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Synthesis and Characterization of Paraffin Wax-Based Composite Phase Change Materials With Improved Thermal Properties for E-Vehicle BTMS

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Keywords: composite phase change material | energy storage | latent heat | phase change material | thermal conductivity

ABSTRACT

Phase change materials (PCMs) are increasingly essential in thermal energy storage (TES) systems (TES) because of their excellent energy storage density per unit volume, particularly in low- and medium-temperature applications. This investigation focuses on the improvement of advanced composite phase change materials (CPCMs) by integrating 20 wt% carbon quantum dots (CQDs) into paraffin wax (PW) to increase thermal conductivity. The CPCMs were synthesized using the ultra-sonication technique. The microstructural morphology of the PCMs and CPCMs was characterized using scanning electron microscopy (SEM). Thermal conductivity measurements were conducted using a Heat Flow Meter, while latent heat and melting temperature were determined through differential scanning calorimetry (DSC). The findings revealed an important enhancement in thermal conductivity with the addition of CQDs mixed with PCM matrix. Specifically, the addition of 20 wt% CQDs into PW increased the thermal conductivity to 0.452 W/m K and enhanced the latent heat by 10.4%. Furthermore, the CPCMs exhibited a larger and higher melting temperature range compared to conventional PCMs, highlighting their improved thermal performance.

1 | Introduction

Finding a solution to environmental problems such as pollution and energy scarcity requires the development of the latest technology. Maximizing the utilization of thermal energy has remained difficult owing to the fact that many different operating and material parameters are at work. Thermal energy loss commonly occurs through hot flue gases, power stations, and

Abbreviations: BTMS, battery thermal management system; CPCM, composite phase change material; CQDs, carbon quantum dots; DSC, differential scanning calorimeter; EG, expanded graphite; LHTEES, latent heat thermal energy storage system; MWCNT, multiwall carbon nanotubes; MWCNT, multiwall carbon nanotubes; PCM, phase change material; PW, paraffin wax; SEM, scanning electron microscope; TES, thermal energy storage.

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industrial processes. Thermal energy storage (TES) systems offer a solution by enabling the storage of both sensible and latent heat from unwanted heat sources [1]. Nonetheless, the intermittent nature of the renewable energy in many cases due to weather conditions, the intensity of solar energy, wind circumstances and so on, has necessitated the development of efficient technologies for the storage of thermal energy at a reasonable cost for optimum utilization [2]. This capability is particularly useful for the interconnection of such renewable assets such as solar and wind energy which have an erratic nature. The relevance of TES is explained by its ability to increase the efficiency of converting energy production to energy consumption, as well as minimize negative impacts on the environment, and further introduce cost-effectiveness in facilities [3]. A material's internal energy change through sensible heat, latent heat, and thermochemical heat enables TES.

TES exploits latent heat storage; PCMs provide the highest storage density and take up the smallest volume [4]. While latent heat storage uses PCMs that store large quantities of heat during phase change, most of which occur in solid–liquid transition. Thermochemical storage utilizes reversible chemical reactions to store and release energy [5]. PCMs are renowned for their great energy storage capacity and their ability to maintain an almost constant system temperature during phase transitions. This characteristic provides a distinct advantage over sensible heat storage materials, which require significant temperature fluctuations to achieve a similar storage capacity [6]. The energy involved in phase change is understood to depend on PCM properties. Organic and inorganic, PCM can be grouped mainly according to the type of material they possess [7].

Over the years, extensive research has been conducted on organic PCMs with the aim of developing advanced composite PCMs capable of performing multiple functions for thermal energy management systems [8]. Among the organic PCMs studied, PW stands out as one of the most versatile due to its wide range of melting temperatures. Its low cost, chemical stability, and non-toxicity make it suitable for various engineering applications, such as solar thermal energy storage, waste heat recovery in industries, and insulation in construction. PW is widely used in TES systems for latent heat storage [9, 10]. However, despite its high latent heat, PW's poor thermal conductivity significantly limits the heat transfer rate during charging and discharging processes. Additionally, the generalized structure of paraffin in its liquid phase restricts its effectiveness in engineering applications. To address these challenges, several approaches have been explored in the literature. One of the latest strategies involves incorporating nanoparticles with high thermal conductivity into PW to create composite phase change materials (CPCMs) and enhance its thermal conductivity [11].

