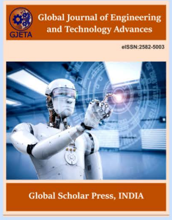
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(RESEARCH ARTICLE)

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Thermal and structural performance of graphene–paraffin phase change material composites for advanced energy storage applications

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Global Journal of Engineering and Technology Advances, 2025, 25(02), 156–165

Publication history: Received on 23 September 2025; revised on 02 November 2025; accepted on 05 November 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.25.2.0319

Abstract

Paraffin wax is widely recognized as a promising phase change material (PCM) for latent heat thermal energy storage (LHTES) systems due to its high latent heat, chemical stability, and low cost. However, its inherently low thermal conductivity limits the charging and discharging rates. To overcome this limitation, nanomaterials such as graphene, with ultra-high thermal conductivity, large surface area, and excellent mechanical strength, have been integrated with paraffin wax. This paper reviews in detail the application of graphene–paraffin wax nanocomposites. Various studies have reported conductivity enhancements with minimal reduction in latent heat, demonstrating graphene's superiority over conventional fillers. Emphasis is placed on experimental investigations, characterization techniques, and real-world applications in renewable energy, electronics cooling, and building materials. graphene–paraffin nanocomposites represent a transformative approach toward efficient thermal energy storage systems. Paraffin wax-based phase change materials (PCMs) are widely used in latent heat thermal energy storage (LHTES) due to their high energy density and chemical stability. Recent advancements demonstrate that incorporating graphene, a two-dimensional nanomaterial with ultra-high thermal conductivity and large surface area, significantly improves the heat transfer capability of paraffin wax while preserving its latent heat capacity. This paper reviews the role of graphene as a thermal conductivity enhancer in paraffin PCMs, with applications in solar thermal systems, building integration, industrial safety equipment, and electronics cooling.

Keywords: Photovoltaic Systems; Cooling Techniques; Nanofluids; Phase Change Materials; Electrical Efficiency; Thermal Regulation.

1. Introduction

The demand for efficient and sustainable energy systems has grown significantly with the increasing adoption of renewable energy sources. However, the intermittent nature of solar and wind power requires reliable energy storage methods. Latent heat thermal energy storage (LHTES) using phase change materials (PCMs) has emerged as a highly efficient solution. Paraffin wax, a common organic PCM, exhibits desirable properties such as high latent heat, chemical stability, and non-corrosiveness. Nevertheless, its low thermal conductivity (0.2–0.3 W/m·K) restricts its practical applications. Nanomaterials with superior thermal properties are increasingly used to address this limitation. Graphene, with thermal conductivity above 3500 W/m·K, is among the most promising nanofillers. This paper explores the integration of graphene with paraffin wax and its role in improving thermal energy storage performance. The growing global energy demand and the transition toward renewable energy systems necessitate efficient and reliable energy storage solutions. Thermal energy storage (TES) systems play a crucial role in balancing energy supply and demand. Among TES methods, latent heat thermal energy storage (LHTES) using phase change materials (PCMs) offers

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high energy density and near-isothermal operation. Paraffin wax is one of the most commonly used PCMs, but its low thermal conductivity (~0.2 W/m·K) restricts its charging/discharging rates. Graphene, with thermal conductivity exceeding 3500 W/m·K, provides an effective solution to this challenge by enhancing heat transfer pathways within the PCM matrix.Although paraffin wax has been widely employed as a phase change material (PCM) due to its high latent heat storage capacity, its practical application remains limited because of several shortcomings. The most critical issue is its inherently low thermal conductivity, which restricts rapid heat transfer and leads to reduced cooling efficiency in systems such as photovoltaic panels. Furthermore, paraffin wax suffers from leakage during the phase transition and exhibits volume expansion, which compromises material stability and long-term performance. a systematic exploration of graphene–paraffin composites remains scarce. In particular, limited data are available on the role of graphene's superior thermal and electrical conductivity in simultaneously improving heat dissipation and multifunctional energy storage capabilities. Moreover, most investigations are confined to small-scale laboratory testing without long-term durability assessment, optimized concentration studies, or comparative evaluation with other graphene derivatives such as graphene oxide or reduced graphene oxide.

Paraffin wax has very low thermal conductivity (\~0.2 W/m·K), leading to slow heat charging and discharging.It undergoes volume expansion and shrinkage during phase change, causing structural instability.Leakage during melting reduces reliability and demands costly encapsulation methods.Poor cycling stability results in phase segregation and loss of latent heat over time.Its narrow melting range limits high-temperature applications. Paraffin is electrically insulating preventing multifunctional thermal–electrical applications.

The objectives include investigating the influence of graphene loading on thermal and structural properties, evaluating leakage resistance and durability under repeated cycles, and analyzing its potential for enhancing photovoltaic panel cooling efficiency. Additionally, this study seeks to compare the performance of graphene–paraffin composites with conventional paraffin-based PCMs and propose an optimal design strategy for large-scale applications in energy storage, building cooling, and renewable energy systems.

