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Nano-enhanced Phase Change Materials for Efficient Thermal Energy Storage and Cooling in Solar Systems: A Comprehensive Review

S. Mathan Kumar[1], A. Marshal Safin[2], A. Jayakanth[3] & A. Megalingam[4,5,*]

[1]Assistant Professor, Department of Civil Engineering, Noorul Islam Centre for Higher Education, Thuckalay, Tamil Nadu, India. [2]Scholar, Department of Civil Engineering, St. Xavier's Catholic College of Engineering, Chunkankadai, Tamil Nadu, India. [3]Scholar, Department of Computer Engineering, ST Hindu College, Nagercoil, Tamil Nadu, India. [4]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia. [5]Faculty of Mechanical Engineering, M.E.T Engineering College, Anna University, Kanyakumari, Tamil Nadu, India. Corresponding Author (A. Megalingam) Email: megalingammahesh@gmail.com[*]

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ABSTRACT

Nano-enhanced phase change materials (NePCMs) have also appeared as viable alternatives for enhancing thermal energy storage (TES) and cooling effectiveness in solar systems. The addition of nanoparticles to phase change materials (PCMs) increases thermal conductivity, facilitates faster heat transfer, and suppresses supercooling, thus overcoming some major drawbacks of traditional PCMs. The review herein focuses on the mechanisms, synthesis procedures, and thermal characteristics of NePCMs, with special reference to their application in solar thermal energy storage and cooling. Recent developments in nanoparticle selection, dispersion stability, and encapsulation methods are highlighted, in addition to system-level integration approaches for solar collectors and photovoltaic cooling. Challenges including cost, long-term reliability, and environmental issues are also evaluated. The review is completed with future research directions to enhance NePCMs for effective and sustainable use of solar energy.

Keywords: Thermal Energy Storage; Nano-Enhanced Phase Change Materials; Solar System; Cooling Applications; Nano Materials; Thermal Conductivity; Photovoltaic; Viscosity; Challenges; Limitations; Applications.

1. Introduction

The world transition towards sustainability in energy is heavily reliant on utilizing solar energy, but its intrinsic intermittency is an overarching challenge [1]. Thermal Energy Storage (TES) by Phase Change Materials (PCMs) is a promising option by utilizing latent heat and has a storage density 5-14 times more than traditional sensible heat storage with materials such as water or rock [2]. Yet, the large-scale use of PCMs is greatly hindered by their poor thermal conductivity, generally 0.15 to 0.3 W/m·K for paraffins of organic origin, which causes inefficient heat transport and long charging/discharging cycles that impair system performance. From the Gürbüz et al.'s studies, which explored that the dispersion of nanoparticles with high thermal conductivity (e.g., carbon nanotubes at 3000 W/m·K and CuO at 76 W/m·K) to form nano-enhanced PCMs (NePCMs) has emerged as a crucial mitigation approach, the literature remains scattered [3]. There is a real research gap in quantitatively addressing the trade-offs between increased conductivity, the resultant loss in latent heat capacity, and long-term stability of the nanocomposite in actual operating conditions. Hence, this review is intended to provide systematic analysis and synthesis of recent developments in NePCMs, critically assessing their thermophysical performances, to establish an unambiguous rationale for their optimal design and integration into efficient and sustainable solar thermal and photovoltaic cooling systems [4].

Researchers have investigated nano-enhanced PCMs (NePCMs), wherein high-conductivity nanomaterials such as graphene, CNTs, metal oxides, and new MXenes are used in PCMs to enhance thermal transport [5]. Research shows that 1–5 wt.% graphene nanoplatelets can raise conductivity by 200–300%, while dispersions of CNTs provide nearly 2.5× higher heat transfer rates than pristine PCMs. Likewise, Al_2O_3- and TiO_2-based NePCMs have exhibited 20–40% reduced charging times in solar collectors and CSP systems [6]. These improvements have a direct implication of enhanced solar efficiency, longer operation under low radiation, and improved load matching. With promising outcomes, though, challenges persist, such as nanoparticle agglomeration, viscosity, decreased latent heat, and long-term cycling stability [7].

