

Intelligent Parameter Tuning of Nanomaterial-Enhanced Phase Change Material Systems Using Neural Networks and Grey Wolf Optimization: A Comprehensive Review

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Abstract:

Enhancing consumer demand for effective energy storage systems stimulates much research on phase change materials (PCMs), especially for applications with nanomaterial enhancement, to address issues such as low thermal conductivity and slow charging–discharging rates. With the improved heat transfer properties associated with the nanomaterials, the performance of nanomaterial-enhanced PCMs (NEPCMs) is quite sensitive to many interacting parameters like nanoparticle type, concentration, dispersion stability, encapsulation geometry, and operating conditions. However, traditional trial-and-error approaches or single-variable optimizations rarely grasp the nonlinear and coupled behavior unless manipulated into a controlled setting. Being comprehensive in nature, intelligent optimization techniques therefore represent powerful tools for performance prediction and parameter tuning. This review presents a detailed study on developments in the modeling with Neural Networks (NNs) and optimization with Grey Wolf Optimization (GWO) concerning the intelligent optimization of the parameters of the NEPCM systems. The work critically discusses the useful application of artificial neural networks in modeling the nonlinear thermal behavior, determining the latent heat storage efficiency, melting/solidification time, and thermal conductivity enhancement. Additionally, it addresses the integration of GWO as a metaheuristic optimization method for the identification of the best design and operating parameters with potential benefits of simulating the conducting of the search process across different scales in the leadership hierarchy as well as the hunting mechanism of grey wolves. The hybrid model NN-GWO method is reviewed instead on the grounds of its modeling accuracy, convergence speed, robustness, and efficiency, while also examining its comparative results with other optimization techniques, current issues, and future directions for real-time control and further scalability in energy storage applications. Overall, this paper aims at giving a submission to the efforts of making use of intelligent optimization strategies so that the PCM-based thermal energy storage systems will be undergoing more programmability in the future.

Keywords: Phase change materials; Nanomaterial enhancement; Neural networks; Grey Wolf Optimization; Thermal energy storage; Intelligent optimization; Hybrid soft computing

I. INTRODUCTION

The recent surge in global energy consumption fuels the quest for energy intensive technologies, given the worries of global warming and depleting sources of fossil fuel. Waste is produced while reaping energy itself during the processes of conversion, transmission, and utilization due to the non-reuse of a notable portion of energy [1]. Energy storage systems store thermal energy that is generated that may be used later well with the ever-growing improvement of the overall efficiency, reliability, and sustainability. TES proves to be a very significant application technology in a range of applications: renewable systems, heating and cooling in buildings, electronic thermal management, and industrial waste heat recovery systems [2]. Among the various TES techniques, latent heat thermal energy storage using phase-change materials (PCMs) attracts the most interest because they can store an enormous amount of energy while phase transition temperatures. PCMs usually absorb/release large amounts of heat within a fairly constant or narrow temperature range, typical of the phase change, like ice melting or freezing in our everyday experiences, passing from solid to liquid states or liquid to solid states [3]. These materials offer remarkable heat buffer properties whenever an application calls for a sudden peak or fall in temperature. Organic, inorganic, and eutectic PCMs are commonly used based on availability, suitable phase change temperatures, and relatively high latent heat capacities, depending upon the application requirements [4].

Conventional PCMs carry along several inherent limitations along with the set of added advantages they provide, which restrict their mass-scale deployment and high performance. One of the most significant drawbacks is the low thermal conductivity, thereby signifying slow heat transfer and lengthy melt/solidification processes [5]. As a result, PCM's charging and discharging efficiency is significantly compromised in TES systems. Other challenges include phase separation in inorganic PCMs, supercooling effects, leakages during the liquid phase, and thermal cycle-induced

deterioration within physico-chemical properties. Consequently, composite development or system enhancements to magnify PCM performance have received a rave of investigative attention [6].

The past few years have witnessed the blend of restricted nanomaterials to PCMs as an optimistic alternative for the above limitations. Nanomaterials-enhanced phase-change materials (NEPCMs) represent a good compromise linking the superior heat storage potential of PCMs with the excellent thermal conductivity of nanoscale additives [7]. Also, to talk about the potential applications, they can be identified with respect to metallic nanoparticles, metal oxides, and carbon nanoforms like carbon nanotubes and graphene [8]. When settled with PCMs, macro materials form conducts with somewhat enhanced heat transfer, reduced phase transition time, and improved thermal-decision-making system. Consequently, the thermal performance is expected to be higher than that of conventional PCM-based materials and makes them suitable for evolving TES applications. On the other hand, an inappropriate use or overload of nanoparticles may create difficulties in phase-change momentum during a solidification and subsequent reeling. Agglomerations, an increase in viscosity, lower natural convection, and reduced effective latent heat storing capacity would be the consequences [9]. These coupled nonlinear effects then complicate the design and optimization of NEPCM building up too many challenges that are not effectively addressed by traditional trial and error or single-parameter optimization techniques.

