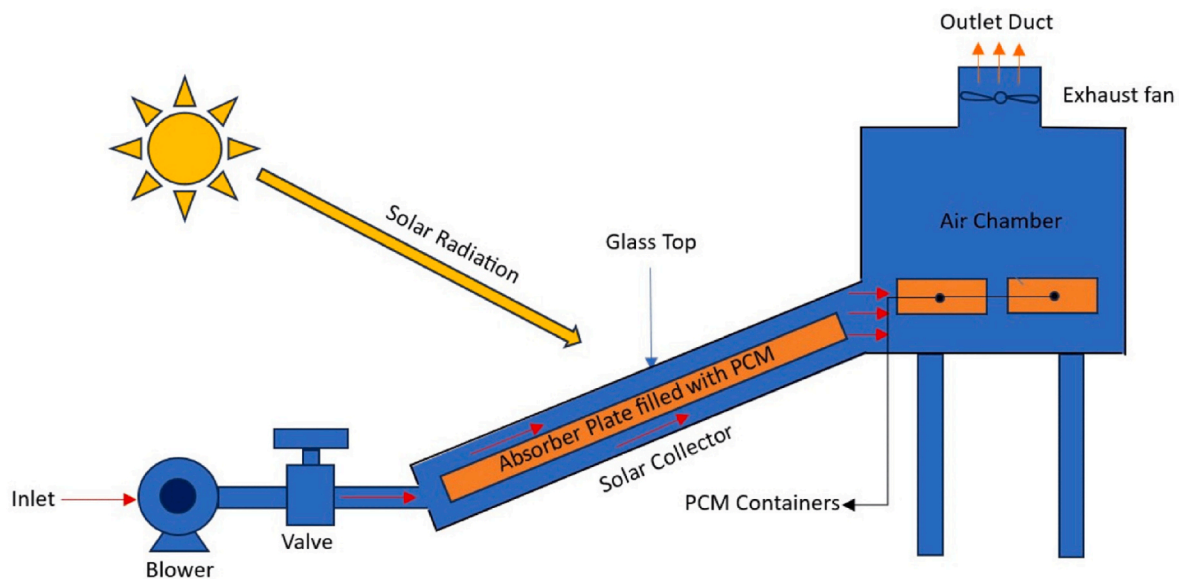


Fig. 7. Schematic diagram of a solar dryer system integrated with PCMs, where solar radiation is absorbed through the collector and stored in PCM-filled absorber plates. The stored thermal energy is subsequently released to maintain stable drying conditions. The incorporation of NePCMs further improves heat storage capacity, temperature regulation, and drying efficiency under fluctuating solar conditions. Reproduced from Kavva and Ramana [230] Licensed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Malakar and Arora [228] concluded that the PCM-ETD could be used to dry food commodities while retaining quality attributes. To improve the thermal performance of solar dryers, NePCMs with high latent heat and a large surface area for heat transfer are required. This reduced heat loss and the disparity between supply and demand, thereby improving the system's energy efficiency [229]. Fig. 7 illustrates a solar dryer system incorporating PCM-based thermal storage, where NePCMs can enhance temperature stability and improve drying performance under intermittent solar radiation.

Despite the demonstrated benefits of NePCMs in improving drying efficiency under laboratory conditions, several practical challenges must be considered for real-world applications. The incorporation of nanoparticles increases material costs, potentially limiting adoption in low-cost or rural drying systems. In addition, ensuring uniform dispersion of nanoparticles within the PCM is critical to achieve consistent thermal performance. Long-term stability during repeated heating and cooling cycles is another concern, as agglomeration and material degradation can reduce effectiveness over time [144]. Encapsulation techniques are also necessary to prevent leakage and maintain the PCM's structural integrity during operation. Furthermore, scaling up the system for industrial use requires careful consideration of manufacturing processes and integration with existing drying technologies [231]. Recent approaches, including encapsulated composite PCMs and surface-treated nanoparticles, show promise in improving stability and performance, thereby enhancing the feasibility of NePCMs in solar drying applications. These diverse applications highlight the versatility of NePCMs across different solar thermal systems, underscoring the importance of material optimization and system-level design to achieve reliable and efficient energy storage solutions.

5. Challenges and limitation

Despite the several advantages of NePCMs for solar thermal energy storage systems, there are also certain limitation that obstructs the full performance of NePCMs due to the addition of nanoparticles [232]. These limitations include, increased viscosity of the nano conductive materials, stability and the reliability due to the charging and discharging rate or cycles. This can deteriorate the performance of NePCMs as a result non-uniform distribution of the nanoparticles due to migration and deposition in the PCM matrix [33]. Though there exist limited literature on the stability of NePCM, however, maintaining stable nanoparticles dispersion through the preparation techniques is very crucial for ensuring constant thermal performance of the solar storage systems [144].

