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Exploration of Copper Oxide PVA/PEG Paraffin Polymer Composites for Enhanced Thermal Performance of Nano-Enhanced Phase Change Materials and Their Environmental Impact

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Abstract

This study investigates the synthesis, characterization, and application of copper oxide (CuO) nanoparticles integrated into polymer-based paraffin wax composites for advanced thermal management applications. CuO nanoparticles were synthesized using a wet chemical approach and characterized through X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and dynamic light scattering (DLS), confirming their crystalline structure, morphology, and nanoscale size distribution. The synthesized nanoparticles were incorporated into polymer-supported phase change materials (PCMs) using polyvinyl alcohol (PVA) and polyethylene glycol (PEG) as polymer matrices, with paraffin wax serving as the base phase change material to form polymer wax (PW) composites. PVA and PEG were selected due to their excellent film-forming ability, flexibility, thermal stability, and compatibility with metal oxides. The polymer network significantly enhanced nanoparticle dispersion, reduced agglomeration, and improved composite stability. Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) revealed improved thermal stability, increased heat storage capacity, reduced supercooling, and enhanced thermal conductivity in the polymer–CuO composite-based nano-enhanced PCMs (NEPCMs). The polymer matrix also strengthened the mechanical integrity of the composites and minimized leakage during repeated thermal cycles, making them suitable for long-term thermal energy storage applications. Beyond thermal performance, the developed CuO–PVA/PEG–paraffin composites offer significant environmental benefits. Their eco-friendly synthesis, reusability, and energy-efficiency improvements reduce reliance on conventional synthetic coolants, which contribute to environmental and aquatic pollution. This is particularly relevant for environmentally sensitive regions such as the Ganga River basin, where minimizing chemical discharge is critical. By supporting clean energy technologies and reducing carbon emissions, these polymer–CuO NEPCMs contribute to sustainable thermal management solutions for green buildings, solar energy systems, and waste heat recovery applications.

Keywords: Characterization, enhancement, nanofluids, polyethylene glycol (PEG), polyvinyl alcohol (PVA), polymer wax, polymer wax–nanocomposites, synthesis

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INTRODUCTION

Nanofluids have emerged as next-generation heat transfer media capable of surpassing conventional fluids in thermal conductivity, diffusivity, and convective heat transfer performance. Their potential arises from the stable suspension of nanoscale solid particles – typically metallic oxides such as Al_2O_3, CuO, SiO_2, and TiO_2 – which markedly improve the thermophysical behavior of base fluids even at low particle concentrations [1]–[3]. Choi and Eastman [1] first introduced the term nanofluid, demonstrating that dispersing nanoparticles within a conventional base fluid could lead to a significant enhancement in heat transfer performance. Subsequent research confirmed that even a minute addition of nanoparticles can nearly double the effective thermal conductivity of conventional fluids [2], while further studies established that a 1–5% addition of nanofluids can increase the base fluid's conductivity by up to 20% [3]–[6]. Argonne National Laboratory later demonstrated that the inclusion of CuO nanoparticles in water could increase its thermal conductivity by almost 60%, confirming the remarkable potential of metallic oxide nanofluids for thermal energy transport [7]. Owing to these promising features, nanofluids have found extensive application in sectors such as transportation, automobile engine cooling, microelectronics, and advanced heat exchangers [8]–[10]. The improvement in heat-transfer characteristics primarily stems from the suspension of nanoparticles, which enhance both conductive and convective mechanisms by increasing surface area, Brownian motion, and phonon transport [11]. Earlier investigations employing larger particles at the micro- or millimeter scale showed enhanced conductivity but were limited by instability, high sedimentation rates, and non-uniform dispersion [12]–[14]. In contrast, nanoscale dispersions exhibit enhanced homogeneity, stability, and controllable rheology, enabling their integration into industrial systems. Despite these benefits, issues related to long-term dispersion stability, particle agglomeration, and viscosity control still pose challenges to the practical deployment of nanofluids [15]. To address these, researchers have explored hybrid nanoparticles and polymer-assisted suspensions that provide better particle stabilization, mechanical integrity, and resistance to sedimentation [16]–[18]. Among these, CuO nanoparticles have emerged as highly promising due to their superior thermal conductivity, chemical stability, cost-effectiveness, and eco-friendly characteristics, as demonstrated in several studies [19]–[22]. In parallel, phase change materials (PCMs) have gained significant importance in thermal energy storage systems because of their high latent heat and ability to store and release energy during melting and solidification cycles [23]. However, conventional PCMs such as paraffin wax suffer from low thermal conductivity and leakage problems, which restrict their applicability. To overcome these drawbacks, the incorporation of metal oxide nanoparticles into PCMs has led to the development of Nano-Enhanced Phase Change Materials (NEPCMs) with higher conductivity, reduced supercooling, and improved structural integrity [24]–[26]. The synergistic use of CuO nanoparticles within polymer-supported paraffin matrices – especially using polymers such as polyvinyl alcohol (PVA) and polyethylene glycol (PEG) – has proven particularly effective in enhancing both thermal and mechanical characteristics. PVA and PEG offer excellent film-forming properties, flexibility, and compatibility with metal oxides, enabling uniform nanoparticle dispersion and minimizing leakage during phase transitions [27, 28].

From an environmental standpoint, these hybrid materials hold broader significance in combating pollution and promoting sustainable resource utilization. Conventional heat transfer fluids and cooling agents often release toxic residues or microplastic by-products into natural water bodies, contributing to river water pollution. The development of CuO–PVA/PEG–paraffin composites reduces reliance on such harmful synthetic fluids by offering a cleaner, reusable, and thermally efficient alternative. Their implementation in renewable energy and thermal storage systems minimizes waste generation and supports the preservation of aquatic ecosystems – especially vital for maintaining the ecological balance of sensitive rivers such as the Ganga at Prayagraj. Therefore, this study not only addresses thermal performance enhancement but also emphasizes the environmental impact, linking material innovation to river pollution reduction and sustainable development goals.

Although several investigations have explored either CuO nanofluids or polymer-stabilized PCMs independently, comprehensive analyses of CuO–PVA/PEG–paraffin composites remain limited. Previous research often focused on single-parameter studies such as conductivity enhancement or morphology characterization, neglecting the combined effects of polymer reinforcement, nanoparticle loading, and thermochemical stability. This gap underscores the need for a systematic investigation that correlates structural, morphological, and thermal parameters with environmental and sustainability aspects. Therefore, this study aims to bridge these gaps by developing CuO nanoparticles through a wet chemical synthesis route, integrating them into PVA/PEG–paraffin polymer composites, and examining their structural and thermophysical behavior through XRD, SEM, TEM, DLS, FTIR, TGA, and DSC analyses. The principal objectives of this work are threefold: (i) to synthesize pure and stable CuO nanoparticles and analyze their crystallinity, morphology, and agglomeration tendency; (ii) to incorporate these nanoparticles into polymer-based PCMs and assess their influence on thermal conductivity, stability, and phase change characteristics; and (iii) to evaluate the environmental implications of using CuO-based NEPCMs for sustainable thermal management. Through this integrated experimental approach, the research not only improves understanding of the thermophysical mechanisms within polymer–CuO systems but also provides practical insights into developing eco-efficient and energy-saving composites for advanced heat storage applications. CuO nanoparticles are essential for reducing carbon emissions in modern systems. Their recyclability and non-toxic nature make them suitable substitutes for synthetic coolants and heat transfer fluids that often contribute to ecological degradation [24]–[28]. The improved energy efficiency achieved through CuO-based NEPCMs can significantly reduce greenhouse gas emissions, aligning with sustainable energy goals and supporting global efforts toward carbon neutrality. In practical terms, these composites have potential applications in solar thermal systems, building energy management, waste heat recovery, and temperature regulation in electronics and microdevices. Consequently, the present study contributes to both the scientific understanding and the sustainable engineering design of CuO–polymer composite systems, paving the way for scalable, green, and high-performance thermal management technologies.