In attempts to tackle this complexity, intelligent modeling and optimization techniques have gained increasing recognition. Artificial neural networks (ANNs) have been specifically put into practice in obtaining the nonlinear relationships among input parameters and the associated heat transfer performance of NEPCM systems [10]. These neural networks can effortlessly predict key performance indicators, including the enhancement of thermal conductance, melting and solidification times, and efficiency of energy storage, as long as sufficient connections have been made to learn from the experimentally or numerically obtained datasets [11]. Simultaneously, metaheuristic optimization algorithms such as Grey Wolf Optimization (GWO) have presented potential for efficiently exploring a large number of search domain squares characterized as large and complex. The integration of NN within GWO has opened the door for developing hybrid intelligent tuning methodologies for NEPCM systems. NN within these frameworks gets deemed predictive models. GWO tunes (system) parameters in order to meet the performance objectives. This review assesses the recent advancements and critical views behind neural network-based modeling and GWO-mediated optimization in nanofluid-suspended PCM systems [12]. Further the review aims to become a zoo of ideas for various research contexts gaining strength from synthesized researches to address current challenges and underscore potential advances for researchers interested in optimizing the kind of advanced thermal energy systems [13].

Thermal energy storage is essential for improving energy efficiency and supporting renewable energy integration. Phase change materials (PCMs) have been identified as incredibly viable candidates for energy storage applications due to their properties, such as high latent heat storage capabilities. In recent times, PCM research and development have focused on hybrid performance improvement by coupling nanomaterials and intelligent optimal techniques to advance energy storage systems. Thermal energy storage devices save surplus heat energy for later use, thereby cutting energy losses and enhancing system reliability for solar energy systems, buildings, and industrial waste heat recovery [10]. Materials such as phase change materials are of immense importance due to their ability to store and release high quantities of energy with almost constant temperature helping in creating latent heat thermal energy storage systems that are compact, efficient, and stable.

Table 1: Limitations of Conventional PCMs. [9]-[10]

Limitation	Description	Impact on Performance
Low thermal conductivity	Most organic and inorganic PCMs conduct heat poorly	Slow charging and discharging rates
Phase segregation	Components separate during phase change cycles	Reduced long-term reliability
Supercooling	Delay in solidification below phase change temperature	Inefficient energy release
Leakage during melting	Liquid PCM escapes from containment	System failure and material loss
Poor thermal stability	Degradation over repeated cycles	Shortened operational lifespan

Nanomaterial-Enhanced PCMs: An Overview

Nanomaterial-enhanced phase change materials (NEPCMs) have been recognized as highly promising thermal energy storage media overcoming the inherent drawbacks of the conventional PCM systems. Organic and inorganic PCMs, though highly promising for storing latent heat, suffer from low thermal conductivity, restricting the rate of heat transfer and

prolonging the cycles of melting and solidification [11]. Several kinds of nanomaterials that demonstrate promising potentialities are added into the basic PCMs to improve their thermophysical properties without significantly affecting their phase change characteristics. Examples of commonly used nanomaterials are metallic nanoscale materials, including nanoparticles of copper, aluminum, and silver, oxide nanoparticles of metals (such as Al_2O_3 , CuO , TiO_2 , and SiO_2), and carbon-based nanostructures such as carbon nanotubes, graphene, graphene oxide, and expanded graphite. These nanomaterials inherently uphold high thermal conductivity, requiring the formation of particulate networks within the PCM medium to provide good heat transfer for the phase transition mechanism of NEPCMs to be enhanced [12]. As a consequence, reduced melting and solidification times, improved temperature uniformity, and augmented charging and discharging efficiency occur within NEPCMs. Boasting a super elevation in their thermal conductivity, nanomaterials can also influence further properties of PCMs [13]. It has been evidenced that well-chosen nanoparticles have the power to suppress supercooling effects while enhancing the thermal stability and mechanical strength of encapsulated PCM systems carved out of composites. Furthermore, surface-functionalized nanoparticles may lead to a better compatibility between the nanomaterial and the PCM and a resulting dispensability. This benefit would exist even through the multitude of thermal cycles. [14]. Figure 1 represents NE-PCM ideal properties.