Solar system efficiency is essentially limited by thermal considerations: solar thermal collectors need sturdy storage to bridge day-night cycles, and photovoltaic (PV) panels suffer efficiency degradation of 0.4-0.5%/°C with increasing operating temperature [8]. Latent heat storage in Phase Change Materials (PCMs) provides an enticing solution, but their poor thermal conductivity (<0.5 W/m·K) inhibits the high-speed heat transfer required for efficient load shifting and active cooling [9]. Nano-enhanced PCMs (NePCMs), engineered through the incorporation of metallic, metal oxide, or carbon nanoparticles, have shown a pioneering promise to overcome this limitation, dramatically enhancing the rate of heat transfer [10]. Nevertheless, the research field is diversifying and unfolding at a speedy pace, leaving a gap within an integrated vision of how such nanoscale additions affect not just conductivity but also vital practical issues such as cycling stability, viscosity, and cost-feasibility for large-scale solar implementation.

The aim of this review is to consolidate this scattered knowledge, providing a quantitative analysis of NePCM performance metrics to identify key trends, address existing commercialization barriers, and outline a path forward for their implementation in high-efficiency, next-generation solar energy systems.

1.1. Study Objectives

This review seeks to systematically assess the state of the art in nano-enhanced phase change materials (NePCMs) for solar thermal and photovoltaic applications. The overall goals are:

- To synthesize and critically examine the scattered literature on the thermophysical properties such as thermal conductivity, latent heat capacity, specific heat, and viscosity of different NePCM formulations.

- To offer a quantitative evaluation of the performance of NePCM in solar thermal systems, highlighting parameters like energy storage density, charging/discharging rates, and overall system efficiency.

- To evaluate the efficacy of NePCMs in photovoltaic (PV) thermal management and cooling, quantifying the improvements in reducing PV cell temperature, electrical efficiency, and operational lifetime.

- To determine and discuss the main technical issues and commercialization hindrances, e.g., long-term stability, dispersion of nanoparticles, cycling life, and cost-effectiveness.

- To present future research trends and avenues for optimizing NePCM formulations and system integration to enable the development of next-generation, high-efficiency solar energy systems.

The paper is structured to first establish the core concepts behind NePCMs, then detail their synthesis and material properties. Following this, their application in solar thermal storage and PV cooling is reviewed, culminating in a discussion on prevailing challenges and future prospects.

2. Fundamentals of Nano-Enhanced PCMs

Phase Change Materials (PCMs) are materials that absorb and release large quantities of latent heat upon phase change, normally melting and freezing at a temperature close to constant, thus being best suited for thermal energy storage [11]. Their main role is to offer high-density energy buffering, but their universal application is discouraged by intrinsically low thermal conductivity, leading to sluggish charge and discharge rates, lowering system efficiency and responsiveness. NePCMs are sophisticated composites designed by dispersing nanoparticles of high thermal conductivity like metals, metal oxides, or carbon allotropes in a base PCM to create a stable colloidal dispersion that highly enhances heat transport [12]. The main advantages are significantly improved thermal conductivity, less supercooling, and quicker cycling rates, though issues such as long-term dispersion stability, elevated viscosity, and a compromise in latent heat capacity are still active research areas for achieving their optimal application.

Current research has indicated that the addition of nanoparticles like Al_2O_3, CuO, TiO_2, graphene, and carbon nanotubes to PCMs improves thermal conductivity by 20–80%, and this depends on particle concentration and dispersion methodology. Scientists have also emphasized that nanoparticles' shape, size, and surface engineering significantly affect stability and heat transfer efficiency, with graphene- and carbon-type additives being more superior in improvements owing to their high inherent conductivity and large surface area [13]. Encapsulation techniques, such as micro- and nano-encapsulation, have been investigated to avoid leakage and enhance thermal reliability upon multiple melting solidification cycles [14]. Excessive loading of nanoparticles, however, increases viscosity and decreases latent heat capacity, creating a precarious balance between enhancing conductivity and energy storage efficiency. These observations stress the importance of optimized nanoparticle choice and integration methodologies specially designed for solar thermal applications [15].

2.1. NePCMs Conceptualization

The inclusion of nanoparticles in normal phase change materials (PCMs) has proven to be a successful method to mitigate their inherent disadvantages, especially low thermal conductivity and the phenomenon of supercooling [16-18]. Nanoparticles are used as high-conductivity additives that form conductive paths within the PCM matrix and facilitate quicker energy transfer while melting and solidifying. Preparation and Mechanism of NePCM is shown in Figure 1.