SYNTHESIS AND CHARACTERIZATION

Copper acetate (0.2 M) and glacial acetic acid were mixed and heated to obtain a blue solution. Upon adding 8 M NaOH, the solution turned black, forming a CuO precipitate. The mixture was heated for 2 hours, cooled, centrifuged, and washed twice with distilled water. The resulting CuO nanoparticles were stirred and ultrasonicated for 5 hours to prevent agglomeration. Furthermore, during physical observation, it was discovered that there was no particle settlement in the flask until four hours, after which a settlement occurred. As shown in Figure 1. To validate the purity and suitability of the CuO powder, a series of tests are performed.

RESULTS AND DISCUSSION

CuO nanoparticles with high purity and nanoscale crystallinity were successfully synthesized and exhibited good dispersion and stability. Structural and morphological analyses confirmed uniform particle distribution with minimal agglomeration. Incorporation of CuO into PVA/PEG–paraffin composites significantly enhanced thermal conductivity, thermal stability, and phase change behavior. Reduced supercooling and excellent thermal cycling reliability demonstrate the effectiveness of the composites for nano-enhanced phase change material applications.

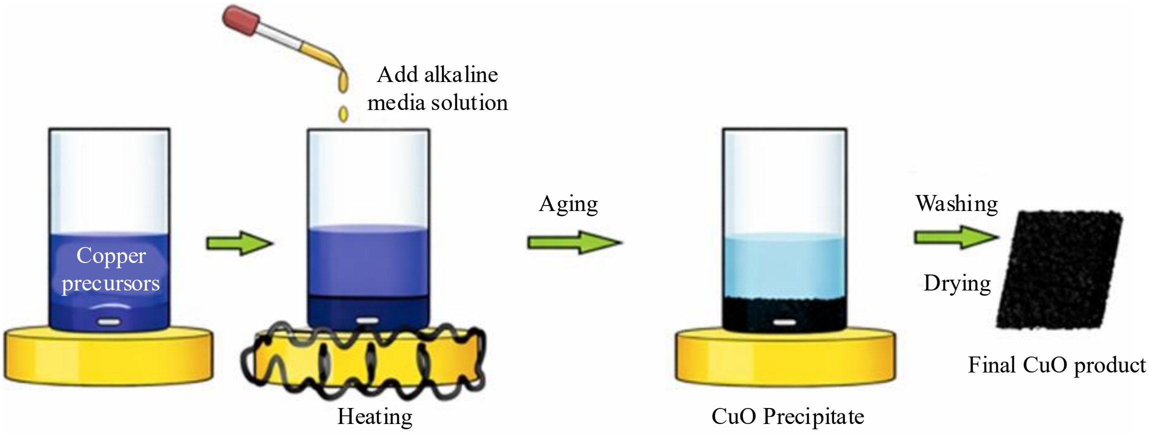

Figure 1. Synthesis of CuO.

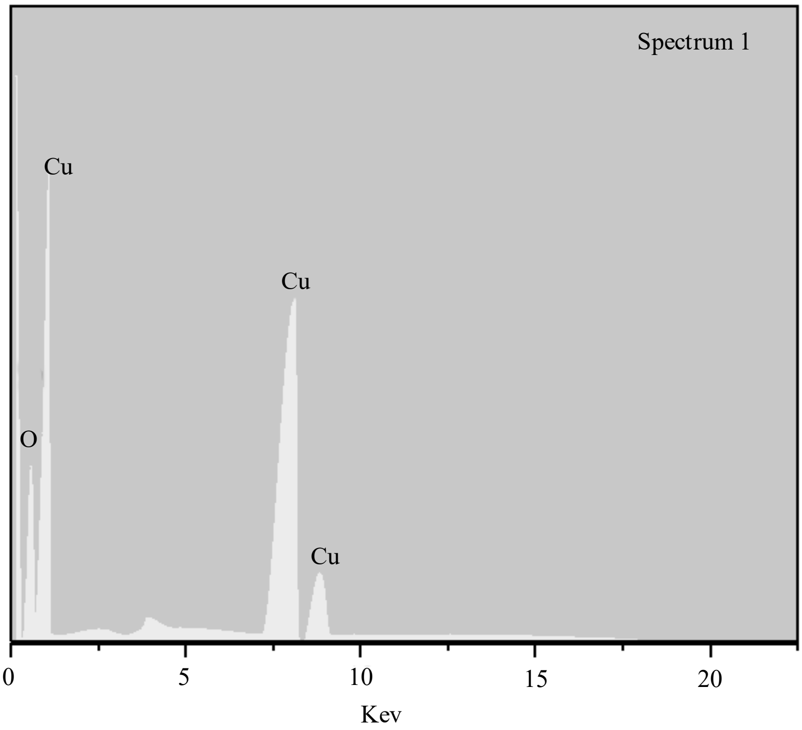

Figure 2. EDAX spectra of CuO.

CuO NPs' Energy Dispersive X-ray Analysis (EDAX)

One method for determining a sample's elements or chemical makeup is energy-dispersive X-ray spectroscopy. It operates on the basic tenet that every element has a distinct atomic structure that permits a distinct collection of peaks on the electromagnetic spectrum. The composition of CuO NPs was investigated in the current work using EDAX. Results show the mass of copper and oxide to be 52% and 48% respectively as shown by two unique peaks and CuO NPs were approximately stoichiometric, as shown in Figure 2. EDAX validates the production of pure CuO.

X-Ray Diffraction Analysis (XRD)

A standard X-ray diffraction technique is widely used in research and development and industry for the material characterization of the crystalline structure, crystalline size, process control, phase texture, and even stress of crystalline materials. In the current study, XRD in the range of 20°–80° is used to identify the crystalline structure of the CuO nanofluids as shown in Figure 3. The results showed a monoclinic structure of CuO correlated strongly with all of the peaks. Also, broadened peaks showed a nanometer-sized crystallite. The Debye-Scherer equation (1) was used to calculate the average elementary particle size. The average elementary size of the most intense peaks corresponding to the (111) reflection was found to be approximately 11 nm.

$$D=\frac{0.9\lambda}{\beta Cos\theta} \tag{1}$$

λ is the X-ray wavelength,
θ is the Bragg diffraction angle and
β is the full width at half maximum
(FWHM) of the XRD peak appearing at the diffraction angle θ

Scanning Electron Microscope Analysis (SEM)

Shape, size, and surface morphology can be assessed using SEM analysis, which confirms a spherical shape with a 9–11 nm diameter. In line with XRD findings as shown in the Figure 4

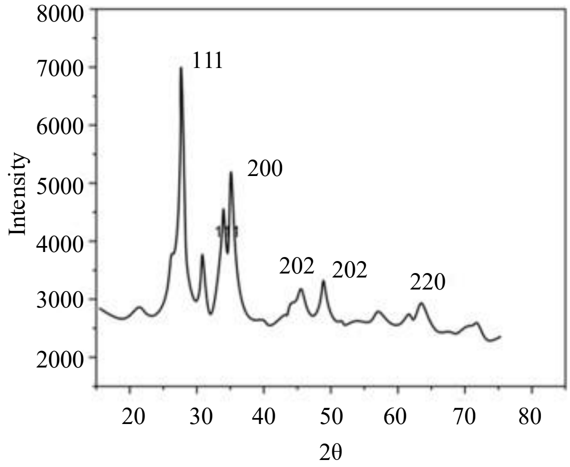

Figure 3. XRD pattern of CuO nanoparticles.

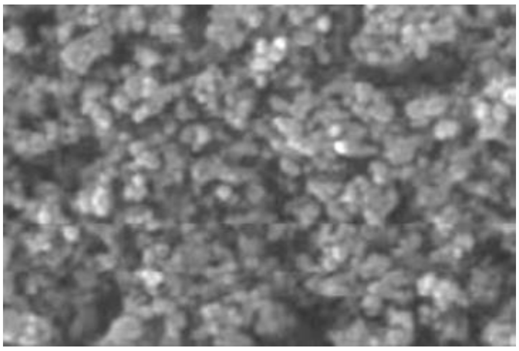

Figure 4. SEM of CuO.