In recent years, graphene–paraffin composites and graphene-based PCMs have attracted extensive research attention, with a steadily increasing number of publications reported between 2015 and 2025. The majority of these studies focus on enhancing the thermal conductivity of paraffin wax by incorporating graphene in different concentrations and morphologies. Graphene not only addresses the intrinsic low thermal conductivity of paraffin but also improves its structural stability and cycling reliability. Various applications of graphene–paraffin PCMs have been demonstrated, including photovoltaic (PV) panel cooling, electronic device thermal regulation, battery thermal management, and building energy efficiency. Reported studies also highlight improvements in latent heat storage, melting point stability, and heat transfer characteristics when compared with conventional PCMs. Collectively, the growing body of literature confirms that graphene-based PCMs represent a versatile and scalable approach for advanced thermal energy storage and thermal management systems

2. Literature review

Various methods have been tested to provide a cooler helmet environment for the wearer. Some of these include ventilation openings, battery operated forced convection and air-cooled systems using air blowers [1]. The inside space between head and helmet is very confined due to which the heat gets accumulated thereby increasing the teem-premature inside the helmet. For better comfort, the inner liner of the helmet shall have high thermal conductivity [2]. Under hot environ- mental conditions, the temperature within the helmet may rise up to 38 °C. This not only affects the physiological and/or psychological be- haviour of the worker but also decreases his/her concentration level to a greater extent. Thermoregulatory factors need to be managed for a better thermal comfort of the wearer's head, as it can have the impact on the whole body [3]. Thermal comfort management through head cooling plays an important role to avoid heat strokes [4].

Head protection is vital in any field of engineering. Industrial helmets are designed to protect head from injuries [5]. Besides head injuries, workers who are exposed to open sunlight require additional protection from unbearable heat [6]. Hotness is one of the factors that created a negative impression for wearers in tropical developing countries [7]. The increased level of discomfort was observed even at an ambient temperature of 16 °C [8]. An experiment conducted in Lulea University Sweden confirmed that even at cold temperature conditions, helmets can stimulate sweating due to the heat rejection from the wearer head. When the body is at rest, head releases one-third of the body heat [9]. The heat released from head can be stored using any one of the thermal energy storage systems namely the Sensible heat storage system, Latent heat storage system and Thermo-chemical energy sto- rage system. Among these, the Latent heat thermal energy storage systems (LHTES) have the ability to provide high energy storage density and are available in various temperature ranges at relatively low price.

Phase Change Materials (PCMs) belonging to LHTES can store more heat per unit volume (5–14 times) in comparison with the sensible heat storage materials, in addition to maintaining a constant temperature during the phase change process. As they can melt and solidify throughout the range of temperatures under study, PCM are good candidates for thermal energy storage [10]. Below are some of the studies reported with regard to the cooling applications of PCM. Heat pipe systems assisted by PCM are used for electronic cooling application. Behi et al. [11] reported that heat pipe utilizing PCM provides a maximum of 86.7% of the necessary cooling load within the required power range (50–80 W). The main consideration to be taken during the design process was overviewed and the different concept and design typologies of PCM storage were introduced and analysed [12]. The use of PCM with various approaches helped to maintain the temperature inside buildings within the thermal comfort range for occupants which in turn reduce the energy consumption [13]. Yet another interesting application of PCM is in cooling vest. Ouahrani et al. [14] found that an improved cooling effect can be obtained by covering the upper torso with a PCM of melting point 28 °C and covering lower torso with that of 18 °C. PCM thus helps to enhance an individual's thermal comfort [15]. One of the problems related to PCM is its performance getting af- fected due to its low thermal conductivity. By introducing the metallic foams, encapsulation, adding nanoparticles and expanded graphite, the thermal conductivity can be enhanced and thereby also the heat transfer rate [16]. Besides the mentioned techniques, some researchers proposed other efficient ways to enhance the heat transfer rate. Yang et al. [17] used annular fins in LHTES unit and found a reduction in the full melting time by 65%. Yang et al. [18] numerically studied the performance of porous metal foam on the heat transfer enhancement for a thermal energy storage tube and found an increase in the tem- perature response rate, heat flux and j-factor by 834.27%,774.9% and 5186.91% respectively. Yang et al. [19] in a experimental study on composite phase change material made by filling paraffin with foam copper of pore size 2–3 mm and 97% porosity found that addition of copper foam improved the heat transfer performance of PCM. Xiao et al.[20]in a study calculated the thermal conductivity of paraffin/copper foam and paraffin/nickel composite and found its enhancement. Zhang et al. [21] carried out both experimental and numerical investigations and reported the heat transfer characteristics of paraffin/copper foam composite. They found uniformity in temperature distribution and improved heat transfer rate. Yang et al. [22] explored the influence of orientation of PCM in the performance of metal foam composites. In their experiment, they studied the melting behavior of PCM at 0 °C, 30 °C, 60 °C and 90 °C. The results revealed that the orientation of PCM has a greater influence in its full melting time.