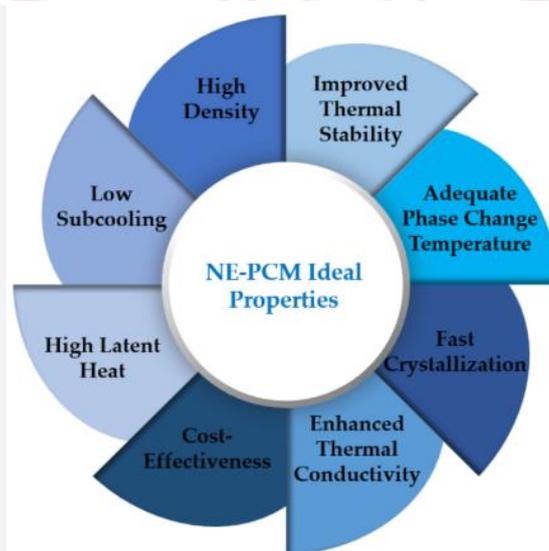


Figure 1: NE-PCM ideal properties

The introduction of nanomaterials gets the assignment to address many intricacies. At high concentrations of nanoparticles, thermal sagging and centrifugation become quite likely, and in turn this leads towards extremely nonuniform heat transport and serious degradations in the durability of performance over a greater period [15]. Higher viscosity at the crux of higher nanoparticle loading could negatively impact natural convection within liquid PCMs, thereby reducing in part the degree to which heat content benefited from such a system by enhancing volume conduction. On account of this, putting more nanoparticles might also result in a decrease in the effective latent heat that the storage material can ideally accept, being the reason that nanomaterials do not participate in phase change [16]. Fresh research gives much importance on smart nanoparticles selection, surface modification, and hybrid enhancements pairing of nanoparticles with porous matrices or encapsulated materials. The performance of NEPCM based on several interacting parameters, such as the type, size, shape, concentration of nanoparticles, dispersion method, and operation conditions. Therefore, models have been introduced with intelligent optimization strategies, with increased usage toward optimal solutions. All in all, NEPCM offers a possible path for high-performance, compact, and efficient thermal energy storage capacities for renewable energy applications in buildings, electronic cooling, and industrial waste heat recovery [17].

The objective of this review was to investigate intelligent modeling and optimization approaches for the nanomaterial-enhanced PCM systems. The review presents the neural networks, Grey Wolf Optimization, hybrid frameworks, applications, challenges, and future research directions.

II. FUNDAMENTALS OF NANOMATERIAL-ENHANCED PCM SYSTEMS

Nanomaterial enhanced phase change material systems, developed for the integration of additives at the nanoscale into conventional PCMs to improve heat transfer performance, can greatly benefit from the knowledge of fundamental characteristics of PCMs, nanomaterials, and interaction mechanisms involved for effective design, modeling, and optimization of advanced thermal energy storage systems [18].

Classification of Phase Change Materials

Based on the chemical composition of phase-changing materials and the significant characteristics of their phase transition, PCMs can be categorized into inorganic, organic, and eutectic types. Among organic PCMs, paraffin and fatty acids are most commonly used in a way that besides being chemically stable, they do not corrode and possess a congenial melting behavior. They are seen to possess low thermal conductivity. Inorganic PCMs—such as salt hydrates or metal plates—exhibit high thermal conductivity and high latent heat, yet their main drawback is phase segregation, peculiarities such as supercooling, and corrosion [19]. Eutectics, on the other hand, are congenial phase change mixes that usually are capable of melting and solidifying congruently at a fixed temperature. This provides controlled temperature at which it delivers energy change and addition, thus, compensating for thermal reliability. PCMs can also be classified based on the working temperature range. Consequently, PCMs can be low-temperature, medium-temperature, or high-temperature PCMs. Thus, PCMs can be used in such applications as building-energy storage, solar-thermal systems, and industrial heat recovery [20].

Thermophysical Properties of PCMs

The thermophysical properties primarily decide the performance of phase change materials in any thermal energy storage application. The Latent Heat of Fusion is a crucial parameter since it greatly influences the amount of energy absorbed or released during phase change. A large latent heat value makes possible the design of compact storage systems showing high energy density [21]. Phase change temperature is of equal importance; it must, by definition, coincide with the operational temperature range of the said application. Thermal conductivity impacts essentially the rate of transfer of heat during the processes of melting or solidification. Unfortunately, most common PCMs offer extremely low thermal conductivity and thus remain far from maximal practical efficiency [22]. The Specific Heat is key for sensible heat storage outside the phase change region, any variation in density between the solid and liquid phases can cause adequate modification in terms of volume stability and implementation. Steady parameters, such as thermal stability intercepting consistent performance during operational cycles and chemical compatibility with the materials of the container, are supplemented by super cool behavior, viscosity in the liquid state, and volumetric expansion as supporting properties that can greatly affect the reliability and durability of PCM-based systems [21]-[22]. Enhancing the TES performance requires these other parameters to be optimized.