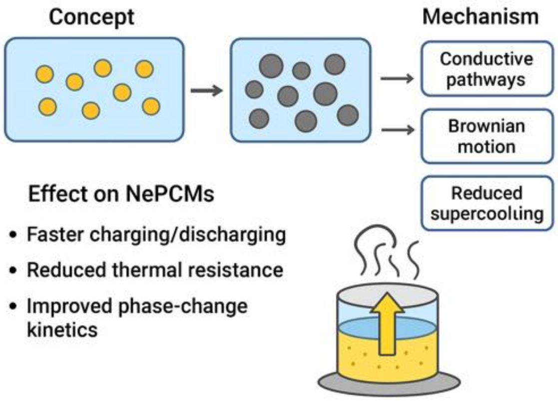

Figure 1. NePCM preparation and Mechanism [17]

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 95-109, July-September 2025

Moreover, Brownian motion of nanoparticles increases micro-convection within the liquid PCM, and surface energy of the nanoparticles offers nucleation sites that inhibit supercooling. All of these mechanisms jointly allow NePCMs to obtain accelerated charging and discharging cycles, thermal responsiveness, and increased system reliability for thermal energy storage and solar cooling systems [19]. The effect of Nanoparticle Characteristics on Thermophysical Properties of NePCMs is given in Table 1.

Table 1. Effect of Nanoparticle Characteristics on Thermophysical Properties of NePCMs [16-19]

Nanoparticle	Size (nm)	Shape	Conc. (wt%)	Conductivity Increase (%)	Supercooling Decrease (°C)	Viscosity Increase
Al_2O_3	20–80	Spherical	1–5	20–40	2–5	slight
CuO	30–70	Spherical	1–3	30–50	3–6	moderate
TiO_2	10–50	Spherical/Rod	0.5–3	15–35	2–4	slight
Graphene	~2D sheets	Sheet	0.1–1	60–80	4–8	high
CNTs	Φ10–30 µm	Tubular	0.1–2	50–70	3–7	moderate
Ag	20–50	Spherical	0.5–1	40–60	2–5	moderate
Nanodiamond	5–20	Spherical	0.5–2	25–45	2–4	slight

2.2. Synthesis and Preparation Methods for NePCMs

2.2.1. Two-step method

The two-step process is a common and relatively easy to use method for NePCMs synthesis, which mainly consists of dispersion of pre-formed and normally dry nanoparticles into a molten PCM base fluid. It starts with the production or synthesis of nanoparticles like metals, metal oxides, or carbon-based materials using specialized processes like chemical precipitation or sol-gel, followed by drying them nicely [20].

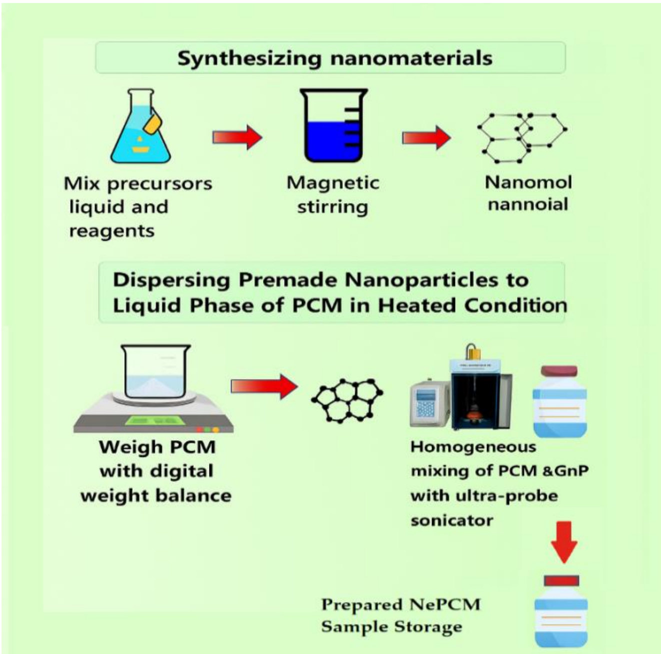

Figure 2. Two step preparation method representation [20]

The next preparation step is to obtain a homogeneous and stable colloidal solution by suspending these pre-prepared nanoparticles into the liquid PCM with mechanical stirring, magnetic stirring, or more efficiently with high-intensity ultrasonication to disperse agglomerates and distribute evenly. In order to ensure the long-term stability of the resultant nano-enhanced PCM and to avoid sedimentation, surfactants or surface modification agents are used to functionalize the surface of the nanoparticles in order to enhance the nanoparticle compatibility with the organic PCM matrix and minimize the van der Waals forces causing clustering [21]. The NePCM two-step preparation process is shown in **Error! Reference source not found.**.