An additive enhances the thermal conductivity of PCM depending upon its concentration. When 10% by weight of Carbon Fibre (CF), Carbon Nano Tubes (CNTs) and Nano Graphene (NG) are added as additives, the thermal conductivity gets enhanced by an increase of 7.4 times for NG compared to the others. The enhancement order was given by NG > CF > CNTs [23,24]. The weight of the helmet should be minimum, to improve the comfort for the wearer. Since weight of the PCM is a concerning factor for industrial helmets the better option would be a PCM/NG composite. Copper, nickel and silver nanoparticles are excellent thermal conductivity promotors but they have weak thermal stability during phase change, high density and poor dispersion in PCM [16]. The thermal conductivity of PCM can thus be improved by adding nano-graphite of different weight percentage into it but at the expense of decrease in its latent heat [24]. The thermal properties of PCM can also be improved by adding Aluminium oxide and carbon black. Colla et al. [25] found that addition of aluminium oxide pena- lizes the thermal conductivity while the addition of carbon black im- proves it by 35% and 24% for RT20/CB and RT25/CB respectively. Another study to improve the thermal conductivity was conducted by using copper and aluminum oxide [26]. They found that the melting behavior of PCM and nano-PCM remains almost the same. A faster melting rate was observed for copper oxide nanoparticle than Aluminum oxide. Addition of Al, Cu, SiO_2, TiO_2, CNT, CNF, Al_2O_3, NaOH- KOH nanoparticles was commonly used with PCM to improve their thermo-physical properties [27]. Another study for thermal con- ductility was conducted using Al_2O_3, SiO_2, hydrophobic SiO_2 and TiO_2 [28]. Their results showed that thermal conductivity of hydrophobic SiO_2 is lower compared to hydrophilic SiO_2 when incorporated with PCM. For TiO_2, the thermal conductivity increased up to 3% by weight beyond which it started decreasing. Ji et al. [29] in their experimental work on PCM with ultrathin graphite foams reported that the thermal conductivity was improved by 18 times with a volume fraction of 0.8–1.2%, while the PCM melting temperature was not much affected by the addition of nanoparticles. Nano materials of 4% by weight of Carbon nano fibres can improve the thermal diffusivity and thermal conductivity by 1.77 times and 1.4 times respectively [30]. Investigate- tion on stearic acid–TiO_2 nanofluids as a phase change material was reported by Harikrishnan et al. [31]. They found that 0.3 wt% nano- particles, enhanced the thermal conductivity of base material by 70.53%. Unlike paraffin for certain phase change materials addition of nanoparticles like silica-alumina significantly increase the heat capacity of PCM. Addition of Al_2O_3 nanoparticles to paraffin reduced the latent heat of fusion and enhanced thermal conductivity [32].nanoparticles. Addition of surfactants, is an effective way to prevent the agglomeration of nanoparticles within the nanofluid [33]. But these surfactants are very sensitive to hot atmosphere and may produce foams at hot temperatures [34]. Excess addition of surfactants is not preferred because it causes a rise in viscosity of the fluid and reduces the thermal conductivity [35,36]. Long term self-stability for nanofluids is achieved by modifying the surface of nanofluids by introducing functionalized nanoparticles into base fluids, which prevents agglom- eration to a greater extend [37]. Passing ultrasonic waves through the nanofluid can also improve the stability of nanofluid by rupturing na- noparticle attractive force within the sediments [38]. Two types of ul- trasonic agitations are available namely the probe type and bath type among which the probe type can enhance more stability [39]. Stability of dispersed nanoparticles can be improved by changing the nano- particles surface on manipulating the pH of nanofluids [40,41]. Since the stability of nanofluids depends on the electro kinetic properties, altering the zeta potential value can promote its stability. The zeta potential value above +30 mv and below −30 mv is considered stable because zeta potential creates a repulsive force among nanoparticles which in turn increases the stability of nanofluids. Non-reactive alkaline or acidic solution can change the pH of the nanofluid [42]. Another application of PCM is found in motor cycle helmet cooling.

Comfort cooling is provided to the wearer's head as the PCM absorbs and stores the heat produced by the head [43]. Tan et al. [44] found that PCM integrated helmet can provide a cooling time for about 2 h. The design of a helmet cooling system for construction purpose is an- other application of PCM. A helmet incorporated with PCM and solar fan can provide a better working environment for the construction workers for longer period of time. Ghani et al. [45] found that the temperature at the inner channel was reduced from 47 °C to 40.6 °C and the PCM pad was maintaining at a temperature of 25 °C for more than 2 h.

A study reveals that n-eicosane (C20) / Expanded pearlite (ExP) composite with carbon nano tubes shows excellent thermal energy storage properties [46]. Thermal conductivity of ExP/C20 composite increased by nearly 113.3% by the addition of carbon nano tube (1% wt). PCM composite with 10% expanded graphite showed improved thermal conductivity and exceptional thermal energy storage properties [47].

2.1. Progress of Graphene & its composite research growth in last 10 year.

The Fig. 1 the trend in the number of research papers published on graphene composites from 2015 to 2025. It shows a steady increase in publications from around 20 papers in 2015 to nearly 200 papers by 2021, reflecting growing research interest in this field. The trend further accelerates, with publications crossing 250 in 2022, about 320 in 2023, and peaking at approximately 370 papers in 2024. However, in 2025, there is a sharp decline to nearly 150 papers, which may be due to incomplete data for the year or a shift in research focus. Overall, the graph highlights the significant rise in research activity on graphene composites over the decade, followed by a sudden drop in the final year.