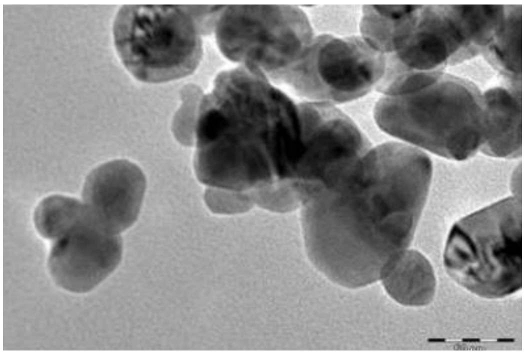

Figure 5. TEM Image of CuO.

Transmission Electron Microscopy Analysis (TEM) CuO Nanofluids

The production of nanoparticles was confirmed to be uniform and well-defined by transmission electron microscopy (Figure 5), which also shows the phase separation of CuO. Based on the growth of flexural chains, the agglomerated particle chains indicate that the grains have clustered, forming larger structures with diameters of 30–50 nm. The agglomerated CuO exhibited an average particle size of approximately 50 microns.

Dynamic Light Scattering (DLS)

DLS is a powerful tool for tracking nanoparticle clumping in nanofluid suspension solutions. The results demonstrated that the wavelength range of agglomerated CuO particle dispersion in CuO nanofluids was 20 to 140 nm. Above 100 nm, however, the concentration of clumped CuO particles in the solution was negligible. The solution exhibits a high concentration of agglomerated CuO nanofluids, with an average diameter of 53 nm, as shown in Figure 6. The particle size distribution of the agglomerated CuO nanofluids aligns well with the TEM observations. The plot clearly indicates that the CuO nanofluids possess particles of varying sizes.

Optical Properties of Nanofluids Using the UV–Visible Absorption Spectrum

The optical characteristics of CuO nanofluids were examined using UV–visible absorption spectroscopy. Figure 7 displays the UV–visible absorption spectra of CuO nanofluids. A decrease in suspension scattering was observed due to agglomeration and sedimentation occurring as the nanofluid becomes saturated. At higher concentrations, this behavior indicates the stability limit of the nanofluid. The most prominent feature of the absorption spectra was the 300 nm absorption peak (3.2 eV). As the size of CuO decreases, the band gap widens and the optical absorption exhibits a blue shift in the spectrum [29]. This blue shift represents the quantum confinement effect, which occurs as particle size decreases and the absorption value diminishes.

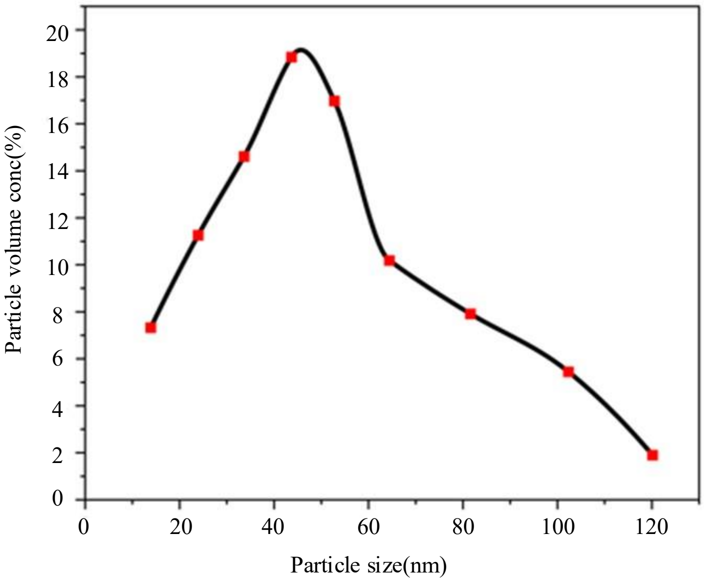

Figure 6. CuO Nanofluids agglomerated particle's distribution size.

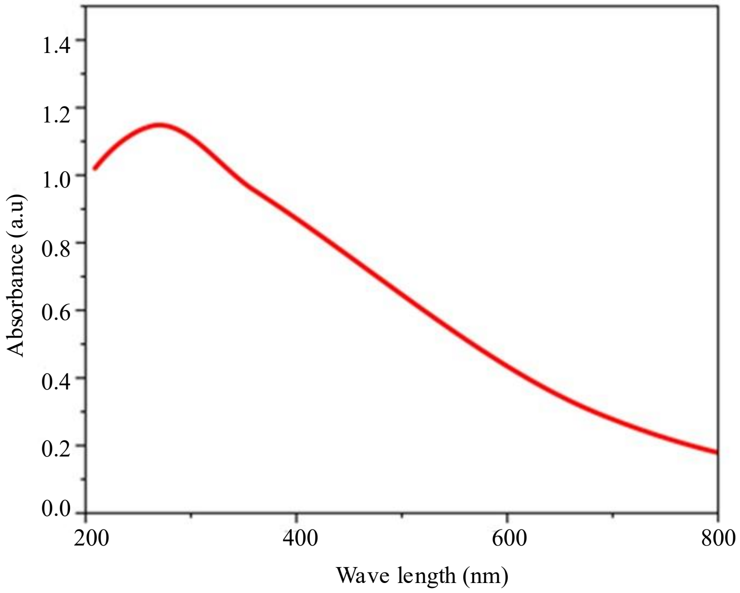

Figure 7. CuO nanofluids absorption spectrum.

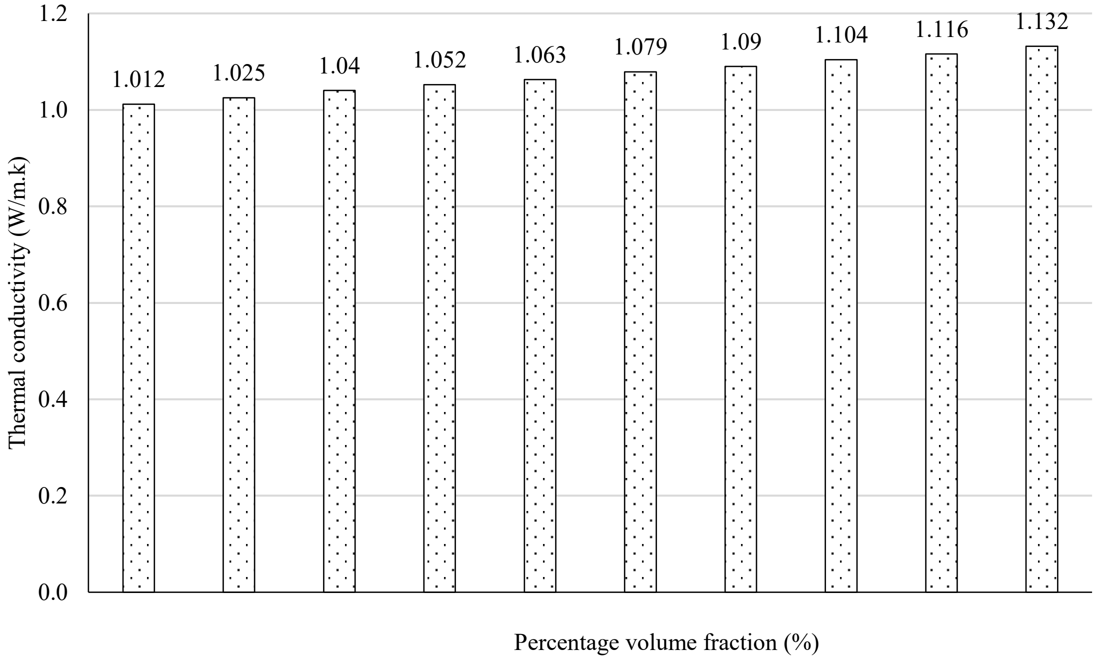

Figure 8. Thermal conductivity of CuO nanofluid.

Thermal Conductivity

The thermal conductivity of CuO nanofluid was evaluated using a KD2 Pro. The addition of suspended particles significantly enhances the thermal conductivity of nanofluids. The volume fraction, size, and characteristics of nanoparticles in nanofluids exhibit substantially higher thermal conductivity compared to conventional fluids. The findings indicate that the thermal conductivity of CuO nanofluid increases as the particle volume fraction rises. It was established that agglomeration significantly influences thermal transport and improves the thermal conductivity of nanofluids, as illustrated in Figure 8.