The long-term stability of NePCMs is a critical factor that necessitate its suitability for solar thermal energy applications. Addition of nanoparticles to PCMs can also increase the presence of viscosity, which impacts the heat transfer rate in NePCMs, making it difficult to move through the storage systems. Though the introduction of nanoparticles in PCM helps to solve the supercooling problem [233]. However, some NePCMs exhibit supercooling as a result of the parent PCM remaining liquid below its normal freezing point before solidification. This is a significant challenge which needs urgent attention, as this affects the energy storage efficiency of the material [234]. Another factor that hinders the potential of NePCMs is the nanoparticles' agglomeration and sedimentation, which leads to non-uniform distribution of the nanoparticles. This negatively impact the thermal conductivity and the heat transfer performance of the NePCMs. Addressing these challenges require extensive research to elucidate the long-term realization of NePCM for solar energy applications.

Despite the promising performance enhancements achieved by nano-enhanced phase change materials, several critical challenges continue to limit their large-scale deployment in solar thermal energy storage systems. One of the primary issues is nanoparticle agglomeration, which reduces effective surface area and leads to non-uniform thermal conductivity, particularly over extended operational cycles [235]. In

addition, long-term cycling stability remains a concern, as repeated phase transitions may lead to sedimentation, phase separation, or degradation of thermophysical properties [236]. Economic feasibility is another major limitation, as the high cost of advanced nanomaterials and complex preparation techniques restricts widespread industrial adoption [237]. Furthermore, inconsistencies in experimental methodologies and testing standards across studies make it difficult to establish reliable performance benchmarks. Addressing these challenges requires future research to focus on developing cost-effective nanoparticle materials, improving dispersion stability through surface functionalization or encapsulation techniques, and establishing standardized testing protocols for long-term performance evaluation. Advancements in scalable preparation methods and system-level integration will also be essential to transition NePCMs from laboratory research to practical solar thermal energy storage applications.

6. Conclusion and future perspectives

In summary, nano-enhanced phase change materials play an important role in solar thermal energy storage by improving thermal conductivity, heat transfer behavior, thermal stability, and temperature regulation. Their greatest value lies in thermally driven solar applications such as solar cookers, solar dryers, solar water-heating systems, and solar-thermal-assisted power and heat recovery units. In hybrid photovoltaic-related systems, their contribution is primarily thermal rather than electrical. Despite these advantages, challenges such as nanoparticle agglomeration, stability over repeated thermal cycles, and increased viscosity remain key barriers that require further investigation. Clarifying the thermal role of NePCMs and addressing these limitations will strengthen their potential as promising materials for latent heat storage and heat management in sustainable solar thermal technologies. The reviewed studies demonstrate that NePCMs can enhance thermal conductivity by approximately 5% to 100%, depending on nanoparticle characteristics, dispersion stability, and preparation methods.

Despite the significant advancements in nano-enhanced phase change materials, several key research challenges remain that must be addressed to enable their widespread practical application. Future research should focus on developing a deeper understanding of the microscopic mechanisms governing nanoparticle-PCM interactions, particularly interfacial behavior and thermal transport. In addition, optimization of preparation techniques is required to achieve uniform nanoparticle dispersion, reduce agglomeration, and improve scalability for industrial production. Engineering advancements in encapsulation technologies, including durable and cost-effective micro- and macro-encapsulation strategies, are also essential to enhance long-term stability and system reliability.

Furthermore, the development of low-cost, environmentally sustainable nanoparticles is crucial to improving the economic feasibility of large-scale applications. Future studies should also explore multifunctional and hybrid composite materials that can simultaneously enhance thermal conductivity, stability, and storage capacity. From a systems perspective, integrating NePCMs into diverse solar thermal applications, including solar cookers, dryers, water heating systems, and hybrid solar-thermal energy systems, requires optimized design strategies and standardized evaluation methods. Addressing these research directions will be critical in advancing NePCMs from laboratory-scale innovation to real-world energy storage solutions.

CRedit authorship contribution statement

Ibrahim Issah: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **M.M. Noor:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **K. Kadirgama:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Navid Aslfattahi:** Formal

analysis, Methodology, Writing – original draft, Writing – review & editing. **K.A. Abou-El-Hossein**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Chee Kuang Kok**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Maryam Sadat Kiai**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **L. Samylingam**: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **M. Samykano**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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