One of the methods that significantly improves the thermal conductivity of PCM is a technique that incorporates nanometre-scale thermally conductive fillers including nanoparticles, nanofibers, nanotubes, and nanosheets [12]. Indeed, incorporation of metal oxides and metals enhances the PCMs' thermal conductivities, but it results in an increase of weight and subsequently the overall heat storage density reduction. This also leads to the destabilization of PCMs, thermally and chemically. Recently, carbon-based fillers such as carbon nanotubes, carbon nanofibers, graphite, and graphene have been incorporated to improve the thermal conductivity of PCMs [13]. However, the integration of these carbon-based nanomaterials into organic PCMs often leads to stability issues and a reduction in thermal conductivity [14]. Comparatively examined diverse forms of PCMs as well as assessed multiple schemes. It has been concluded that carbon-based additive particles have higher thermal conductivity than metal-based additives. Carbon-based nanomaterials are increasingly recognized as promising materials due to their exceptional chemical and physical properties, including high thermal and electrical conductivity, as well as high mechanical strength. These qualities extend its uses in different areas such as biosensors, energy conversion-storage devices [15]. Carried out experimental studies to study the cooling characteristics of a lithium-ion battery pack with PW incorporated with GPN (Graphene Powder), MWCNT (multiwall carbon nanotubes). They also pointed out that at all rates of discharge, the temperature was taken all the way below 50°C [16–19]. Compared to traditional carbon materials like graphene and CNTs, CQDs offer better dispersion due to their ultra-small size and abundant surface functional groups. This minimizes aggregation and thermal resistance while enhancing phonon transport. Unlike CNTs or graphene, CQDs can improve thermal conductivity without a significant increase.

CPCMs are gaining importance in battery thermal management systems (BTMS) due to their ability to effectively regulate temperature and enhance safety in electric vehicles. By addressing the limits of traditional phase change materials (PCMs) such as low thermal conductivity and leakage CPCMs incorporate materials like carbon fibre and expanded graphite, significantly improving both thermal conductivity and structural integrity. For example, one study demonstrated that a CPCM combining a styrene-butylene-styrene framework with carbon fibre fillers attained a thermal conductivity of 4.82 W/m K, ensuring excellent temperature regulation and anti-leakage performance [20, 21]. Another innovative approach involved a double-layer flexible PCM sleeve structure, which enhanced thermal management by reducing thermal contact resistance and improving adaptability across diverse climates. This system achieved a maximum temperature reduction of 14.5°C under specific conditions, demonstrating its effectiveness [22]. Beyond thermal management, CPCMs offer other advantages, including flame retardancy and electrical insulation, making them a promising solution for mitigating thermal runaway risks and enhancing the safety of electric vehicles [23]. Recent advances have explored various strategies to enhance the thermal and structural performance of PCMs. For example, multi-walled carbon nanotubes (MWCNTs) have been uniformly dispersed in paraffin wax (PW) to form cross-linked PCM coatings applicable to diverse substrates such as fabric and metal, achieving outstanding mechanical properties with an elongation at break of 105% and high enthalpy of 177.8 J/g, even at temperatures above the polymer's melting point [24]. In another study, Ag nanoparticles anchored onto carbonized melamine foam (CMF), followed by CdS deposition, resulted in strong interfacial bonding, enabling a CPCM with 96.1% PEG loading, 94.6% photo thermal conversion efficiency, thermal conductivity of 0.61 W/m K, and excellent antimicrobial performance,

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indicating its suitability for seawater evaporation and thermal management in medical devices [25]. Furthermore, UiO-66-NH_2 modified with amino groups enhanced phonon coupling and hydrogen bonding with stearic acid (SA), reducing thermal resistance by 42.46% and achieving a maximum enthalpy of 71.3 J/g without leakage, with results supported by molecular dynamics simulations [26]. The advancements in CPCMs for BTMS signify a breakthrough in achieving a balance of safety, efficiency, and adaptability, the way for the large-scale commercialization of electric vehicles.

The study developed a bio-based flexible phase change material (FPCM) using lauric acid. By incorporating styrene-ethylene-propylene-styrene (SEPS) and expanded graphite (EG), the resulting CPCM exhibited a 4.97-fold increase in thermal conductivity and significantly improved leakage resistance [27]. Adding 30 wt% ethylene-vinyl acetate (EVA) greatly enhanced the anti-leakage properties and shape stability of the CPCMs, allowing them to maintain their shape after 75 thermal cycles. When applied in a battery module, the CPCM reduced the maximum temperature to 49.2°C at a 4 C discharge rate, a 14.2°C improvement compared to natural convection. The maximum temperature difference within the battery module remained below 5°C during 4 C charge-discharge cycles, ensuring uniform thermal management [28]. The study also showed that composite-based phase change materials (CPCMs) enhanced battery module thermal management, with the expanded graphite (EG) composite lowering the maximum temperature by 4°C. Under 3 C discharge conditions, the module temperature remained close to 39°C, outperforming natural convection methods [29]. A novel shape-stabilized flexible CPCM with a thermal conductivity of 0.786 W/m K demonstrated excellent cycle stability, with only a 1.29% decrease in melting enthalpy after 500 cycles. During a 6 C discharge rate, the battery's maximum temperature was 43.64°C, with a maximum temperature difference of 2.39°C [30].