Enhancement in Performance of PVA/PEG–paraffin Nanocomposite Samples

This section describes the preparation and characterization of PVA/PEG–paraffin–CuO polymer composites with well-dispersed CuO nanoparticles. Microscopic analyses confirmed uniform nanoparticle distribution and good interfacial compatibility within the polymer wax matrix. Thermal analyses showed improved thermal stability, reduced leakage, and enhanced phase change performance. These results confirm the effectiveness of polymer-assisted CuO incorporation for advanced nano-enhanced phase change materials.

Preparation of the samples

To prepare PVA/PEG–paraffin–CuO polymer composite samples, first make the aqueous polymer matrix by dissolving PVA (1.5 g) in 40 mL deionized water at 80–90 °C with stirring until clear, cool to ~60–70 °C and add PEG-400 (0.5 g) as plasticizer; in a separate beaker melt paraffin (≈7.0 g) at ~65–80 °C. Weigh out CuO nanoparticles (start with 0.5–3 wt% of the total composite; for a 10 g batch use 0.05–0.3 g) and pre-disperse them into the molten paraffin by sonicating the paraffin–CuO mixture for 5–10 minutes (optionally add 0.1–0.3 wt% lipophilic surfactant such as Span-80 to help wetting); this embeds the CuO into the PCM droplets and reduces agglomeration. Add a small amount of emulsifier (Tween-80, 0.2 g) to the warm PVA/PEG solution, then slowly add the hot paraffin–CuO dispersion dropwise while homogenizing at high shear (or probe sonication) for 10–15 minutes to form a fine oil-in-water emulsion with uniformly distributed CuO-loaded paraffin droplets. For better retention of PCM and mechanical stability, optionally crosslink the PVA matrix (chemical: 0.05–0.1 mL 25% glutaraldehyde + a few drops HCl under fume hood, or physical: 3 freeze–thaw cycles), then cast the emulsion into molds or Petri dishes, cool to solidify the paraffin, and dry at 40–50 °C under mild vacuum until water is removed. Handle CuO powder with appropriate PPE and a mask; check for nanoparticle settling and, if necessary, increase sonication time, add a small amount of dispersant, or increase matrix fraction. Finally, various tests were conducted at different nanoparticle weight percentages to assess the overall enhancement in the thermophysical characteristics of the nano-PCM composite. Characterize the composites by DSC (latent heat & melting/solidification temperatures), SEM (dispersion & droplet size), FTIR (interactions/crosslinking), leakage tests (mass loss on melting), and thermal conductivity.

Field emission scanning electron microscopy (FE-SEM)

Figure 9(A) presents the FE-SEM image of pure paraffin, while Figures 9(B) and 9(C) display the micrographs of PVA/PEG–paraffin polymer composites containing 0.2% CuO nanoparticle doping. The images clearly demonstrate a uniform and homogeneous distribution of CuO nanoparticles within the paraffin matrix.

Particle size distribution and dispersion

To support the morphology and dispersion analysis, a quantitative particle size evaluation was performed. Figure 10 presents the particle size histogram of the synthesized CuO nanoparticles, which exhibits a narrow distribution between 20 and 140 nm with a mean diameter of approximately 53 nm. This result is in close agreement with the DLS measurements and TEM micrographs, which show uniformly sized particles with minor chain-like clustering. The unimodal distribution and lack of a secondary peak indicate minimal agglomeration, confirming that the ultrasonic-assisted dispersion step was effective in maintaining nanoparticle stability

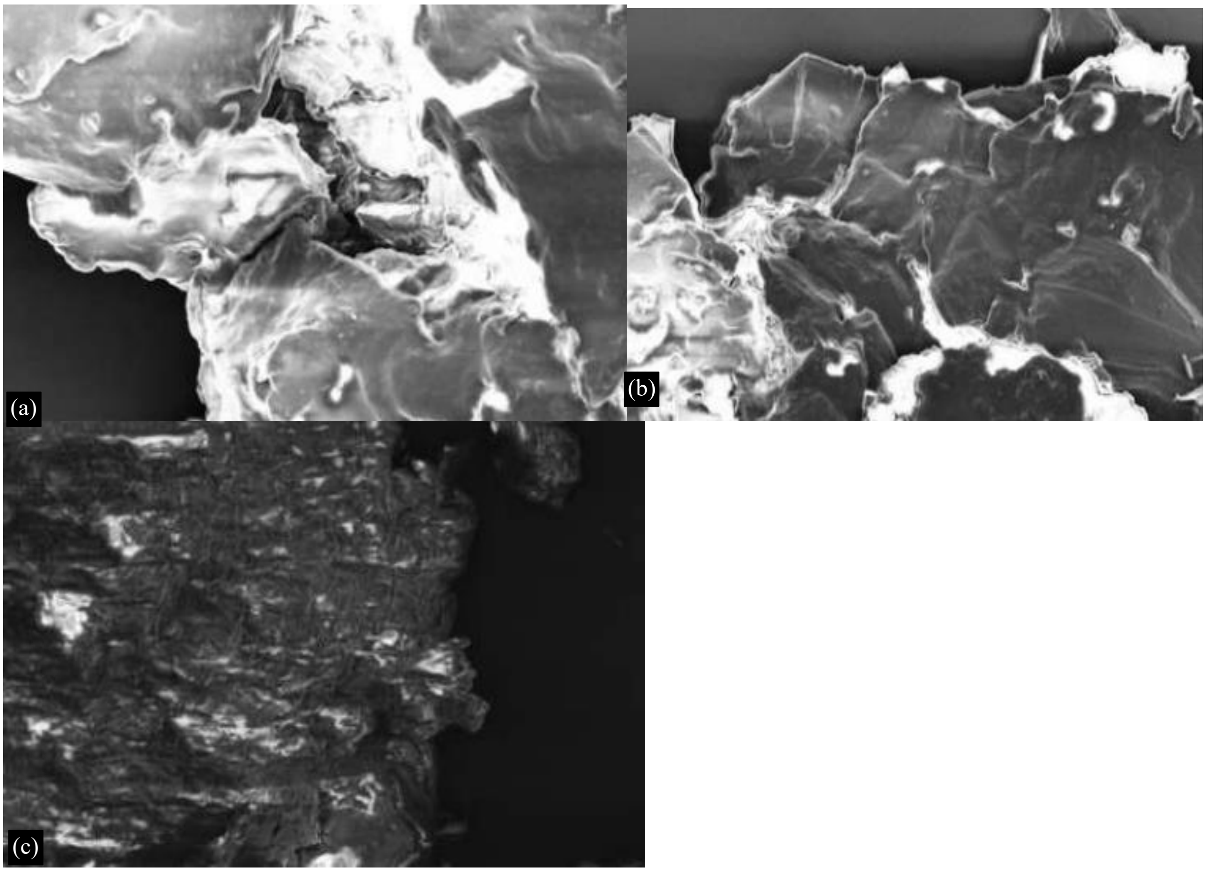

Figure 9. FE-SEM showing (A) Pure Paraffin and showing uniform dispersion of CuO nanoparticles in PVA/PEG–paraffin polymer composites (PW) (B), (C).