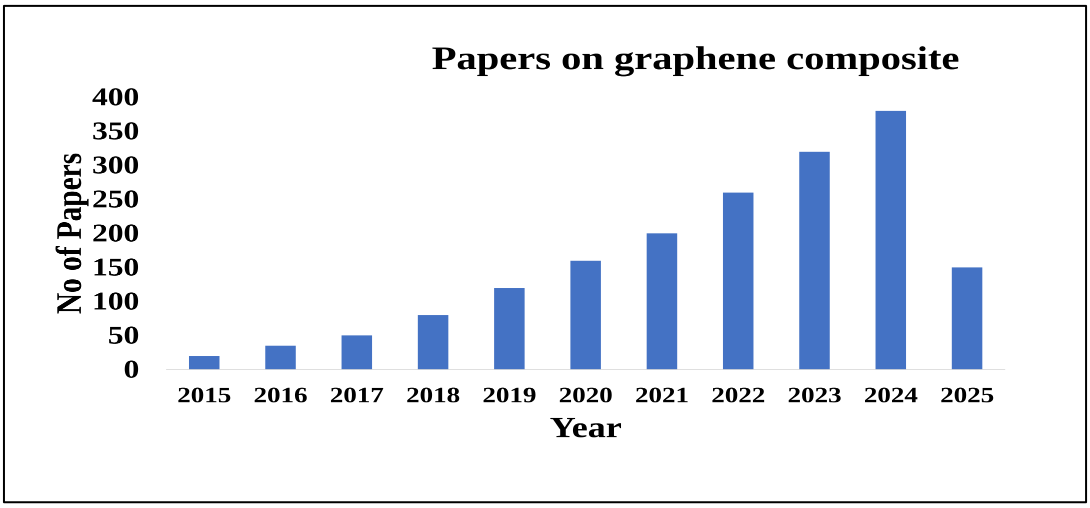

Figure 1 Papers published on graphene

2.2. Implementation of Graphene in thermal and energy storage management

Figure 1 presents the different applications of graphene across various fields. The largest share, 25%, is devoted to electronics and conductive inks, highlighting graphene's exceptional electrical properties. This is followed by energy storage and thermal management at 20%, and structural composites and lightweight materials at 15%, demonstrating graphene's potential in enhancing strength and reducing weight in materials. Sensors and flexible electronics account for 10%, while biomedical applications such as drug delivery and scaffolds make up 8%. Applications in coatings, corrosion protection, and EMI shielding represent 7%, whereas water purification and filtration catalysis and chemical processing, and other emerging applications each contribute 5%. Overall, the chart shows graphene's versatility with major applications in electronics and energy-related fields, while also expanding into biomedical and environmental sectors.

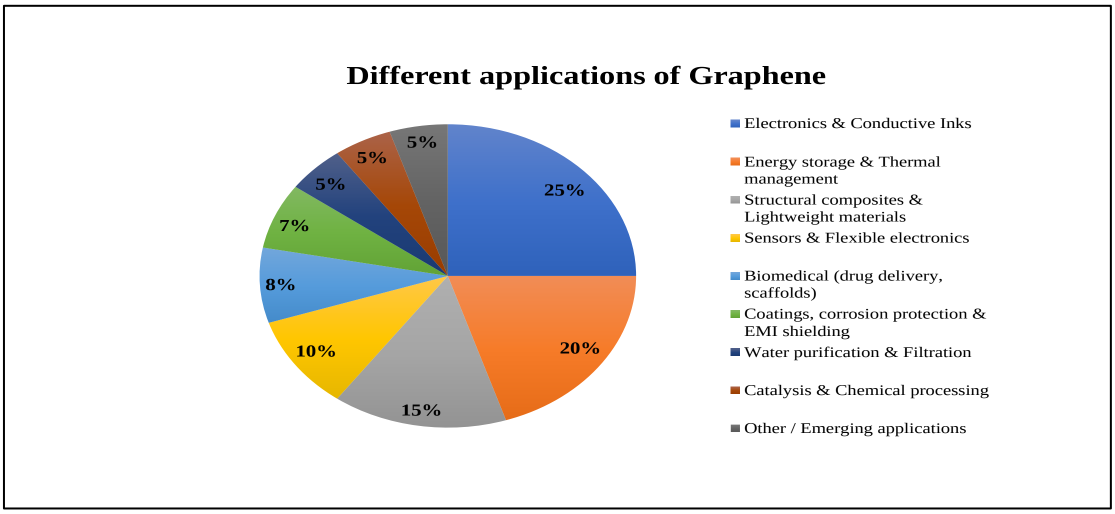

Figure 2 Different applications Of Graphene composite

2.3. Properties of Paraffin Wax as PCM

Paraffin wax is an organic PCM belonging to the alkane family, typically characterized by melting points in the range of 20–70 °C depending on molecular weight. It offers several advantages such as high latent heat capacity (150–250 kJ/kg), chemical inertness, and long-term reliability. Its drawbacks include low thermal conductivity and volume expansion during phase change. When used in solar energy storage, building materials, and electronics cooling, paraffin's heat transfer limitations often lead to inefficient charging/discharging cycles. Hence, enhancing its thermal conductivity without compromising latent heat storage is crucial.