A study revealed that multi-walled carbon nanotube (MWCNT)-based nanofluids significantly improve the cooling efficiency of BTMS compared to pure water and binary fluid mixtures. A maximum temperature drop of 17.1°C was achieved at a 0.45% MWCNT volume fraction [31]. The proposed BTMS with CPCM attains an extreme temperature of 39.3°C and a 3°C temperature difference under 3 C charging, reducing liquid cooling operation time by 35.2%. At 10°C, it effectively preheats the battery, reaching 29.2°C with a 2.5°C temperature variance. This performance surpasses traditional liquid heating methods, demonstrating superior thermal management [32]. A new CPCM, consisting of paraffin, styrene-butadiene-styrene flexible support, aluminium nitride for improved electrical insulation, and expanded graphite to enhance thermal conductivity, provides a wide flexible temperature range of 25°C–60°C and remains stable through 500 thermal cycles [33]. Developed a novel CPCM that had a leakage rate less than 1% and thus demonstrated both high flame resistance and thermal performance for lithium-ion battery systems. Compared with the same discharge rate, the extreme temperature of batteries was under 50°C, with the temperature variance under 5°C. The maximum temperature and temperature difference decreased by 30.31% and 29.53%, respectively, at a 3 C discharge rate. The benefits of CPCMs in improving battery safety and performance are thus clearly revealed by these results [34].

An experimental investigation on PW/high-density polyethylene (HDPE) and expanded graphite (EG) ratio was conducted. Based on the results for 2 wt. % HDPE and 0.1, 0.3, and 0.5 wt % of EG, it was determined that the latent heat was decreased [35]. It was also incorporated 1%, 2%, and 3% mass fractions of CuO, TiO_2, Al_2O_3, and graphene to paraffin. These findings showed that the incorporation of nanoparticles into paraffin reduced the onset melting temperature and latent heat of the composites [36]. Thus, a series of experiments were conducted on PW and graphite PCM to enhance the thermal conductivity characteristics of PW. For 2%, 4%, and 6% weight percentages of graphite, they observed an impressive improvement in thermal conductivity of 170%, 190%, and 200%, respectively. Substantial studies have been performed in the area of promotion of PCMs thermal physical characteristics, using carbon materials for TES [37]. In carbon materials currently available, there are carbon tubes or carbon fibres, graphene or porous carbon networks, the new emerged carbon dots possess fluorescence properties inherently and thus are most suitable candidates for the fabrication of fluorescent functional PCM. The integration process is more beneficial when CQDs are included in PCMs as the latter have a remarkable thermal conductivity attributed to the nanoscale structure and the larger surface area which enhances the transfer of heat inside the composite PCM [38].

The enhanced thermal properties observed in CQD-doped CPCMs result from several synergistic mechanisms beyond the intrinsic high thermal conductivity of CQDs themselves. These mechanisms include improved phonon transport, reduced interfacial thermal resistance, and the formation of continuous thermal conduction pathways within the PW matrix. First, CQDs possess a nanoscale graphitic structure with a high surface area and good crystallinity, which facilitates phonon transfer across the matrix.

In addition to their inherently high thermal conductivity, CQDs significantly influence the overall thermal performance of the CPCMs through their interaction with the PW matrix and the reduction of interfacial thermal resistance. A scalable Joule-heating carbonization method was used to regulate the amorphous-to-graphitic phase ratio in polymer nanotubes, enhancing both electromagnetic wave absorption and thermal conductivity. Nitrogen species transformation during carbonization promoted polarization relaxation, defect generation, and dipole polarization, leading to improved charge transfer. The optimized material achieved a bandwidth of 3.46 GHz, and thermal conductivity up to 4.20 W/m K, demonstrating strong potential for next-generation electronics [39]. A robust, thermally conductive skeleton was fabricated by aligning graphene nanoparticles (GNPs) under a rotating magnetic field and optimizing sodium alginate (SA). Vacuum impregnation with n-docosane (C22) produced phase change composites (PCCs) with excellent thermal and energy conversion performance. At an optimal SA/GNPs ratio of 1:2, the composite exhibited a thermal conductivity of 16.567 W/(m K), electrical conductivity of 75.36 S/cm, and melting enthalpy of 172.2 J/g. Photothermal and electrothermal conversion efficiencies reached 88.51% and

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85.82%, respectively, demonstrating potential for renewable energy storage [40].

Recent advancements have further demonstrated the effectiveness of CQDs in paraffin-based PCM systems. Mai et al. reported that doping paraffin with CQDs significantly enhances thermal conductivity and photothermal conversion efficiency, leading to faster thermal regulation, particularly useful in confined electronic environments [41]. In addition, Liu et al. (2025) fabricated magnetic lignin/manganese ferrite-modified reduced graphene oxide carbon aerogels as a porous supporting network to encapsulate polyethylene glycol, achieving high thermal storage capacity and efficient multi-source-driven energy conversion [42]. These studies emphasize the multifunctional benefits of CQDs in PCM systems.