2.2.2. One-step method

The one-step procedure differs from the two-step process basically in that it combines the synthesis and dispersion phases in a single step to avoid the independent drying and powder-handling that lead to extensive agglomeration. It entails dissolving a chemical precursor directly in molten PCM and subsequently initiating in situ nanoparticle formation using heat, a reducing agent, or ultrasonication [22,23]. The key benefit is that the nanoparticles are nucleated and instantaneously encapsulated by the PCM matrix, reducing their surface energy and inhibiting the creation of hard clusters, thus resulting in a better homogeneity and stability nano-enhanced PCM with improved dispersion and less clustering. The NePCM one step preparation process is illustrated in Figure 3.

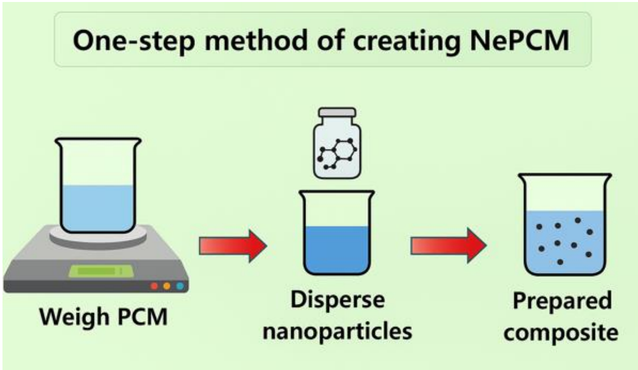

Figure 3. One step preparation method representation [22]

Magnetic stirring gives the first, basic mixing with a rotating magnetic field causing a stir bar to rotate inside the PCM-nanoparticle mixture, producing gross agitation and inducing the macroscopic dispersion of the particles in the base fluid to create an initial homogeneous mixture [24]. Ultrasonic agitation (sonication) is an even more energetic secondary process involving high-frequency sound waves being introduced to the mixture through a probe or bath, creating microscopic cavitation bubbles that collapse violently; the resulting energy produces localized extreme temperatures and pressures that break down recalcitrant nanoparticle agglomerates, de-bundle nanostructures, and provide nanoscale dispersion and wetting [25]. Surfactant application involves the incorporation of surface-active molecules that adsorb on the nanoparticle surface, forming a protective barrier or producing steric/electrostatic repulsive forces between particles; this important step targets the cause of agglomeration by preventing van der Waals attractive forces, thus ensuring colloidal stability, inhibiting re-agglomeration after sonication, and improving suspension integrity over the long term.

3. Thermophysical Properties of NePCMs

The addition of nanoparticles to phase change materials (NePCMs) has universally provided quantifiable increases in thermal conductivity [26]. Improvements in the range of 15–40% have been reported in low loadings of 0.5–2 wt.% with Al_2O_3, CuO, or graphene nanoplatelets, with graphene-based systems frequently having a better

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 95-109, July-September 2025

performance than metal oxides because of their superior intrinsic conductivity [27]. Observed improvements are described by processes like percolation network formation, Brownian motion–driven micro-convection, and the creation of interfacial nanolayers enabling phonon conduction. Although increased concentration levels (>3 wt.%) can drive conductivity improvements above 50%, they tend to do so at the expense of stability, indicating a compromise between improvement and dispersion stability. Notwithstanding improvements in conductivity, NePCMs have disadvantages in latent heat capacity and phase transition stability. A number of experimental works report a 5–20% reduction in latent heat upon the introduction of nanoparticles, mainly attributed to the lower PCM mass fraction and existence of thermally inactive interfacial areas [28].