Types of Nanomaterials Used in PCMs

Various nanomaterials are incorporated into PCMs to enhance their thermal performance. These nanomaterials are selected based on their intrinsic thermal conductivity, chemical stability, compatibility with PCMs, and cost-effectiveness. Common categories include metallic nanoparticles, metal oxide nanoparticles, and carbon-based nanomaterials [23]. Each type offers distinct advantages and limitations in terms of thermal enhancement, dispersion stability, and impact on latent heat storage. The choice of nanomaterial significantly influences the overall efficiency and long-term reliability of nanomaterial-enhanced PCM systems.

a) Metallic Nanoparticles

Metallic nanoparticles are the most commonly implemented nanomaterials in terms of enhancing PCMs' performance as phase changers. The most popular metallic material is Ag, followed by Cu and Al. In spite of commonly existing stability issues, these nanopowders are good thermal conductors. A wide range of techniques exists in which metal nanoparticles can be integrated into PCMs. In some cases, advanced nanoparticles can generate localized heating during solidification. Kindly refer to the reviewed articles [7, 8] for detailed information about miscellaneous case studies.

Metallic nanoparticles such as Cu, Al, Ag, and Ni are widely studied for PCM enhancement due to their exceptionally high thermal conductivity. These nanoparticles, when dispersed within the PCM matrix, form conductive pathways finalized for rapid heat transfer during phase transitions. Metallic nanoparticles are particularly effective in reducing the melting and solidification time, thereby improving charging and discharging rates [10]. However, their high density may make them prone to sedimentation issues, especially during repeated thermal cycling. Additionally, the addition of metallic nanoparticles also increases the overall cost of the PCM system, and they can introduce compatibility or corrosion concerns depending on the base PCM. Careful control of particle size, concentration, and surface treatment is required to balance thermal enhancement with acceptable levels of system stability and economic feasibility [13].

b) Metal oxide nanoparticles

Metal oxide nanoparticles, such as aluminum oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), and silicon dioxide (SiO_2), are some of the most commonly used options in PCM enhancement with nanomaterials. This is due to their chemical resistance, reasonable cost, and straightforward synthesis processes.[15] Although the thermal conductivity of metal oxides is low when compared with that of metallic nanoparticles, they offer better dispersion stability and no tendency to sediment. These nanoparticles improve the effective thermal conductivity, while maintaining an acceptable latent heat capacity. Metal oxide nanoparticles are also less reactive, due to which they are suitable for long-term thermal cycling.

Through their widespread availability and balanced performance, both excellent practical options are considered for the PCM enhancement for building and solar thermal applications.[17]

c) Carbon-Based Nanomaterials

Carbon-based nanomaterials like carbon nanotubes, graphene, graphene oxide, and expanded graphite have attracted huge attention because of their extraordinarily high thermal conductivity and low densities. These materials afford interconnected thermal networks throughout the PCM matrix, contributing to significant heat transfer enhancement even with low loading fractions. Compared to the metallic additives, carbon-based nanomaterials offer excellent thermal stability but compromise on the detrimental effect on latent heat [18]. However, challenges like poor dispersion, agglomeration, and increased material costs may deter large-scale applications. Nonetheless, expertise in carrying out surface functionalization and hybrid composite development is available for gaining enhanced compatibility and dispersion inside PCMs, rendering carbon-based nanomaterials as practically attractive candidates in high-performance TES [20].

Heat Transfer Enhancement Mechanisms

Heat transfer enhancement within nanomaterial-enhanced PCMs follows a multitude of pathways. One is the very high intrinsic thermal conductivity shown by a nanoparticle that increases the effective heat conduction into the PCM. The formation of a percolation network speeds up heat diffusion during phase change [21]. Also, the nanoparticles come into play with regard to the modification of convection patterns in the liquid phase which, in turn, affects the collective heat transfer behaviour. Brownian motion of nanoparticles also could marginally contribute to thermal transport. Together, these effects lower the melting and solidification times compared to conventional PCMs [22].

Stability and Compatibility Issues

Nanomaterial-enhanced PCMs have shown decreased performance in sectors such as stability and compatibility. As time proceeds, nanoparticle sediments would create an obstacle to the promoters and thus nanomaterial-enhanced PCM performance deteriorated [23]. Higher viscosities could prevent natural convection from happening and may in turn have an effect on heat transfer efficiency. Issues related to the chemical compatibility of nanoparticles with PCM material and materials from the container would affect long-term reliability. Maintaining stability, encasing uniform dispersion, selecting nanoparticles with the lowest attraction force, and picking good material to be compatible are crucial for deployment of NEPCM systems [24].