While previous studies have explored the enhancement of PCMs using various carbon-based nanomaterials such as carbon nanotubes, graphene, and graphite, this study introduces CQDs as a novel and multifunctional additive. Unlike conventional fillers, CQDs with ultra-small size (< 10 nm), high surface area, which facilitate better dispersion and enhanced phonon transport within the PCM matrix. Our results demonstrate significant improvements in both thermal conductivity and latent heat storage, confirming the superior energy performance of CQD-based CPCMs. Although we employed conventional techniques such as ultra-sonication, SEM, and DSC for synthesis and characterization, these methods ensure high reproducibility and reliable comparison with existing literature. The focus of this study is on material-level innovation using CQDs, with a strong potential for practical application in TES and battery thermal management systems.

2 | Materials and Methodology

2.1 | Materials

The PW granules used in this study were obtained from Metro Composites Pvt. Ltd., Chennai, India. The physical properties of PW include a melting point between 46°C and 59°C and a latent heat of 145.3 kJ/kg. The CQD powder used in this study was also purchased from Metro Composites Pvt. Ltd., Chennai, India. The thermophysical properties of the PW and the CPCM are shown in Table 1.

2.2 | Preparation of Composite Phase Material

In this study, the process involved melting the PW at around 47°C, to which CQDs were added in a ratio of 20% of the wax's weight. To produce a uniform distribution of CQDs and to avoid nanoparticle agglomeration. Before the ultra-sonication, the mixture was stirred at 500 rpm using a magnetic stirrer for 15 min to ensure initial homogeneity. The mixture was then subjected to ultrasonic treatment for 30 min at a frequency of 50 kHz and a power of 130 W. During the ultra-sonication process, the bath temperature was maintained at 80°C to keep the paraffin in a fully molten state and to promote uniform dispersion of the carbon quantum dots (CQDs) within the matrix. The molten composition was then lightly mixed and poured into silicon moulds and permitted to cool at ambient conditions until it solidifies. Then the samples were checked from surface points of view and only the perfect samples were used further in the experiment. Figure 1 illustrates the step-by-step sample preparation process conducted during the experiment.

2.3 | Characterization Techniques

2.3.1 | Differential Scanning Calorimetry

Thermal analysis, specifically differential scanning calorimetry (DSC), is a technique that measures the heat flow of a sample during heating or cooling processes. During a conventional DSC measurement, a sample weighing 1–20 mg is placed into a sample crucible, whereas an empty reference crucible is used to calibrate the system. The sample is heated or cooled at a flow rate using a specified purge gas, while a detector measures the difference in heat input between the reference and the sample, providing insights into the sample's energy properties. DSC works with different sample temperatures through the programmed sequence, and measures not only the temperatures of the sample material and position but also the heat that occurs from the temperature difference. This heat flow is then used for phase transition analysis and reactions. In this study, a Shimadzu Differential Scanning Calorimeter analyser, DSC-60 A, was used with an operating temperature range from 140°C to 600°C. For this test a 3 mg sample was placed in an aluminium pan to reduce the sample mass and prevent sample oxidation during the test, carried out under a nitrogen flow and with a temperature range 30°C–120°C and a heating rate of 10°C per minute. In the present assay, the DSC instrument had

TABLE 1 | Thermophysical properties of PW and CQDs.

Properties	Paraffin wax	Paraffin + 20% Carbon dots
Density of the solid phase (kg/m^3)	818	840
Density of the liquid phase (kg/m^3)	817	838
Melting temperature (°C)	46	53.3
Thermal conductivity (W/m K)	0.229	0.452
Latent heat (kJ/kg)	145.3	160.5
Specific heat (kJ/kg K)	1.81	1.52

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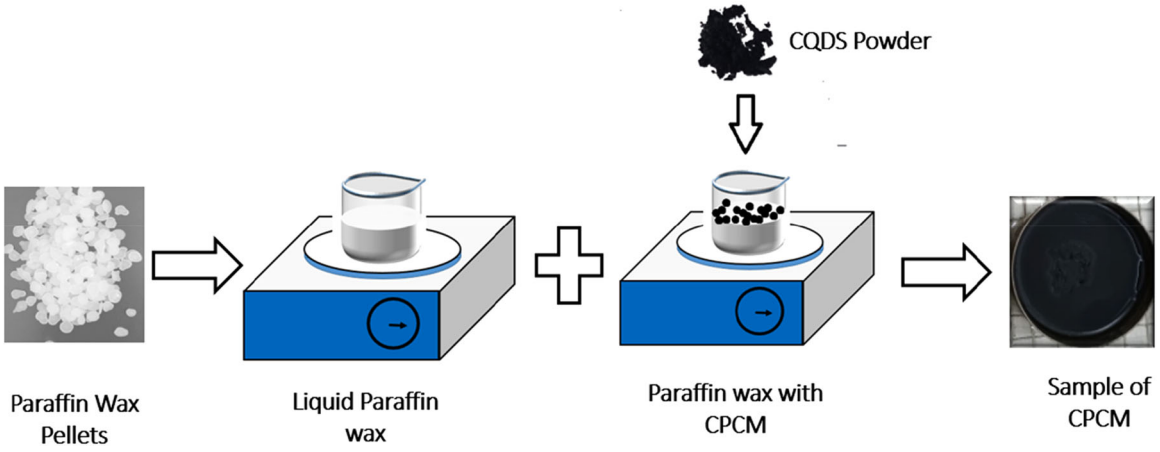


FIGURE 1 | Schematic diagram of the sample preparation for PCM and CPCM.

consistent measurement counts and high accuracy; the temperatures acquired had an error margin of ± 3% while the temperature variance was ± 0.2 K for heat flow and ± 0.02 K for the temperature.