Phase change temperatures, on the other hand, tend to shift in a small range of ±2–3 °C, indicating that nanoparticles will not perturb phase equilibria to a significant extent but modify storage enthalpy. The impact on the specific heat capacity (Cp) is still non-conclusive: graphene and CNT addition record 3–10% improvement based on interfacial energy storage, whereas oxide nanoparticles like TiO_2 and Al_2O_3 tend to reduce Cp by 5–12% due to their relatively lower intrinsic Cp. This inconsistency emphasizes particle chemistry, size, and dispersion quality dependency of thermal response. NePCM properties comparison study is shown in Table 2.

Table 2. Comparison of NePCM Properties [26-28]

NePCM = Base PCM +Nanoparticle	**Conc. (wt%)**	**Method**	**k (Change) Increase**	**ΔH (Change) Decrease**	**T_m (Change)**	**C_p (Change)**
Paraffin + Graphene	0.5–2	Ultrasonication	30–60%	5–10%	Stable	Slight Increase
Paraffin + CNTs	0.5–2	Two-Step	20–50%	3–7%	Stable	Increase
Paraffin +Al_2O_3	1–5	Two-Step, Surfactant	10–35%	2–6%	Stable	Decrease/ Stable
Fatty acids + SiO_2	1–3	Stirring	8–25%	4–8%	Stable	Stable
PEG +CuO	1–4	Two-Step	15–40%	5–12%	Slight Decrease	Decrease
Salt Hydrate + TiO_2	0.5–2	Direct Mixing	12–30%	5–10%	Slight Increase	Stable

k: Thermal Conductivity, ΔH: Latent Heat of Fusion, T_m: Melting Temperature, C_p: Specific Heat Capacity.

Rheological and long-term cycling characteristics also present challenges for real-world applications. Viscosity measurements reveal increases of 30–80% at 1 wt.% loading, with some showing shear-thinning behavior, while others have extreme pumping penalties that restrict integration on a large scale [29]. Stability during multiple phase transitions is also paramount: surfactant- or surface-functionalized and well-dispersed nanoparticles keep >95% of their latent heat capacity after 500–1000 cycles, while destabilized NePCMs can experience 15–25% loss due to agglomeration and sedimentation.

These results highlight the fact that although the thermophysical benefits of NePCMs are clear, their actual implementation in solar thermal systems depends on meticulous balancing of conductivity increase against latent heat storage, viscosity control, and dispersion stability over extended periods [30]. A summary comparison table summarizing information on base PCMs, nanoparticle type, concentration, preparation method, and important property changes (k, ΔH, Tm, Cp) gives a clearer basis for choosing material–process combinations with applications in specific thermal energy storage.

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 95-109, July-September 2025

4. Applications in Solar Thermal Systems

The incorporation of NePCMs in solar water heaters has shown remarkable performance improvement. Experimental research proves that it is possible to enhance thermal conductivity by 20–35% using NePCMs in storage tanks or PCM modules, which facilitate quicker charging and can decrease charging time by almost 25% compared to traditional PCMs. For instance, paraffin–Al_2O_3 composites recorded 15% improvement in overall system efficiency and increased the duration of hot water supply by 2–3 hours, highlighting the significance of nanoparticle dispersion in promoting heat transfer [31-33]. In the same vein, NePCMs integrated in solar space heating and building integration (walls, ceilings, plasterboards) have exhibited enhanced thermal management, where reports indicate peak load shifting by as much as 30% and indoor comfort gains of 2–4 °C during extreme outdoor temperatures. These results affirm that NePCMs can aid in passive solar building design by leveling diurnal temperature variations and decreasing HVAC load. For CSP power plants, nano-en- hanced molten salts used as high-temperature TES media have been shown to enhance operating temperature as well as efficiency. Investigations show that adding 1 wt.% SiO_2 or Al_2O_3 nanoparticles increases thermal conductivity of molten salts by 10–18%, corresponding to a 5–7% increase in Rankine cycle efficiency. Furthermore, NePCM-based TES systems allow stable operation at 50–80 °C higher temperatures than other salts, thus enhancing overall energy yield. However, issues like increased viscosity (20–40% increase) and possible corrosion with metal containment materials are still in question. Therefore, although NePCMs offer optimistic advantages for water heating, building integration, and CSP, their practical scalability requires a balance between improved efficiency, material stability, and long-term operational dependability [34,35]. Applications of solar are presented in Figure 4.