III. NEURAL NETWORK-BASED MODELING OF NEPCM SYSTEMS

A novel parameter classification framework based on deep learning deep neural networks was introduced in [1] with application to the nano encapsulated phase-change materials. The deep learning method exhibited a high capability of efficiency and accuracy in describing nonlinear thermal behavior of PCM systems. For some basic thermophysical parameters and parameters for geometric properties, a training dataset is furnished aiming at improving prediction accuracy on valuable insights were obtained based on the preliminary training data. The output results were validated against well-accepted numerical results. The proposed approach was demonstratively proficient in solving admissible problems in heat transfer with respect to traditional solvers in terms of computational efficiency. This advanced framework, based on AI, is more likely to be suitable for further advanced phase-change materials' analysis. However, there is no comprehensive research on optimizing the framework or the results of these works. A comprehensive literature review was presented in [2] to describe how energy storage was achieved by the PCMs in the presence of metal fins equipped with numerical treatment. Fins provide important elements of heat transfer to allow heat to be conducted faster and to further reduce the time taken to melt; geometry and arrangement critically dominate, as shown in the parametric analysis. The approach presented here suggests that the possibility of promoting storage pads or container walls with the addition of PCMs, and the application of numerical methods could attain the most efficient work. In addition to being effective, the technique used here is based on numerical modeling with no significant incorporation of intelligent optimization methods. These results establish a solid base on which to build future paths enhancing hybrid systems. In [3], solidification behavior in a nanomaterial-enhanced storage system was analyzed using the Galerkin method. The study showed that nanomaterials improve solidification uniformity and reduce thermal resistance. Temperature distribution and phase change evolution were examined in detail. The numerical set-up showed good stability and accuracy. However, long-term cyclic performance was not addressed. The study rather highlights the role of nanomaterials in improving solidification dynamics. For practical applications, further optimization is advised. Tech [4] investigated the melting process of non-Newtonian nanoscale PCMs in a cylindrical thermal fins storage module. It devoted a comprehensive account of influence of the rheological behavior and fin configuration. The calming effect of the combined nanomaterials with fins was observed on the melting rate. It was also observed that the fluid behavior significantly influences heat transfer. The complex flow patterns were simulated successfully; however, the computational overhead is quite high. Suggestions to capitalize on an intelligent surrogate model for improvement in the future. The study-based reverse hybrid LBM prediction model had an experimental baseline for the solar-water-heating applications in [5]. In all cases, 3E analyses were performed. After the proposed analysis and

predictions were made possible, the efficiency of the systems improved significantly. There was still importance that was attached to the 3E analysis; in essence, it may still profoundly deepen the PCM enhancement concepts of NEPCM. The work in [6] analyzed a miniature PCM (Phase Change Material) heatsink with a heat pipe in connection with its thermal performance. The influence of phase transition temperatures and system orientation was studied. Results reveal that correct selection of a PCM considerably promotes the heat dissipation capability. The orientation was a strong influence on melt behavior and convection resistance. The information herein is useful for cooling compact electronics. Nanomaterial enhancement is not considered. NEPCMs need to be merged for a further increase in performance. The comprehensive study based on [7] discussed methodologies for improving the thermal performance of PV/T collectors in detail. Various measures were analyzed, including nanomaterials, PCMs, and hybrid methods were discussed in the research. The study is sufficient for stating that the observed performances between the various enhancement techniques were good with a slightly higher performance for a combination of methodologies. The concept of enhancing thermal performance in this article is clearly indicated. Additionally, it was possible for thermal and electric efficiencies to be improved. Despite this, this kind of information was found to be highly relevant in making any comparisons. Thus, a lot of ground for intelligent optimization is left unexplored. A comprehensive review paper should raise the relevance of the work towards sustainable systems, including NEPCMs. The diffusion of CO₂ and N₂ from a binary gas plasma is investigated in the meantime. The aim of this chapter is to assess the potential elucidation of thermal conductivity and diffusivity, uni-formative heat flow, and up-scaling of those transport properties from kinetic phenomena in limbo. Our wide focus should make data assessment for any natural type of transport explicit. Anything taken from the GERR-combined [8] considered of previous to that, its credibility was simply hardly able to detract itself from only theoretical and tested on one person. Thus it is clear that, while the exact geometrical model should be able to facilitate some large computational studies, particular multiple concepts with the advantages of other presented commenting areas ought to be linked if thermal simulation is hope to be elevated in the direction wherein ventricular a computer model staged mainstream for this purpose. The earlier scholarship [9] embarked on findings regarding porous hydrodynamic journal bearings with nano-lubrication from the theoretical viewpoint to determine the performance as regards the bearing with respect to enhanced load-carrying capacity and reduced friction. Presence of nanoparticles affects the transport phenomena in porous media. The focus is not sections specific to PCMs; instead, the role of nanomaterials in confined systems is brought out. The modeling strategy is general and provides insights that can be applied elsewhere. It thus reinforces the template of nanomaterials' functional aspects. Still, the work could significantly advance mutual nanoparticle-fluid interaction study. They employed artificial neural networks [10] to examine latency features of nano-enhanced PCMs. The performance of the ANN model was rated to be fairly high relative to the experimental data. Blend of nanoparticle concentration and thermophysical properties were the designated input variables for the model. The work has made it very computationally easy to explore it. The study has proved that ANN offers a reliable predictive tool. However, no optimization algorithms were used. The work gives strong backing for AI-based PCM modeling.