2.3.2 | Scanning Electronic Microscopy

The scanning electron microscopy (SEM) of PW and composite samples was carried out using the HITACHI S-3800N SEM, whose magnifying power range was between 5 and up to 30,000 μm. The use of this technique offers a large amount of information concerning the form and surface properties of the materials. It permits seeing features of the material that are critical for its behaviour, such as surface roughness, grain boundary distribution and distribution of particles.

2.3.3 | Thermal Conductivity

Thermal conductivity was determined with the help of FOX 50 Heat Flow Meter. It was prepared in a sample holder with two shiny parallel plates, which are capable of heating control. These plates were kept at a constant but distinct temperature in order to develop a thermal gradient. Experiments were performed to study steady-state, one-dimensional heat transfer, and the thermal conductivity was determined using Fourier's law of heat conduction. The instrument operates within a temperature range of −10°C to 110°C and a testing range of 0.2–10 W/m K. For the test, the sample thickness was 3 mm.

3 | Results and Discussion

3.1 | SEM Analysis of Microstructure and Composition

SEM images of the surface morphological images were taken. For the preliminary observation of PW, the SEM image at 100 μm is provided in Figure 2. The microstructure analysis of PW indicates that it possesses a layered structure. The imaging was conducted in low-vacuum mode. SEM image at 20 μm of carbon dots powder is depicted in Figure 3.

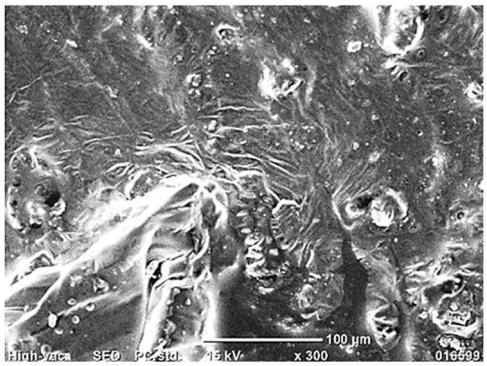


FIGURE 2 | SEM image of paraffin wax.

The wax material surface by SEM at 100 μm magnification shows a rugged, great surface profile with grooves, ridges and small pits, meaning that the material is heterogeneous. These features imply certain forms of processing-induced defects or shows crystallization during the solidification process. The structural properties can be seen at larger scales as well as at the micrometre scale, indicated by the 100 μm scale bar. This morphology is crucial to its application, operating successfully in technologies such as PCMs.

The SEM micrograph of carbon dot powder shows a scattered powder sample with an amorphous-shaped particle between the submicron ranges to nearly 20 μm in size as shown by the scale bar as shown in Figure 3. The particles have irregular shapes with the contours indicating high surface area and thus the particles may be useful. The sample image was taken in high vacuum at 15 kV with a secondary electron detector for better examination of surface structure. This was found to be due to the polydispersity, suggesting that there is variation in particle size, which may affect the behaviour of the material in particular uses.

Figure 4 presents SEM images of the composite PCMs under a broad perspective. These images effectively depict the extent of completion of incorporating CQDs in PW matrix and confirm the presence of CQDs in the composite. Besides, most of the images involved fluoresce characteristics of CQDs, the actual special advantages of CQDs in the images, which also proved

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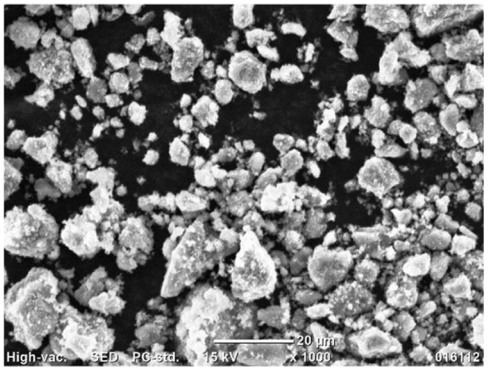


FIGURE 3 | SEM image of carbon quantum dots powder.