Figure 4. Applications of Solar [34]

5. Applications in Photovoltaic (PV) Thermal Management and Cooling

5.1. The Problem of PV Efficiency Loss

One of the most significant drawbacks of photovoltaic (PV) technology is its high sensitivity of electrical efficiency to operating temperature. Several studies have shown that the efficiency of crystalline silicon PV cells reduces by about 0.4–0.5% with each increase in temperature of 1 °C over the reference test condition of 25 °C. For instance, a

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 95-109, July-September 2025

65 °C PV module might experience efficiency losses of almost 15–20%, greatly decreasing power output and shortening its lifespan through enhanced material degradation [36]. This issue becomes especially pronounced in areas with high solar irradiance and ambient temperatures, where modules frequently run greater than 50 °C. As such, efficient thermal management techniques are necessary to preserve PV performance and prolong operating reliability.

5.2. PV-Thermal (PVT) Systems with NePCMs

Recent studies have proved that the use of nano-enhanced phase change materials (NePCMs) in PV-thermal (PVT) systems is effective. In these configurations, a NePCM layer is placed at the back of the PV module to harvest excess heat and store it as latent energy to be utilized as a secondary application, e.g., water preheating or space heating. The incorporation of nanoparticles like Al_2O_3, graphene, or TiO_2 into PCMs has been found to increase thermal conductivity by 20–60%, which speeds up heat dissipation from the PV modules [37]. Experimental work indicates that PVT systems based on NePCM can decrease the surface temperature of PV by 10–18 °C with an improvement in electrical efficiency by 4–8% relative to standard PV modules. Also, the trapped heat enhances the system energy utilization factor as a whole by as much as 70–80%, pointing to the double advantage of electrical performance improvement and thermal energy recovery.

5.3. Passive PV Cooling with NePCMs

In addition to integrated PVT systems, NePCMs have been applied as passive cooling media in the shape of heat sinks or encapsulated layers directly bonded to PV backsheets. These systems both store excess daytime heat and release it at night with lower average operating temperatures. Research employing paraffin-based NePCMs doped with carbon nanotubes (CNTs) or graphene nanoparticles has shown a PV module operating temperature reduction of 8–15 °C under maximum solar irradiation [38]. This temperature decrease is equivalent to 3–6% improvement in electrical output depending on the climatic conditions and PCM design. In addition, long-term simulations indicate that such cooling can increase PV module lifetimes by 5–10 years through decreased thermal stress. Passive NePCM-based cooling therefore provides an easy yet very efficient strategy for improving PV performance without intricate active systems.

░6. Challenges, Limitations, and Future Perspectives

6.1. Technical Challenges

One of the primary technical problems hindering the bulk uptake of NePCMs is ensuring their long-term stability in view of the fact that nanoparticles tend to agglomerate and settle over time, impairing the enhanced thermal properties and rendering the material inhomogeneous. Moreover, addition of nanoparticle significantly increases the viscosity of the PCM, which can suppress natural convection, increase pumping power requirements, and render system design challenging for effective heat transfer. Lastly, corrosion risk is a serious issue, particularly with metal nanoparticles with high electrical conductivity, which can promote higher degradation of metallic containment materials, hence the life and dependability of the system [39-42]. Technical Challenges Comparisons are provided in Table 3.

Table 3. Comparison of Technical Challenges of NePCMs

Material	Stability	Viscosity	Corrosion	Thermal Reliability	Future Focus
Graphene [39]	Agglomeration	Moderate	Low	Good	Surface functionalization
CNTs [40]	Agglomeration	High	Container issues	Reduced enthalpy	Hybrid composites
Al_2O_3 [41]	Stable	Low	Mild	Phase segregation	Encapsulation
CuO [42]	Sedimentation	Moderate	Risk	Latent heat loss	Corrosion coatings
Metals (Ag) [43]	Oxidation	High	High	Enthalpy loss	Protective coatings
Nanodiamond [44]	Excellent	Low	Stable	Excellent	Green synthesis

6.2. Economic Viability

The economic feasibility of NePCMs is highly threatened by the expensive nature of nanoparticles, especially developed carbon-based materials such as graphene and carbon nanotubes, which are still costly to manufacture in large quantities. This high material cost directly affects the system price, raising serious issues regarding the cost-benefit balance and leading to a longer payback period for solar thermal systems; for large-scale take-up, the shown increases in efficiency and energy storage have to firmly justify the high front-end capital expenditure over the lifetime of the system [43-45]. Comparison study of economic viabilities are given in Table 4.