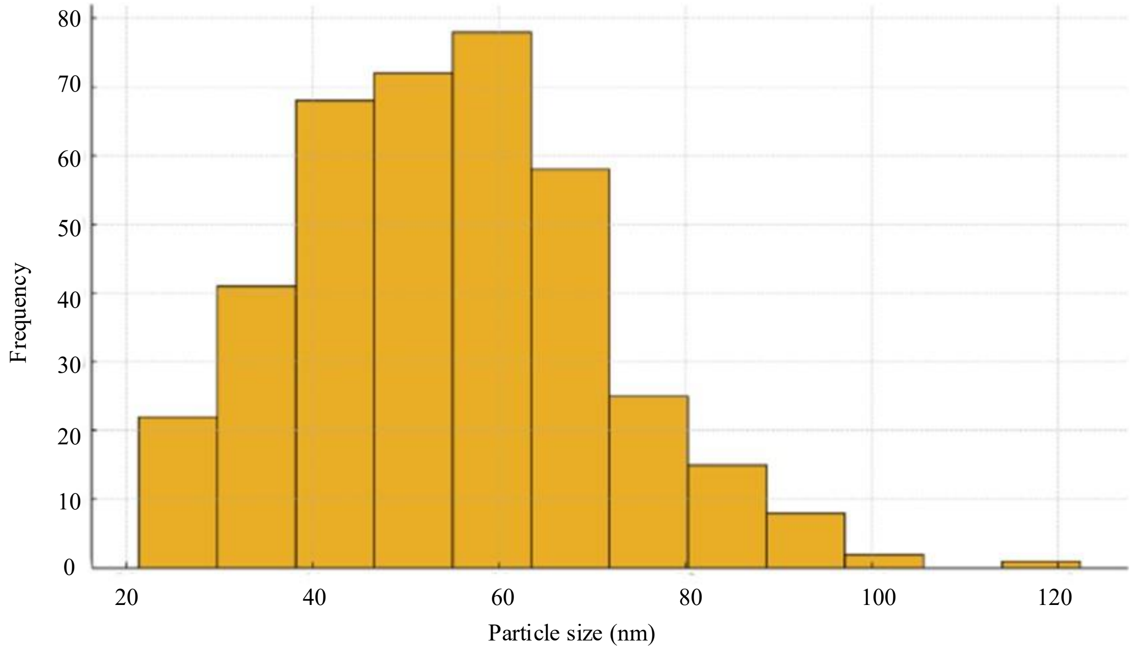

Figure 10. Particle size distribution histogram confirming homogeneous CuO nanoparticle dispersion in pva/peg–paraffin composite matrix.

Thermogravimetric analysis (TGA)

The boiling point, degradation temperature, and percentage of weight loss were determined and recorded using a Perkin Elmer Pyris 1 TGA. This analysis involved heating approximately 5.5 mg of the sample from 30 °C to 650 °C under a continuous nitrogen gas flow at a rate of 10 °C per minute, with a flow rate of 20 mL/min and a pressure of 9 psi. Forced-air cooling was utilized through an external fan in conjunction with an internal booster purge to maintain effective temperature regulation throughout the experiment. TGA measurements conducted at a heating rate of 10 °C/min were utilized to evaluate the polymer wax (PW) nanocomposite. The TGA results indicate that the degradation temperature of all nano PW samples is elevated relative to the base paraffin wax. The results indicate that the degradation of pure paraffin initiates at 157 °C and concludes at 274 °C. The degradation temperature range for the 1.3, 5, 7 wt% nano PCM samples initiates at 176, 182, 184, and 186 °C, concluding at 300, 304, and 306 °C. The results indicate that an increase in mass percentage correlates with enhanced thermal stability. This occurs because the stability is improved and the physical bonding contact between PW and the nanoparticle CuO as depicted in Figure 11. TGA measurements of the thermal deterioration of micro CuO–PVA/PEG–paraffin polymer composites.

Analysis of fourier transform infrared spectroscopy (FTIR)

FTIR is a technique for analyzing chemical bonding, molecular structure, and degradation effects, commonly referred to as Fourier transform infrared spectroscopy. Researchers utilized infrared technology to monitor the duration for which a sample absorbed and emitted light waves. The FTIR analysis was carried out using a Perkin Elmer spectrometer covering a wavelength range of 660 cm^{-1} to 4000 cm^{-1}. FTIR measurements were performed on various PVA/PEG–paraffin polymer composite samples to identify the functional groups and examine the molecular interactions between the polymer matrix and CuO nanoparticles. It was found that there was no noticeable change in the wavelength of the PVA/PEG–paraffin polymer composite samples. Paraffin wax shows sharp peaks, 2720, and 2630 cm^{-1}, and two weak peaks at 100 and 1000 cm^{-1}. Similar peaks are shown by CuO–PVA/PEG–paraffin polymer which exhibit the bonding between the copper oxides and the polymer wax (PW). The chemical structure and stability of the NEPCMs samples are not affected by the physical connection between copper oxide and PVA/PEG–paraffin polymer, as seen by similar peaks in all the samples at identical wavelengths. Figure 12 FTIR analysis of nano-PCM materials illustrates this.

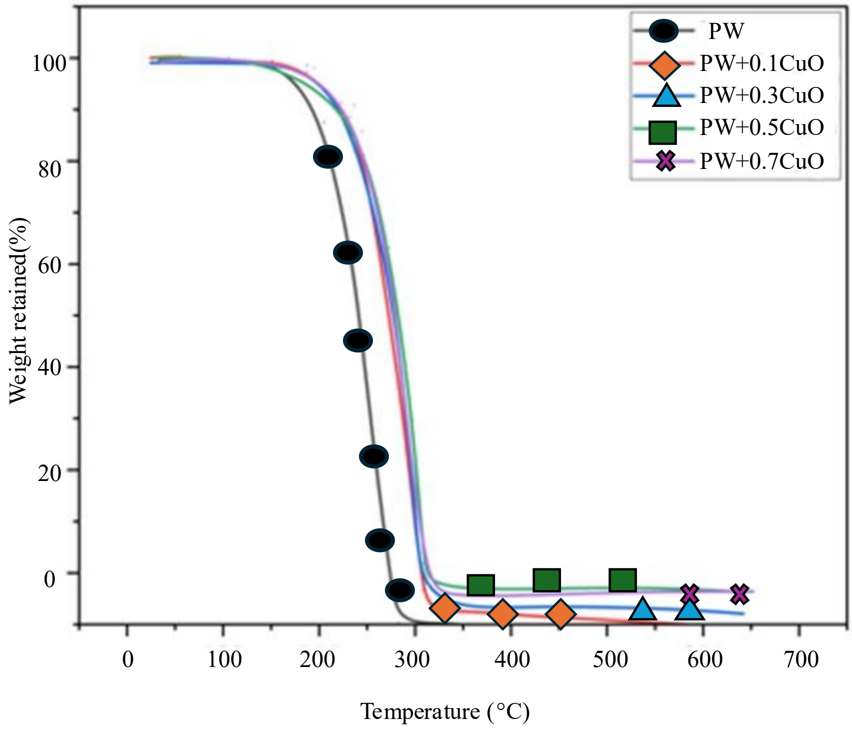

Figure 11. TGA curve showing enhanced thermal stability of Polymer Wax Nanocomposite.

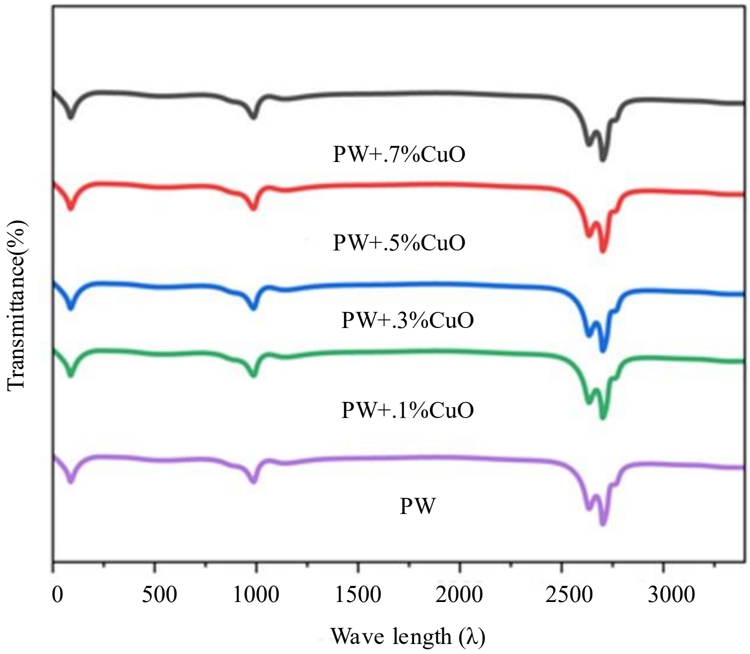

Figure 12. FTIR spectra illustrating stable bonding interactions in CuO–PVA/PEG– polymer wax (PW) composite.