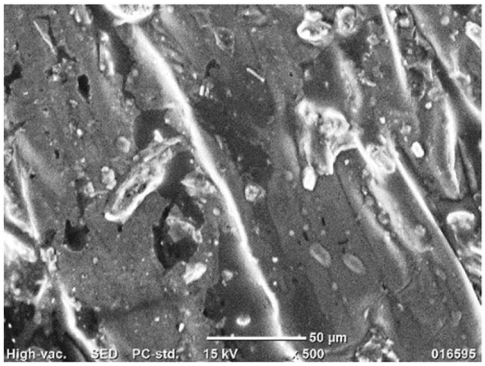


FIGURE 4 | SEM image of composite phase change material.

that CQDs could be incorporated into the composite PCMs effectively.

While the SEM imaging provided confirmation of the morphological integration of CQDs into the PW matrix, the study lacked a detailed correlation between these microstructural observations and the improved thermal properties listed in Table 1. The SEM images suggest effective nanoscale dispersion of CQDs, potentially offering higher surface area and more efficient phonon transport pathways. However, the direct link between this microstructure and the observed increases in thermal conductivity (from 0.229 to 0.452 W/m K) and latent heat (from 145.3 to 160.5 kJ/kg) remains insufficiently discussed. A more comprehensive interpretation could elaborate on how the dispersion of CQDs minimizes thermal resistance at interfaces, reduces agglomeration, and forms continuous conductive networks. Furthermore, the observed surface roughness and particle distribution may influence phase change dynamics, contributing to improved thermal cycling stability. Establishing these relationships would significantly enhance the understanding of structure–property correlations in CPCMs.

3.2 | Latent Heat of the PCM and CPCM

The energy storage capacity of the PCMs was assessed using the latent heat values obtained from the DSC analysis. The initial minor peak in the DSC curves corresponds to a solid-to-solid phase transition, while the subsequent prominent peak indicates the solid-to-liquid phase transition. The DSC graph,

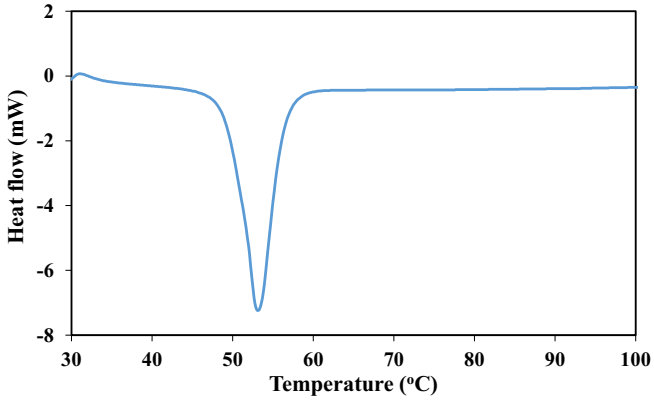


FIGURE 5 | DSC curve of paraffin wax.

shown in Figure 5, illustrates the thermal behaviour of the wax. The graph highlights an endothermic peak, indicating the melting transition of the wax. The onset temperature of the phase transition is observed at 46°C, with a peak temperature at 53.2°C and the process concluding at 59.0°C. This thermal profile demonstrates the energy absorption associated with the phase change, with the sharp dip in heat flow representing the melting point of the wax. Equation (1) can be used to determine the latent heat of CPCM [43].

It is important to highlight that CPCMs demonstrate significantly greater latent heat values than pure PW. Table 2 illustrates the latent heat values of PCM and CPCMs. This clearly emphasizes the superior energy storage capacity of CPCMs compared to PW. The latent heat increased from 145.3 to 160.5 kJ/kg after adding 20 wt% CQDs. The CPCM exhibited the utmost latent heat values to a 10.4% increase, when compared with the PW. The observed 10.4% increase in latent heat, despite the low intrinsic energy storage capacity of CQDs, warrants further explanation. This enhancement is unlikely due to the latent heat contribution of the CQDs themselves. Instead, it can be attributed to interfacial interactions and structural modifications introduced by CQD incorporation. The presence of CQDs may promote more efficient molecular packing and crystallization of paraffin chains during phase transitions, which can enhance latent heat storage. Additionally, the uniform dispersion of CQDs may create a more stable microstructure that reduces thermal resistance and facilitates more complete phase change. The substantially higher latent heat of CPCMs compared to pure PW underscores their remarkable energy storage capacity, making them ideal for diverse TES applications.

$$\text{Latent heat} = \frac{\Delta H_{\text{CPCM}} - \Delta H_{\text{PW}}}{\Delta H_{\text{PW}}} \times 100 \quad (1)$$

The DSC graph presents the thermal characteristics of a CQDs powder sample. A significant endothermic peak is observed, which agrees to the phase transition of the material. The transition begins at an onset temperature of 75.8°C, reaches its maximum at a peak temperature of 107.3°C, and concludes at an end temperature of 111.3°C, as revealed in Figure 6. This behaviour indicates the thermal energy absorption through the phase change, with the pronounced drop in heat flow marking the critical point of the transition.

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TABLE 2 | Latent heat values of paraffin wax (PW) and CPCMs.