2.4. Properties of graphene with PCM.

Table 1 Properties of graphene with PCM

Property	**Pure Paraffin PCM**	**Graphene–PCM Composite**	**Improvement/Remarks**
Thermal Conductivity (W/m·K)	0.2 – 0.3	1.0 – 2.5	4–10× higher thermal conductivity
Melting Point (°C)	55 – 58	55 – 58	Nearly unchanged, suitable for PV cooling
Latent Heat Storage (kJ/kg)	180 – 220	170 – 210	Slight reduction due to graphene addition
Charging/Discharging Rate	Slow	Fast	Faster heat transfers due to graphene
Thermal Stability	Moderate	High	Better cycling stability, less degradation
Leakage Prevention	Poor (needs encapsulation)	Improved	Graphene improves structural integrity
Cost	Low	Moderate	Higher cost due to graphene but justified by performance
PV Panel Temperature Reduction	7 °C	12 – 15 °C	Graphene–PCM shows superior cooling performance

The incorporation of graphene into paraffin wax significantly enhances the thermal and structural properties of the composite material. Paraffin wax, though widely used as a phase change material (PCM) due to its high latent heat storage capacity and chemical stability, suffers from limitations such as low thermal conductivity and leakage during melting. The addition of graphene addresses these drawbacks by improving thermal conductivity, which enables faster heat transfer during charging and discharging cycles, thereby enhancing the efficiency of energy storage systems. Furthermore, graphene's large surface area and high mechanical strength help in stabilizing the paraffin matrix, reducing leakage, and improving durability. This graphene–paraffin wax composite thus combines the high energy storage capability of paraffin with the superior thermal and mechanical properties of graphene, making it highly suitable for applications in thermal energy storage, photovoltaic panel cooling, and building energy management systems.

Table 1: In this table I have Compared to pure paraffin PCM, graphene–PCM composites exhibit significantly higher thermal conductivity, improved heat transfer rate, and enhanced structural stability during phase transition. While pure paraffin suffers from slow charging–discharging cycles and possible leakage, the incorporation of graphene not only accelerates thermal response but also improves cycling reliability and energy efficiency. This makes graphene–PCM composites more suitable for demanding applications such as PV cooling, electronics, and building energy management [48-50]

3. Characterization of graphene powder

Characterization of graphene powder standards is investigated in order to comprehend its characteristics. The graphene powder is subjected to X-ray diffraction tests in a Philips XPert equipment that employs CuKα radiation for phase identification, as shown in (Fig 2a). Using a scanning speed of 0.60° per second and a step size of 0.02°, the diffraction pattern of the powder was produced in the 2θ range of 5° to 90° in this investigation. The thermo-gravimetric analysis (TGA) was used to investigate the thermal stability of the graphene powder. The prepared sample, which contained approximately 5 mg, was subjected to the test using a Mettler Toledo TGA/DSC apparatus in an air environment with a heating rate of 10 °C/min and a flow rate of 60 ml/min. This procedure is illustrated in (Fig 2b).

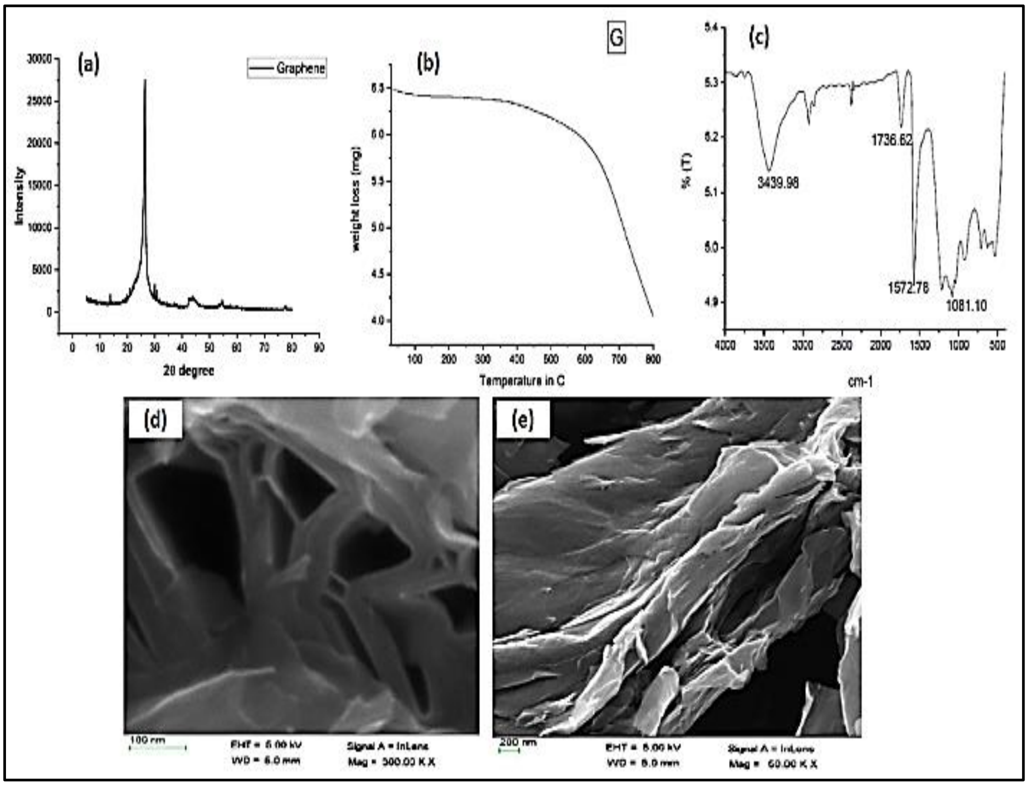

Figure 3 a) The X-ray diffraction analyses of the graphene powder, b) Thermogravimetric analysis (TGA), c) Insulation resistance test (IR), and (d-e) Scanning electron microscopy of graphene powder