IV. GREY WOLF OPTIMIZATION FOR PARAMETER OPTIMIZATION

The study in [11] focused on fabric sensors with carbon nanotube coatings and 2D materials for self-sensing applications. This research used its analysis of the electrical and piezo resistive behavior of sensor materials to show high sensitivity and stability of carbon materials. While this further enabled studying sensors, it intricately portrays the dispersion and durability aspect of the coated nanoparticles, an aspect definitely important in NEPCM stability. The study clearly supports the applications of multifunctional nanomaterials. The paper has valuable implications to NEPCM through thermal vectors. The review in [12] highlighted the latest amalgamation of nanomaterial-based extracellular matrices for tissue engineering. Emphases were made on the subjects of material compatibility and stability. While primarily biomedical, this paper discussed material integrity in the long run. Different surface functionalization technologies were discussed. This information is quite relevant while dealing with fundamental concepts on nanoparticle dispersion into PCMs. Hence, this indirectly contributes to the material design of an NEPCM. Again, this falls in line with its interdisciplinary nature. The doctoral dissertation in [13] had binding proteins for bio sensing applications as its focus. Advanced interactions of material with surfaces were also investigated. The emphasis was on molecular-level stability and specificity. Moreover, in light of outside thermal storage, the discussion will provide leads in material functionalization with some hints of applicability in nanoparticle-PCM compatibility. The research underscores the precision of material engineering, while its indirect relevance echoes in integration strategies of nanomaterials. The subject matter in [14] treated nanomaterial-mediated photo thermal therapy. It emphasized heat generation and transport at the nanoscale. The study illustrates nanomaterial conduct towards efficient thermal conversion. Such a biomedical linkage can be established with the heat transfer mechanisms. Stability and controlled heating have been paramount sources of interest. Such concepts can be translated effectively to thermal storage materials. They provide strong support for the usefulness of nanomaterials.

The second part in reference [15] exemplified further the contribution to controlled photothermics from nanomaterials and cautioned accordingly for the clinical translation constraints. The purpose was to safely generate heat at given times and on a particular scale the behavior of a nanomaterial under successive thermal hostages has been a focus of interest, for new bits for improved PCM stability. The vital interpretation of this paper is that nanomaterials should be counted upon for stability, in a way, whilst cyclic behaviors of PCMs can do so. Ensure that reliability of material can be depended upon for any other model. The deliverable of the study was to give thermal constancy. [F]or the review, the movie was [16] about

the forward steps of decellularized nanomaterial-based matrices. A considerable amount of stress was put on the long structural stability. A discussion on the exhibited mechanisms of degradation to construct the manufactured use against biomedical, is really important. In the long run, this fits conveniently into threads of concern centering on NEPCMs stability. The modus operandi of the study means support to the material lifecycle assessment. Cross-domain connectivity is an open thing.

Reference [17] presented an illuminating account of polymer composites recycling and upcycling options. This upcycling involves exploring sustainable materials. Notwithstanding, for the performance analysis to be done, considerable attention must also be focused on thermal and mechanical states of the recycled composites. These issues ornament appropriate consideration in sustainable PCM design. A prime focus was put on the lifecycle and reusability of such materials; therefore, the work elaborated on possible applications. That application couples the work to the energy storage endeavor meant for green energy. Now [18] channeled valuable information into such profound depths that it expends itself upon critical considerations about 3D-printed microfluidic sensors. Behaviors over thermal and fluids were tightly analyzed at the microscale after exiting the large scale PCM-oriented scopes. Nonetheless, their application for miniature thermal systems has been elucidated. The entire story of AMV stands for all of that. So, this route could possibly intersect with any PCM system out there. The research group in [19] realized that carbon-based nanostructured fluorescent biosensors could be established. Material synthesis and structural optimization were focused on. Carbon nanostructures have shown themselves to be stable and faring quite well in functionality tests. These qualities come with particular relevance for carbon-based NEPCMs. Dispersion and structural integrity were part of the subject matter. The investigation tends to follow indirectly from studies on carbon nanomaterial criteria in particular. Promising thermal potential remains among the challenges for learning.

Also, again in reference to scientific inquiry [20], monobody-based nanomaterial integration was instrumental. There showed to be a high degree of material specificity and robustness. Although the case considered was one of bio sensing, the compatibility considerations hold good elsewhere. Insights into long-term stability are particularly appealing. The work indirectly serves to fuel the materials engineering characteristic of NEPCMs. Some clear-cut findings focused on the surface interactions.