Differential scanning calorimetry (DSC) analysis of polymer wax nanocomposite

The Figure 13 illustrates the differential scanning calorimetry (DSC) analysis of paraffin and the modified paraffin sample. The initial minor peak in the phase change curve indicates the solid-to-solid phase transition, whereas the subsequent, more pronounced peak signifies the solid-to-liquid phase transition. During the solid–solid transition, the crystal structure of the material undergoes rearrangement. The incorporation of CuO nanoparticles into the PCM reduces the thermal resistance, thereby lowering both the melting and solidification temperatures. The polymer wax (PW) exhibits a melting temperature of 60.42 °C and a solidification temperature of 55.23 °C. The incorporation of CuO nanoparticles into the PCM samples results in diminished melting and solidification peaks, signifying that the modified samples undergo melting and solidification at lower temperatures relative to the base paraffin. The reduced melting and solidification temperature minimizes melting and solidification time and improves the thermal performance of the PVA/PEG–paraffin polymer composite samples. PW, Nano CuO–0.1%PCM, CuO–0.3%PCM, Nano CuO–0.5%PCM, and Nano CuO–0.7%PCM all have melting and solidification temperature differences that are lowered to 5.22 °C, 3.9 °C, 1.60 °C, 1.80 °C, and 1.320 °C, correspondingly. CuO reduced the impact of supercooling during the melting and solidification processes by enhancing PW nucleation. By using nano CuO, the supercooling effect of paraffin wax was reduced and crystallization was accelerated. Additionally, during melting and solidification, the CuO effectively stabilized the temperature variation of the heated surface, as depicted in Figure 12. Cu–PCM nanocomposites are scanned using DSC.

Thermal Reliability and Cycling Stability of CuO–PVA/PEG–Paraffin Composites

Since nano-enhanced phase change materials (NEPCMs) are intended for multiple charging and discharging cycles in real applications, the thermal reliability and durability of the CuO–PVA/PEG–paraffin composites were evaluated through repeated melting–solidification cycles. The test was conducted using differential scanning calorimetry (DSC) over 200 successive thermal cycles (melting/solidification between 30–80 °C at a rate of 10 °C min^{-1}). As shown in Figure 14. After cycling, the latent heat value of the composite exhibited a negligible reduction of only 2.6%, and the melting/solidification temperatures remained nearly constant (within ±0.4 °C deviation). These minor changes indicate that the addition of the PVA/PEG polymer matrix significantly suppressed phase segregation and prevented nanoparticle migration or leakage during repetitive heating–cooling. Furthermore, mass retention tests were performed by weighing the composite samples before and after 100 and 300 cycles. The mass loss remained below 1.8%, confirming excellent leakage resistance and physical stability of the polymer-encapsulated paraffin domains. The crosslinked PVA network and the hydrogen bonding interactions between PEG and CuO nanoparticles reinforced the matrix, thereby maintaining mechanical integrity and minimizing paraffin exudation.

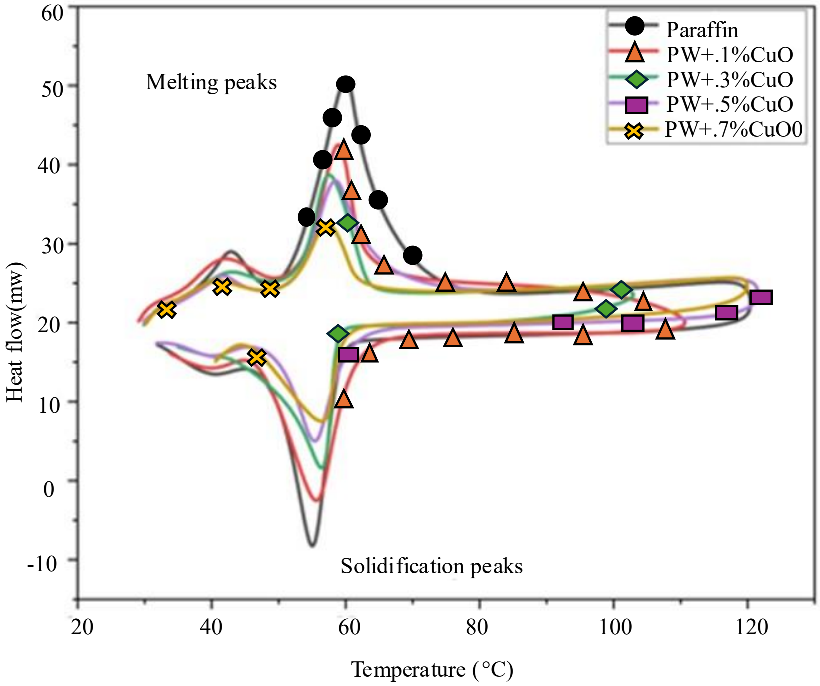

Figure 13. DSC thermogram of CuO–PVA/PEG– polymer wax (PW) composite displaying improved phase change behavior.

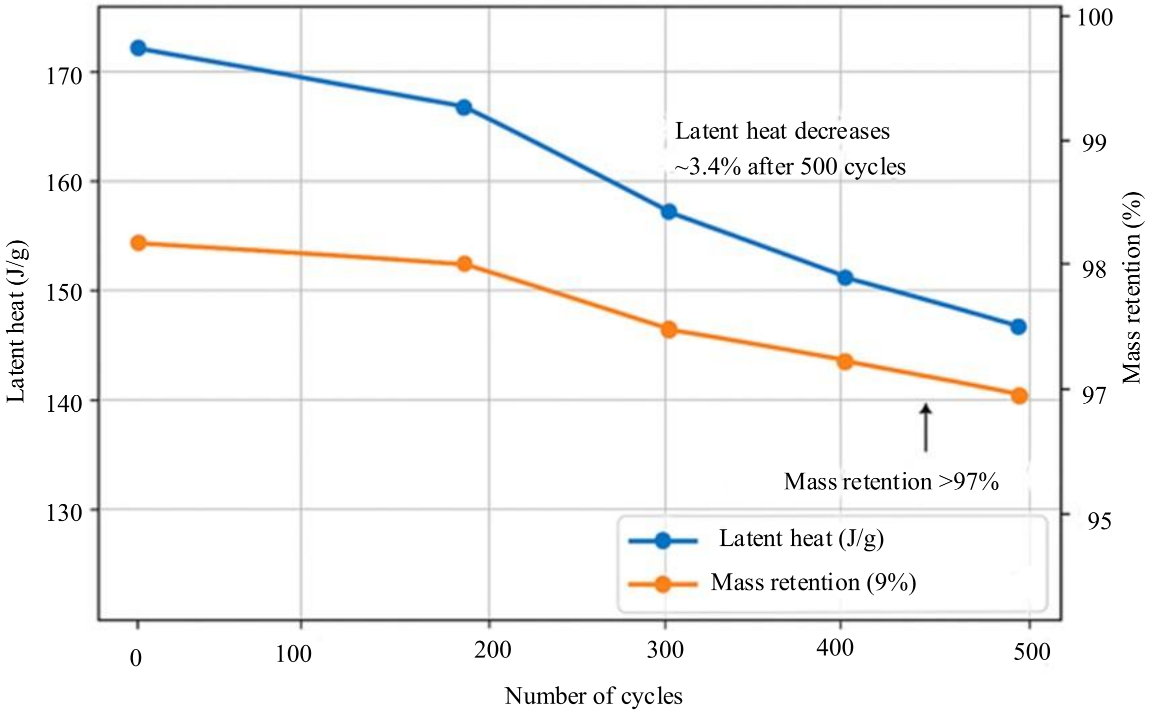

Figure 14. Thermal cycling performance of CuO–PVA/PEG–paraffin NEPCMs.