Graphene powder's IR transmission spectra were analyzed using a Nicolet 8700 IR spectrometer (Band range400-4000cm^{-1}) to determine its insulation resistance, as shown in (Fig 2c). The scanning electron microscopy in Fig 2 (d-e) also makes use of a Novanano SEM 450 that is outfitted with an EDS analysis capability. With this tool, users may get the advantages of cluster element mapping and examine the samples' morphological features at higher magnifications.

3.1. DSC Thermogram of Paraffin Wax Showing Phase Change Transitions

Figure 4 represents the Differential Scanning Calorimetry (DSC) curve of paraffin wax, showing its phase change behavior with respect to temperature. It indicates two distinct transitions: a solid–solid phase change at approximately **34.53 °C**, followed by a solid–liquid phase change (melting) at around **52.97 °C**. The endothermic peaks in the graph correspond to these transitions, where heat is absorbed during the phase change process. The total enthalpy associated with these transitions is **202.91 J/g**, highlighting the significant latent heat storage capacity of paraffin wax, which makes it suitable as a phase change material (PCM) for thermal energy storage applications.

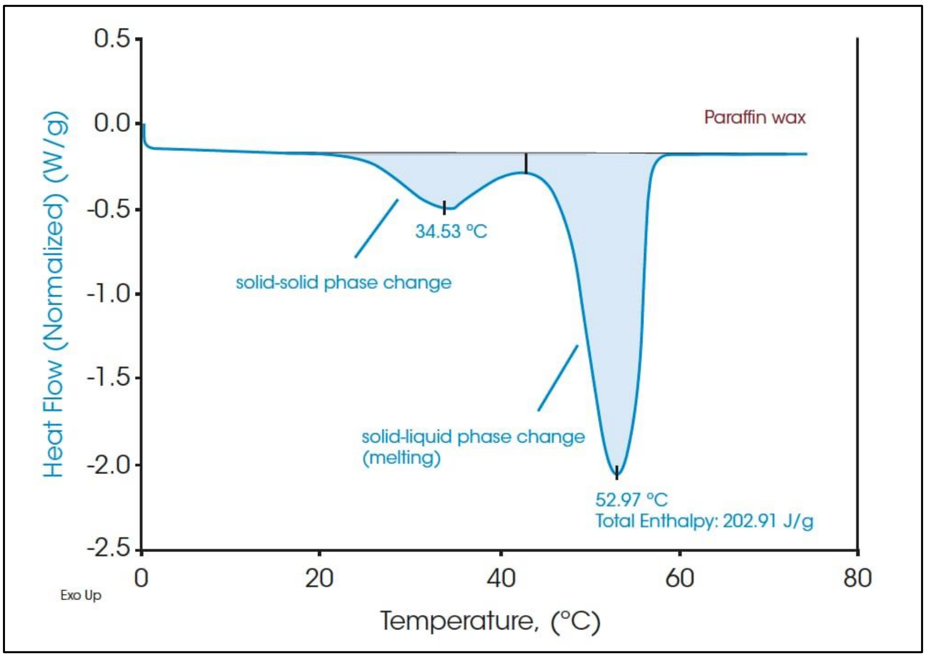

Figure 4 DSC Analysis

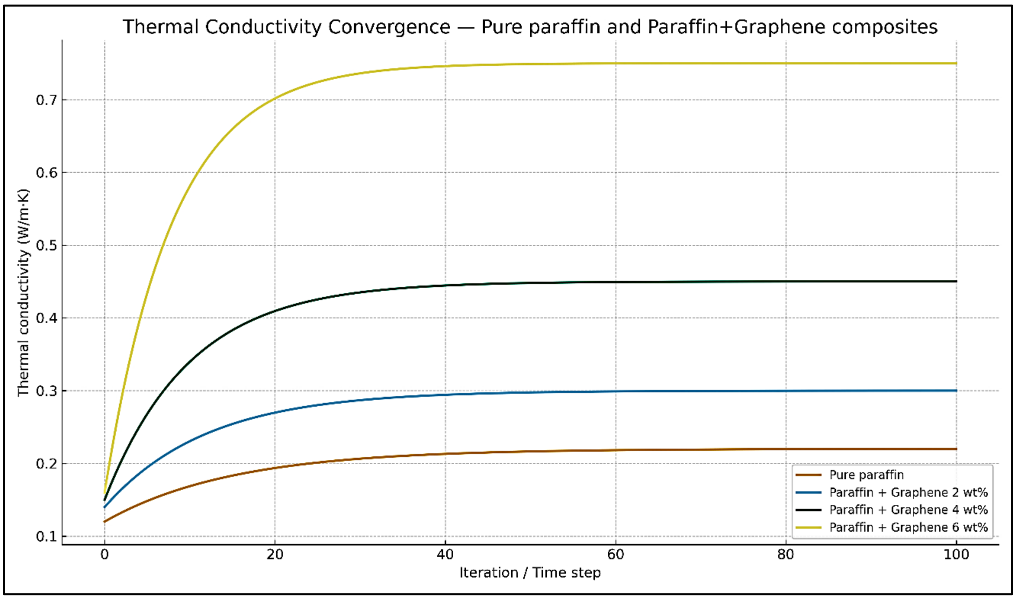

Figure 5 Thermal Conductivity Convergence of Pure Paraffin and Paraffin–Graphene Composites (2–6 wt%)

4. Conclusion

Despite notable improvements, challenges persist. Agglomeration and sedimentation reduce stability over long cycles. At higher graphene concentrations (>10 wt.%), latent heat decreases significantly. Cost and scalability of high-quality graphene production remain barriers. Additionally, ensuring long-term stability under repeated thermal cycling is still a challenge. Addressing these issues requires hybrid additives, functionalized graphene, and multidisciplinary approaches. Future research should focus on hybrid nanofillers (graphene with Al_2O_3, CNTs, or expanded graphite) to balance conductivity and latent heat. Computational modeling (molecular dynamics, artificial neural networks) can help optimize concentration and dispersion. Integration into photovoltaic panel cooling and electric vehicles offers promising areas of application. Development of cost-effective graphene synthesis techniques will be crucial for commercialization. Graphene–paraffin wax nanocomposites demonstrate remarkable improvements in thermal conductivity, stability, and performance. With conductivity enhancements exceeding 100% and minimal losses in latent heat, graphene outperforms conventional fillers. These composites are poised to transform thermal energy storage applications, provided challenges such as dispersion, cost, and stability are addressed. Graphene thus represents a key enabler for the next generation of energy-efficient storage systems.