V. HYBRID NEURAL NETWORK–GREY WOLF OPTIMIZATION FRAMEWORKS

The study in [21] showed a combination of fuzzy-Neural Network, optimized by Grey Wolf Optimization. The said hybrid model demonstrates excellent convergence and enhanced accuracy. It has been found that GWO can efficiently adapt and adjust the parameters for a network. The whole framework surpasses conventional training methods for AI optimization. The less work applied to reach the dreams of original applications. Nevertheless, it reveals the underworked relationship of NN-GWO and potentialities legitimate for the suggested model. The research gives out the design of GWO-based neural net, which is a model used for predicting viscosity for nanofluid in [22]. The model had high prediction accuracy. Various parameter optimizations were successfully handled. The results are all very robust and very suitable for many applications of theoretical investigations. The implementation could be on NEPCM property prediction. Here the relevancy with thermal fluids becomes very strong. It confirms that thermophysical modeling must be done with AI. [23] SSAW-Layer GWO-Tuned Improved Prediction Precedent Performance: The first work presented sophisticated modeling for various kinds of nanoparticle-reinforced alloys' properties. Improvement in prediction precision was visible. On the microstructure and mechanical properties, especially, it brought effective modeling. The study thoroughly tested GWO for complex material systems; parameter tuning was easy. The application is mature to available NEPCM systems. Optimization benefits were fairly well manifested.

In [24], an AI-based power forecast framework was designed using restless waves under nano-electronic sensors. A sweet coincidence intrigued the trickle effect, whereby non-linear energy embeddings fit data very well. The system reliability and the forecast improved. AI techniques could well be crossed in this case with the application of a power system-oriented approach. Therefore, it is quite similar with respect to an optimization method applied to PCM monitoring. This, in turn, suggests the developing intelligent energy systems market. Optimization of the parameters of A Solid Oxide Fuel Cell was Carried Out by ANN–GWO, as proposed in [25]. Significant performance improvement was achieved with the help of GWO optimization, which is known to be effective in this case. By comb-lining with each other, the error margins were reduced. The framework was successfully validated with the strong test date for application development. The method could be utilized for the analysis of various phase-change materials. The energy system doesn't seem to be remote. [26] looked into AI models, testing the Application in ANM and, here, MOR, with some emphasis on GWO again. Here, again, the GWO-based models had better predictive capability. The ever-sophisticated adsorption behavior successfully forecasted, with one more point highlighting the general inclination of the robustness of the algorithm. Strategies for optimal multi-variable optimizations. Variability in applying the above recommended approach can be extended in studying the characteristics of AI for Materials w.r.t thermal properties. [27] described the use of Grey Wolf Optimization algorithm to build artificial neural network for estimating plant performance. The hybrid optimization was found superior to the traditional ANN. The detailed analysis was conducted on every system-level parameter, and it carefully illustrated in the study the scalability and robustness of the method. Since the study primarily focuses on water, the methodology

proved to be transferable. Therefore, developments in energy optimization should also be strong. This study offers opportunities for hybrid AI frameworks in material design. In a review from [28], applications of machine learning in the field of nanomaterial research were highlighted. There was a stressor on data-driven materials discovery. Predictive modeling and optimization were major subjects. Another topic of recent research effort and application of materials are projected. The importance to the optimization of NEPCMs is thus direct. The review strongly supported material design through AI. So the content really agrees with the topic of intelligent PCM growth. [29] established AI models for environmental quality prediction with GWO optimization. A good balance between prediction accuracy and robustness was achieved, with the capability of capturing complex nonlinear relationships among multiple predictors. The stabilization of the integrated framework was demonstrated. Although tailored to the analysis of environmental residuals, the methodological nourishment to apply to other areas is visible as multi-objective optimization. To strengthen the grounds for the effectiveness of the GWO, researchers must ensure careful, exhaustive study. For an investigation, [30] studied the heat exchange investigation-Nanos affluent-filled cavities using deep neural networks integrated with metaheuristic techniques. The amount of enhancement observed in heat transfer was very significant. Good integration of the AI hybrid models was observed to be the best in terms of providing further comfort when compared with traditional methods. Features of magnetic and Nano fluid application were captured accurately. The article provides significant evidence that AI can be applied successfully in thermal optimization. Application in NEPCM systems may be a competent approach. This work further buttresses the suggestion for the development of hybrid intelligent frameworks.