Table 4. Comparison of Economic Viabilities of NePCMs [43-45]

Material	Cost	Fabrication	Cost–Benefit	Large-Scale Use	Future Focus
Graphene	High	High	High perf., high cost	Limited	Low-cost synthesis (GO)
CNTs	High	High	Good perfect, high cost	Limited	Mass production
Al_2O_3	Low	Low	Cost-effective	High	Scaling up
CuO	Medium	Medium	Balanced	Medium	Hybrid systems
Metals (Ag)	Very High	High	Not economical	Low	Nano-alloys
Nanodiamond	Medium	Medium	Good lifecycle value	Emerging	Scalable production

6.3. Measurement Model Equations

Environmental and health issues associated with NePCMs call for a robust lifecycle analysis to determine the complete environmental impact, from energy-wasting nanoparticle synthesis to end-of-life recycling or disposal. A major challenge is controlling the toxicity of some engineered nanoparticles, which can become respiratory hazards upon handling or leaching hazards if spilled, requiring stringent inspections for handling safely in the form of personal protective equipment (PPE) and controlled laboratory environments to avoid potential health risks [46-49]. Comparison of Environmental and Health issues of NePCMs are shown in Table 5.

This study guides future studies on nano-enhanced phase change materials (NePCMs) to develop new, cost-effective, and stable nanoparticles or nanocomposites to improve performance with economic viability. Exploring hybrid enhancement methods, including the combination of nanoparticles with porous matrices or fins, can further enhance thermal management and heat transfer. Standardization of test methods and reporting of thermo-physical properties is a critical requirement for consistent assessment and comparison across research.

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 95-109, July-September 2025

Moreover, extensive real-world demonstrations in large scales and long-term reliability tests are essential to assure performance under realistic conditions [50,51]. Investigation of multifunctional NePCMs with optical, electrical, or other embedded functionalities can provide new avenues for next-generation energy storage and thermal management applications.

Table 5. Comparison of Environmental and Health concerns of NePCMs

Material	Eco-impact	Toxicity	Handling	Regulation	Future Focus
Graphene [39]	Recycling	Uncertain	Dust control	Limited	Biodegradable forms
CNTs [46]	High	Inhalation risk	PPE required	Strict	Safer synthesis
Al_2O_3 [47]	Low	Low	Minimal	Moderate	Eco-friendly processes
CuO [48]	Medium	Aquatic toxicity	Protection needed	Evolving	Green modification
Metals (Ag) [49]	High	Aquatic toxicity	Controlled	Strict	Biodegradable coatings
Nanodiamond [49]	Low	Low	Minimal	Weak	Eco-safe production

7. Conclusion

Nano-enhanced phase change materials (NePCMs) are essential in overcoming the intrinsic limitations of traditional PCMs, foremost by enhancing thermal conductivity, energy storage capacity, and system efficiency as a whole. Significant enhancements in thermal properties have been demonstrated, leading to improved performance in both solar thermal and photovoltaic applications. Nevertheless, despite the advances made, concerns related to long-term stability, cost, and standard assessment procedures need to be overcome before NePCMs can reach commercialization on a large scale. However, with continued research and technological advancements, NePCMs have tremendous potential as one of the enablers of efficient, dependable, and sustainable use of solar energy in the near future.

8. Future Recommendations

The following are some future recommendations concerning this study.

1) Research the long-term thermal and chemical stability of NePCMs upon prolonged phase change cycles.

2) Investigate cost-effective synthesis and large-scale production methods for commercialization.

3) Establish standardized testing procedures to assess thermal, chemical, and mechanical properties.

4) Research the environmental and health effects of nanoparticles employed in NePCMs.

5) Combine NePCMs with hybrid renewable energy systems for increased overall efficiency.

6) Use advanced computational and machine learning models to design for optimizing nanoparticle selection and dispersion.

Declarations

Source of Funding

This study has not received any funds from any organization.

Conflict of Interest

The authors declare that they have no conflict of interest.

Consent for Publication

The authors declare that they consented to the publication of this study.

Authors' Contribution

Data collection, and Writing: S. Mathankumar, Supervision, and Guidance: A. Megalingam, Data alignment and Moral support: A. Marshal Safin and A. Jayakanth.

Ethical Approval

Not applicable for this study.

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