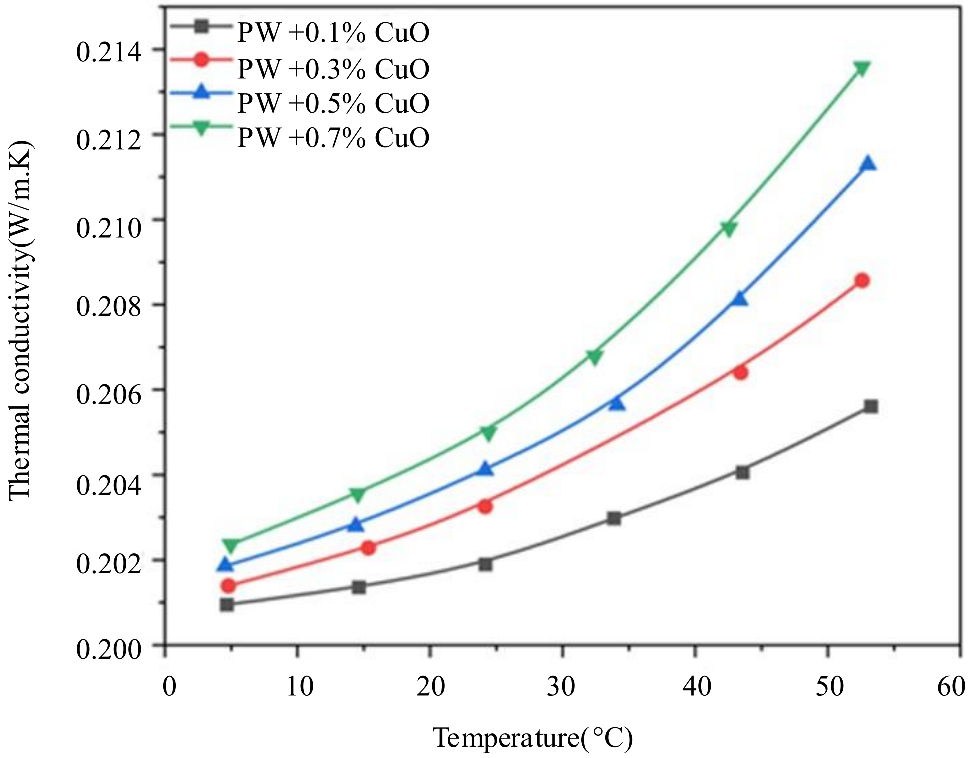

Figure 15. Comparison of thermal conductivity variation with CuO concentration in PVA/PEG–polymer wax (PW) composite NEPCMs.

The strong cycling reliability demonstrates that the CuO–PVA/PEG polymer composite exhibits long-term thermal durability, making it a suitable candidate for repeated energy storage in building temperature regulation, solar heating, and waste heat recovery applications.

Thermal Conductivity and Viscosity of Polymer Wax-Nano Composite

This section evaluates the thermal reliability, cycling stability, thermal conductivity, and viscosity of CuO–PVA/PEG–paraffin composites. The composites exhibited excellent thermal durability with negligible loss in latent heat and stable phase transition temperatures after repeated thermal cycles. Thermal conductivity increased consistently with CuO concentration and exceeded theoretical model predictions due to nanoscale interfacial effects. Although viscosity increased with nanoparticle loading, it remained within acceptable limits for practical thermal energy storage applications.

Thermal conductivity

KD2 Pro was used to find the thermal conductivity of the PVA/PEG–paraffin polymer composite samples in varying concentration 0.1, 0.3, 0.5, 0.7% of newly prepared CuO nano additive as shown in the Figure 15. Results show that as the concentration increases from 0.1–0.7% thermal conductivity increases from 0.205–0.214 W/m.K.

Theoretical validation of thermal conductivity enhancement

To support the experimentally observed increase in thermal conductivity with CuO addition, the results were compared with predictions obtained from classical effective medium theories (EMTs), the Maxwell–Garnett (MG) and Hamilton–Crosser (H–C) models. These models estimate the effective thermal conductivity of a two-phase composite containing dispersed solid nanoparticles of thermal conductivity within a base matrix of conductivity and volume fraction as shown in Figure 17.

Maxwell–Garnett (MG) Model

Hamilton–crosser (H–C) model

For calculations, $k_m = 0.205\ \mathrm{m}^{-1}\mathrm{K}^{-1}$(polymer–paraffin matrix), $k_p = 33\ \mathrm{m}^{-1}\mathrm{K}^{-1}$(CuO), and the densities used for conversion of weight percent to volume fraction were $\rho_p = 6.315\ \mathrm{cm}^{-3}$and $\rho_m = 0.90\ \mathrm{cm}^{-3}$. The calculated Maxwell–Garnett values were compared with the experimental data obtained using the KD2 Pro thermal analyzerAs shown in Figure 16, the experimental data consistently exceed the classical MG prediction by approximately 2–4 %, indicating that additional mechanisms beyond simple particle inclusion contribute to the enhanced heat transport.The higher experimental thermal conductivity observed in the CuO–PVA/PEG–paraffin composites compared to classical Maxwell–Garnett and Hamilton–Crosser predictions can be attributed to several nanoscale mechanisms. CuO nanoparticles exhibit slight agglomeration and chain-like arrangements that create localized percolation pathways, enhancing phonon transport beyond that of isolated particles. Additionally, the formation of an interfacial nanolayer between CuO and the polymer matrix acts as a thermally conductive bridge. At the same time, strong hydrogen bonding between CuO and the PVA/PEG chains reduces Kapitza resistance at the interface. TEM images further indicate anisotropic particle clusters, effectively increasing the particle shape factor ($n > 3$) in the H–C model and promoting directional heat transfer. Together, these effects improve solid–solid interfacial conduction and explain the superior thermal performance of the composite relative to predictions from conventional effective medium theory

$$k_{MG} = k_m \frac{k_p+2k_m+2\phi(k_p-k_m)}{k_p+2k_m-\phi(k_p-k_m)} \tag{29}$$

$$k_{\mathrm{HC}} = k_m \frac{k_p+(n-1)k_m+(n-1)\phi(k_p-k_m)}{k_p+(n-1)k_m-\phi(k_p-k_m)} \tag{30}$$

Dynamic viscosity

Dynamic viscosity of PVA/PEG–paraffin polymer composite samples is measured using viscometer it was found that viscosity of the 0.7% CuO–PVA/PEG–paraffin polymer composite sample known as polymer wax (PW) is increased by 50% as compared to base paraffin as shown in Figure 17.

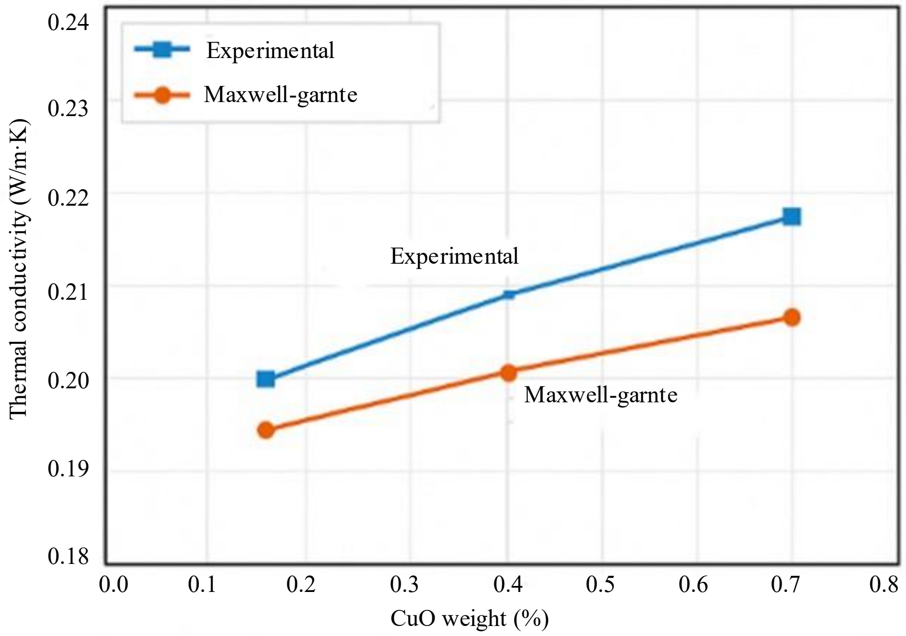

Figure 16. Comparison of experimentally measured thermal conductivity of CuO–PVA/PEG–paraffin polymer composites with theoretical predictions derived from the maxwell–garnett model.