Material	Latent heat (kJ/kg)	Percentage of enhancement
PW	145.3	0
20 wt % of CPCM	160.5	10.4

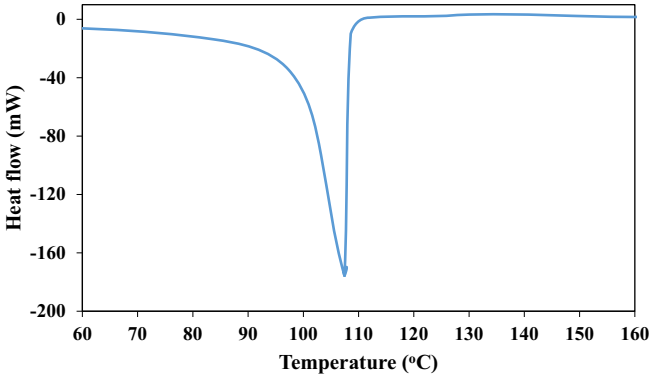


FIGURE 6 | DSC curve of carbon quantum dots.

The DSC graph presents the thermal characteristics of a wax and powder mixture. A significant endothermic peak is observed, which agrees with the phase change of the material. The transition begins at an onset temperature of 53.3°C, reaches its maximum at a peak temperature of 64.5°C, and concludes at an end temperature of 72.8°C, as revealed in Figure 7. This behaviour indicates the thermal energy absorption through the phase change, with the pronounced drop in heat flow marking the critical point of the transition.

3.3 | Thermal Conductivity

Thermal conductivity is a key property of material that defines the rate at which it conducts heat. Heat transfer efficiency of a substance depends directly on its characteristic behaviour. Identifying the thermal conductivity of PCMs becomes essential for performance evaluation in latent heat energy storage systems. PCMs feature a selective design because they contain mechanisms for transferring substantial energy quantities during transitions between solid and liquid phases. The effectiveness of TES and release processes depends on a PCM's heat transfer efficiency, which thermal conductivity determines directly. The appropriateness of PCMs for particular TES purposes depends on this critical information. Tests for thermal conductivity measurements of PW and its composites relied on a Heat Flow Meter testing system.

Temperature dependence of the coefficient of thermal conductivity has significance applications in enhancing the prospects of latent heat thermal energy storage systems (LHTESS). The study devotes considerable effort to learning how variations in thermal conductivity with temperature can improve LHTESS. Thermal conductivity versus temperature for PW and composites are shown in Figure 8, which represent behaviour of such variations.

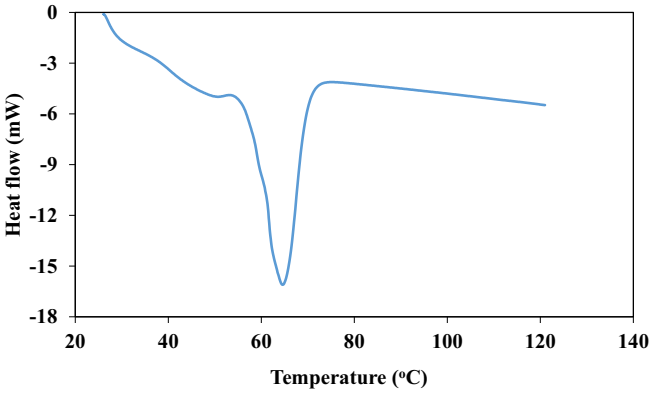


FIGURE 7 | DSC curve of composite phase change material.

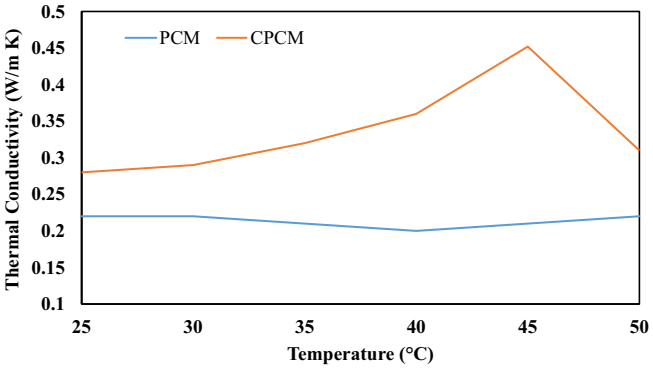


FIGURE 8 | Thermal conductivity of the PCM and CPCMs.

The analysis proves that thermal conductivity rises linearly with the rise in temperature from room temperature 25°C to phase-change temperature of 46°C. Most importantly, thermal conductivity is highly effective in the solid phase and is highest at about 46°C. Thus, the thermal conductivity of PCM depends on its matrix and includes phonon transport over a large spatial area in the perfect crystal lattice as well as the molecular structure of the PCM matrix. The maximum thermal conductivity enhancement of 97.3% was achieved with 20 wt% CQDs incorporated into the PW matrix.