Future Scope and Recommendations

Future work should focus on optimizing graphene concentration and exploring hybrid fillers such as graphene oxide and carbon nanotubes to balance conductivity with energy density. Large-scale testing under real climatic conditions is recommended to validate performance consistency. Computational modeling using Artificial Neural Networks (ANN) and Molecular Dynamics (MD) simulations can further aid in predicting thermal behavior. Additionally, research into cost-effective graphene synthesis and encapsulation techniques will be essential for commercialization.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] EU-OSHA, Calculating the cost of work-related stress and psychosocial risks, (2014), https://doi.org/10.2802/20493.

[2] M.T. Halimi, H. Dhahri, N. Ben Khedher, M. Ben Hassen, F. Sakli, Thermal prop- erties of industrial safety helmets, JASR 5 (2009) 833–844.

[3] C.P. Bogerd, J.M. Aerts, S. Annaheim, P. Bröde, G. de Bruyne, A.D. Flouris,K. Kuklane, T. Sotto Mayor, R.M. Rossi, A review on ergonomics of headgear: thermal effects, Int. J. Ind. Ergon. 45 (2015) 1–12, https://doi.org/10.1016/j.ergon.2014.10.004.

[4] T. Pretorius, D.D. Gagnon, G.G. Giesbrecht, Core cooling and thermal responses during whole-head, facial, and dorsal immersion in 17 8 C water, Appl. Physiol. Nutr. Me. 35 (2010) 627–634, https://doi.org/10.1139/H10-057.

[5] T.D. Proctor, A review of research relating to industrial helmet design, J. Occup. Accid. 3 (1982) 259–272, https://doi.org/10.1016/0376-6349(82)90003-7.

[6] E.M. Hickling, Factors affecting the acceptability of head protection at work, J. Occup. Accid. 8 (1986) 193–206, https://doi.org/10.1016/0376-6349(86)90005-2.

[7] J.D.A. Abeysekera, H. Shahnavaz, Ergonomics evaluation of modified industrial helmets for use in tropical environments, Ergonomics 31 (2007) 1317–1329, https://doi.org/10.1080/00140138808966771.

[8] T.D. Proctor, F.J. Rowland, Development of standards for industrial safety helmets - the state of the art, J. Occup. Accid. 8 (1986) 181–191, https://doi.org/10.1016/ 0376-6349(86)90004-0.

[9] X. Liu, J. Abeysekera, H. Shahnavaz, Subjective evaluation of three helmets in cold laboratory and warm field conditions, Int. J. Ind. Ergon. 23 (1999) 223–230, https://doi.org/10.1016/S0169-8141(97)00055-3.

[10] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345, https://doi.org/10.1016/j.rser.2007.10.005.

[11] H. Behi, M. Ghanbarpour, M. Behi, Investigation of PCM-assisted heat pipe for electronic cooling, Appl. Therm. Eng. 127 (2017) 1132–1142, https://doi.org/10. 1016/j.applthermaleng.2017.08.109.

[12] A. Castell, C. Solé, Design of latent heat storage systems using phase change ma- terials (PCMs), Advances in Thermal Energy Storage Systems, Woodhead PublishingLimited,2015,pp.285–305, https://doi.org/10.1533/9781782420965.2.285.