Table 2: Summary of Recent Studies on Nanomaterial-Enhanced PCM Systems and Intelligent Optimization Techniques

Ref.	Research Focus	Methodology	Key Contribution	Relevance to NEPCM & Intelligent Optimization
[1]	Nano-encapsulated PCM heat transfer	Deep Neural Networks	Classified thermal parameters and predicted convection and storage behavior	Demonstrates AI capability for complex PCM systems
[2]	PCM melting with fins	Numerical simulation	Showed metallic fins significantly enhance melting rate	Supports hybrid structural-material enhancement
[3]	Solidification in nano-PCM	Galerkin numerical method	Improved solidification uniformity using nanomaterials	Highlights nano-enhancement during solidification
[4]	Non-Newtonian nano-PCM melting	CFD with fins	Identified rheology and fin effects on melting	Shows coupled material-geometry influence
[5]	Solar water heating TES	LBM + experimental + 3E analysis	Accurate predictive thermal and sustainability modeling	Applicable to NEPCM-based solar systems
[6]	PCM heat sink performance	Experimental study	Optimized phase change temperature and orientation	Relevant to compact thermal management
[7]	PV/T collectors	Review study	Compared enhancement methods including PCMs and nanomaterials	Confirms benefits of hybrid enhancement
[8]	Nanoporous carbon transport	Lattice Boltzmann method	Revealed pore-scale diffusion mechanisms	Supports carbon nanomaterials in NEPCM
[9]	Nano-lubrication in porous media	Theoretical modeling	Showed nanoparticles alter transport behavior	Relevant to nanoparticle-fluid interaction
[10]	Latent heat prediction	ANN modeling	Accurate latent heat prediction for NEPCMs	Validates ANN for PCM property modeling
[11]	CNT-based smart composites	Experimental sensing study	Demonstrated stability of carbon nanomaterials	Supports durability of carbon-based NEPCMs
[12]	Nanomaterial stability	Review study	Addressed long-term compatibility and stability	Indirect insight into NEPCM durability
[13]	Nanomaterial functionalization	Experimental dissertation	Studied surface-material interactions	Relevant to nanoparticle dispersion strategies
[14]	Nanomaterial photothermal effects	Experimental analysis	Efficient nanoscale heat generation	Supports thermal effectiveness of nanomaterials
[15]	Cyclic photothermal stability	Experimental study	Addressed thermal consistency under cycles	Relevant to PCM cyclic performance
[16]	Material compatibility	Review study	Emphasized structural and chemical stability	Aligns with NEPCM stability concerns

VI. APPLICATIONS OF INTELLIGENT-OPTIMIZED NEPCM SYSTEMS

SOLAR THERMAL ENERGY STORAGE :- These power suppliers can accumulate maximum solar power in a device without allowing the device to run out of energy, facilitating day-hours operation and power generation.

BUILDING HEATING AND COOLING APPLICATIONS:- Lowering energy consumption, LEED requirements of a commercial building, could be described as contributing significant increments to systems that factor in and adjust extreme temperature variations.

ELECTRONIC AND BATTERY THERMAL MANAGEMENT :- Optimized NEPCMs provide effective heat dissipation in electronics and batteries, preventing overheating and extending operational lifespan.

INDUSTRIAL WASTE HEAT RECOVERY :- NEPCM-based systems enable efficient capture and reuse of industrial waste heat, improving process efficiency and reducing overall energy losses.

VII. CONCLUSION AND FUTURE WORK

This review comprehensively examined the role of intelligent optimization techniques in enhancing the performance of nanomaterial-enhanced phase change material (NEPCM) systems for advanced thermal energy storage applications. The review adds that importance of various nanoparticles, specifically metallic, metal oxides and carbon-based nanostructures, in discussing their respective advantages and limits in their enhancement of PCM. The system performance of NEPCM strongly depends, in an intertwined manner, on the nanoparticle type, concentrations, dispersion stability, encapsulation methods, and operating conditions. Furthermore, the complexity of these interactions does not allow for standard interfacing with classical modeling and optimization processes.

Techniques guided by intelligence, specifically through modern applications like artificial neural networks and Gray Wolf Optimization, have emerged as very successful tools in both forecasting and parameter tuning. Indeed, neural networks make accurate prediction of thermophysical properties and system performances, while Gray Wolf Optimization greatens the efficient exploration of huge design spaces to finalize the match of optimal parameters. Hybrid NN-GWO frames surpass all standalone methods in terms of accuracy, robustness, and converging behavior, being very applicable to NEPCM system optimization duty. Finally, the review's focus was manifold: it underlined that intelligent-optimized NEPCM systems demonstrated substantial sophistication; their potential applications ranged from solar thermal energy storage through building energy management and electronics cooling to the recycling of waste heat from industrial processes and smart energy applications; while challenges still remain, including issues relating to data availability, long-term stability, scalability, and real-time implementation. Future research might also focus on areas such as multi-objective optimization and experimental validation, in addition to their realization within the framework of smart control and IoT technologies—shining the way toward trustworthy and extensive adoption of NEPCM-based thermal energy storage systems.

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