With increasing temperature, the molecular vibration in the highly ordered and nonrandom arrangement of a solid increases also and hence the thermal conductivity increases. Whenever the temperature attains 46°C and the PCM changes its state to liquid, the rate of thermal conductivity decreases. During the liquid phase, movement of heat from high to low temperature points gives rise to variation in density and buoyancy forces in the bulk of the PCM that may lead to convection streams. Besides, in the liquid phase, the phonon transport is suppressed by the viscous forces, while the liquid convection also lowers the total thermal conductivity [44]. The conductivity coefficients of pure PW and its composites together with the enhancement ratios with reference to the measurement temperature of 55°C.

This study clearly shows enhancement of thermal conductivity in the composites containing CQDs as compared to the reference pure material PW. They found that the most remarkable increase was observed for the PCM composite containing 20 wt% of CQDs – the enhancement is reached by 0.452 W/m K and maximum latent

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TABLE 3 | Comparative study on the PW and carbon-based materials.

S. No.	Reference	Composite	Wt%	Thermal conductivity	Latent heat
1	George et al. [47]	Paraffin/polyaniline	0.1, 0.5, 1 and 5 wt.%	Thermal conductivity enhancements are 0, 20.6, 46.7 and 21.7%	Latent heat enhanced by 8.2% for 1 wt.%
2	Kumar et al. [48]	Paraffin/copper oxide	0.5, 1, 1.5 and 2 wt.%	Thermal conductivity enhancements are 50 and 95.5%	—
3	Jagadeeswaran and Sundaramahalingam [49]	Paraffin/copper	0.5, 1, 2 and 3 wt.%	Thermal conductivity enhancements are 7, 14, 24, and 30.5%	—
4	Balan et al. [50]	Paraffin/multilayer Graphene	0–10 wt%	Thermal conductivity enhancement is 150% @ 10 wt.%	Latent heat decreased slightly
5	Xie et al. [51]	Paraffin/HDPE/EG	HDPE-2% EG-0.1%, 0.3% and 0.5%	Thermal conductivity enhancement is 2.7 time of paraffin wax	Decreased by about 25%
6	Present work	Paraffin/CQDS	20%	Thermal conductivity enhancement ratio is 97.3% at 20 wt.%	Latent heat enhanced by 10.4% for 20 wt.%

heat obtained by 160.5 kJ/kg. This enhanced thermal conductivity coefficient shows the promise of the CQD-doped composite PCMs as a great effective material for heat transfer applications.

However, the long-term thermal reliability of these CPCMs remains to be evaluated. In practical applications, particularly those involving repeated thermal cycling, the retention of latent heat plays a vital role in determining material suitability. While our study demonstrated a maximum latent heat value of 160.5 kJ/kg, thermal cycling tests were not conducted. Previous studies have shown promising results in this regard. For instance, Cao et al. [45] reported over 87.7% latent heat retention after several cycles along with good chemical compatibility. Similarly, Yang et al. [46] achieved a high latent heat of phase change (134.54 J/g) and a low degree of super cooling (2.3°C). Their eutectic hydrated salt/melamine sponge (EHSs/MMS) composite material also exhibited excellent cyclic and shape stability. These findings underscore the importance of evaluating thermal reliability. Accordingly, in future work, we intend to perform accelerated thermal cycling experiments to assess the latent heat retention and long-term performance of CQD-based CPCMs. Table 3 shows the comparative analysis of paraffin-based composites with various additives.

4 | Conclusion

This experimental study aimed to investigate the thermal properties of PW–CQD composite PCMs. DSC and SEM analysis were performed on the composites, and the results were related with the base material as PW.

- Thermal conductivity of Composite PCMs was higher from that of PW. The maximum thermal conductivity values are recorded 0.452 W/m K for 20% wt. of CQDs.
- Investigation shows that thermal conductivity inside composites drops when the material transitions from solid phase to liquid phase.
- The maximum latent heat was obtained by 160.5 kJ/kg with 20 wt % CPCMs. This represents a significant improvement in energy storage capacity related to conventional PCMs.
- The solid state phase transformation, thermal conductivity and melting point of the composites are higher than that of PW, which suggests these composites can be effectively used for TES in low temperature application such as solar heaters, battery thermal management systems (BTMS).
- However, we acknowledge certain limitations in this study. Only one concentration of CQDs (20 wt%) was tested, and thermal conductivity was measured at select temperatures. Long-term stability, such as thermal cycling, was not assessed. Additionally, only SEM was used for characterization; techniques like XRD or FTIR could provide more insight into dispersion and structure. These aspects will be addressed in our future work.

5 | Future Scope

In previous studies, battery thermal management systems using materials such as MWCNT, graphene nanoplatelets, EG, and

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SWCNT have been shown to reduce temperature within an optimal range. The new CPCM developed in this study will be used in future BTMS, helping to improve the performance of battery packs, maintain the temperature within an optimal range, and effectively store thermal energy. These advancements will contribute to safer, more efficient and longer-lasting battery systems.

Symbols and Abbreviations

°C	temperature
kJ/kg	latent heat
mW	heat flow

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