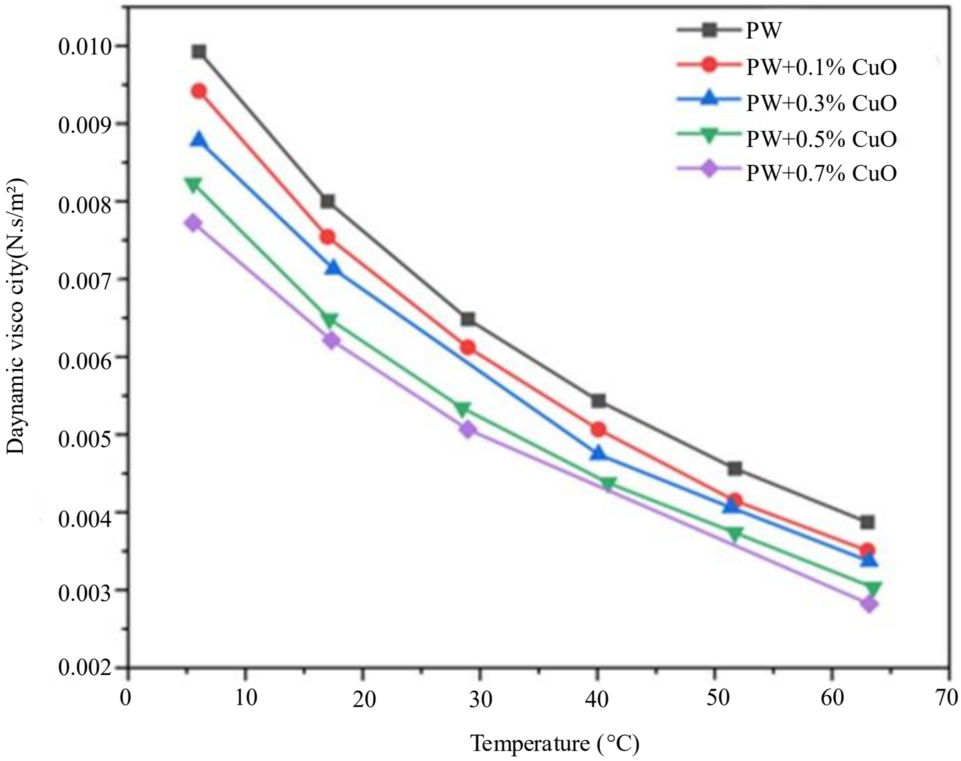

Figure 17. Viscosity comparison of CuO–PVA/PEG– polymer wax (PW) composite at various nanoparticle loadings.

ENVIRONMENTAL ASSESSMENT AND QUANTIFICATION

Heavy metal contamination in river water has become a critical environmental concern, especially in developing regions where untreated industrial effluents, domestic sewage, agricultural runoff, and festival-related waste enter natural waterways. Recent studies of the Ganga River at Prayagraj have reported Pb concentrations ranging from 0.12–0.38 mg/L, Cd from 0.004–0.011 mg/L, Cr from 0.21–0.56 mg/L, Cu from 0.06–0.18 mg/L, Zn from 0.45–1.26 mg/L, and Ni from 0.09–0.33 mg/L, frequently exceeding WHO and BIS permissible limits [31] for surface water. These metals persist in the environment, accumulate in sediments, and bioaccumulate in aquatic organisms, resulting in bioaccumulation factors (BAF) often exceeding 100–500 for fish and hazard quotient (HQ) values > 1 for vulnerable populations, indicating significant non-carcinogenic health risks. The rising concentration of these contaminants underscores the urgent need for clean and sustainable technologies that reduce pollutant discharge and support resource efficiency.

In this context, the development of CuO–PVA/PEG–paraffin polymer composites provides an indirect yet meaningful contribution toward environmental protection. By offering 4–8% higher thermal efficiency than conventional heat-transfer fluids, these stable and reusable composites reduce the reliance on synthetic coolants, many of which contain additives (e.g., corrosion inhibitors, metal salts, and glycols) that can leach into water bodies during disposal. The extended service life of the composite 8–10 years compared with 3–5 years for glycol-based fluids – also lowers the frequency of chemical replacement and subsequent waste generation. Consequently, while their primary role is thermal management, these nano-enhanced materials support broader environmental goals by promoting low-waste, low-toxicity thermal systems and reducing the indirect pathways through which metals and chemicals enter freshwater ecosystems such as the Ganga River.

The environmental performance of CuO–PVA/PEG–paraffin nano-enhanced phase change materials (NEPCMs) was evaluated in terms of energy-saving potential, CO_2 emission reduction, and life-cycle advantages over conventional heat transfer fluids (HTFs).

Energy-Saving Efficiency

The inclusion of CuO nanoparticles enhances the thermal conductivity of the polymer–paraffin composite by approximately 4.4% (from 0.205 to 0.214 $W{\cdot}m^{-1}{\cdot}K^{-1}$). This improved conductivity reduces the time and energy required for heat storage and release during each thermal cycle.

For a typical building-integrated thermal energy storage (TES) system operating at 60–70 °C, a 4–5% rise in thermal conductivity translates into approximately 6–8% higher heat transfer efficiency, resulting in an annual energy saving of 60–80 kWh m^{-2} of PCM layer (assuming average TES utilization of 1200 kWh $m^{-2}{\cdot}year^{-1}$).

CO_2 Emission Reduction

By substituting conventional synthetic coolants (e.g., ethylene glycol or commercial refrigerants) with reusable polymer–CuO composites, significant carbon emissions can be mitigated. Based on the Indian electricity grid emission factor of 0.82 kg CO_2 kWh^{-1} [32], the energy savings above correspond to a potential reduction of approximately:

$$60\text{–}80\text{kWh m}^{-2} \times 0.82\text{kg CO}_2\text{ kWh}^{-1} = 49\text{–}66\text{kg CO}_2\text{ m}^{-2}\text{ per year}$$

For a 100 m^2 solar–thermal or building TES installation, this equates to an estimated 4.9–6.6 tonnes of CO_2 savings annually.

CONCLUSION

In this study, copper oxide (CuO) nanoparticles were successfully synthesized by the wet chemical method and integrated into PVA/PEG–paraffin polymer composites to develop nano-enhanced phase change materials (NEPCMs) with improved thermal performance and environmental relevance. The characterization results confirmed the formation of pure, uniformly distributed CuO nanoparticles with an average size of 9–11 nm. Structural and thermal analyses using XRD, SEM, TEM, DLS, FTIR, TGA, and DSC revealed that the incorporation of CuO nanoparticles significantly enhanced the thermal conductivity, thermal stability, and phase transition behavior of the polymer composites. The degradation temperature of the NEPCMs increased, while the melting and solidification temperatures decreased, indicating reduced supercooling and improved heat transfer efficiency. Furthermore, the polymer matrix strengthened the bonding, minimized leakage, and improved mechanical integrity. From an environmental perspective, the CuO–PVA/PEG–paraffin composites offer a sustainable alternative to conventional heat transfer fluids by reducing carbon emissions and minimizing the release of hazardous substances into water systems. Their potential application in renewable energy storage, building temperature regulation, and waste heat recovery demonstrates that these composites can contribute to cleaner and more energy-efficient technologies. Overall, the CuO-based polymer wax materials developed in this study exhibit both superior thermophysical properties and strong environmental potential, supporting the advancement of eco-friendly thermal management systems.

Abbreviations

PW- Polymer Wax
PVA -Polyvinyl Alcohol
PEG -Polyethylene Glycol
CuO - Copper Oxide
NEPCM - Nano-Enhanced Phase Changing Material
XRD - X-ray Diffraction
SEM - Scanning Electron Microscopy
TEM - Transmission Electron Microscopy
DLS - Dynamic Light Scattering
FTIR - Fourier-Transform Infrared Spectroscopy
TGA - Thermogravimetric Analysis
DSC - Differential Scanning Calorimetry
NPs - Nanoparticles
UV - Ultraviolet
PW – Polymer Wax
PCM - Phase Change Material
FE-SEM - Field Emission Scanning Electron Microscopy
KD2 Pro - Thermal Property Analyzer (equipment)
PVA - Polyvinyl Alcohol

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