[13] A. Kasaeian, L. bahrami, F. Pourfayaz, E. Khodabandeh, W.M. Yan, Experimental studies on the applications of PCMs and nano-PCMs in buildings: acritical review, Energy Build. 154 (2017) 96–112, https://doi.org/10.1016/j.enbuild.2017.08.037.

[14] D. Ouahrani, M. Itani, N. Ghaddar, K. Ghali, B. Khater, Experimental study on using PCMs of different melting temperatures in one cooling vest to reduce its weight and improve comfort, Energy Build. 155 (2017) 533–545, https://doi.org/10.1016/j. enbuild.2017.09.057.

[15] P. Taylor, W.M.B. Tiest, N.D. Kosters, A.M.L. Kappers, A.M. Hein, Phase change materials and the perception of wetness, Ergonomics 55 (2012) 508–512, https:// doi.org/10.1080/00140139.2011.645886.

[16] Z.A. Qureshi, H.M. Ali, S. Khushnood, Recent advances on thermal conductivity enhancement of phase change materials for energy storage system: a review, Int. J. Heat Mass Transf. 127 (2018) 838–856, https://doi.org/10.1016/j. ijheatmasstransfer.2018.08.049.

[17] X. Yang, Z. Lu, Q. Bai, Q. Zhang, L. Jin, J. Yan, Thermal performance of a shell-and- tube latent heat thermal energy storage unit: role of annular fins, Appl. Energy 202 (2017) 558–570, https://doi.org/10.1016/j.apenergy.2017.05.007.

[18] X. Yang, J. Yu, Z. Guo, L. Jin, Y.L. He, Role of porous metal foam on the heat transfer enhancement for a thermal energy storage tube, Appl. Energy 239 (2019) 142–156, https://doi.org/10.1016/j.apenergy.2019.01.075.

[19] X. Yang, P. Wei, X. Cui, L. Jin, Y.L. He, Thermal response of annuli filled with metal foam for thermal energy storage: an experimental study, Appl. Energy 250 (2019) 1457–1467, https://doi.org/10.1016/j.apenergy.2019.05.096.

[20] X. Xiao, P. Zhang, M. Li, Effective thermal conductivity of open-cell metal foams impregnated with pure paraffin for latent heat storage, Int. J. Therm. Sci. 81 (2014) 94–105, https://doi.org/10.1016/j.ijthermalsci.2014.03.006.

[21] P. Zhang, Z.N. Meng, H. Zhu, Y.L. Wang, S.P. Peng, Melting heat transfer char- acteristics of a composite phase change material fabricated by paraffin and metal foam, Appl. Energy 185 (2017) 1971–1983, https://doi.org/10.1016/j.apenergy.2015.10.075.

[22] X. Yang, Z. Guo, Y. Liu, L. Jin, Y.L. He, Effect of inclination on the thermal response of composite phase change materials for thermal energy storage, Appl. Energy 238 (2019) 22–33, https://doi.org/10.1016/j.apenergy.2019.01.074.

[23] Y. Cui, C. Liu, S. Hu, X. Yu, The experimental exploration of carbon nanofiber and carbon nanotube additives on thermal behaviour of phase change materials, Sol. Energy Mater. Sol. Cells 95 (2011) 1208–1212, https://doi.org/10.1016/j.solmat.2011.01.021.

[24] M. Li, A nano-graphite / paraffin phase change material with high thermal con- ductivity, Appl. Energy 106 (2013) 25–30, https://doi.org/10.1016/j.apenergy.2013.01.031.

[25] A.L. Colla, L. Fedele, S. Mancin, L. Danza, L. Colla, L. Fedele, S. Mancin, L. Danza,O. Manca, Nano -Pcms for enhanced energy storage and passive cooling applica- tions, Appl. Therm. Eng. (2016), https://doi.org/10.1016/j.applthermaleng.2016. 03.161.

[26] M.A. Alomair, Y.A. Alomair, H.A. Abdullah, S. Mahmud, S. Tasnim, Nanoparticle enhanced phase change material in latent heat thermal energy storage system: an experimental study, Proc. Int. Conf. Energy Harvest. Storage, Transf, 2017, pp. 1–5,https://doi.org/10.11159/ehst17.119.engineering applications, J. Eng. Sci. Technol. Rev. 9 (2016) 26–36.

[27] A.K. Mishra, B.B. Lahiri, J. Philip, Thermal conductivity enhancement in organic phase change material (phenol-water system) upon addition of Al2O3, SiO2 and TiO2 nano-inclusions, J. Mol. Liq. 269 (2018) 49–63, https://doi.org/10.1016/j.

[28] H. Ji, D.P. Sellan, M.T. Pettes, X. Kong, J. Ji, L. Shi, R.S. Ruoff, Enhanced thermal conductivity of phase change materials with ultrathin-graphite foams for thermal energy storage, Energy Environ. Sci. 7 (2014) 1185–1192, https://doi.org/10. 1039/c3ee42573h.

[29] A. Elgafy, K. Lafdi, Effect of carbon nanofiber additives on thermal behaviour of phase change materials, Carbon N. Y. 43 (2005) 3067–3074, https://doi.org/10. 1016/j.carbon.2005.06.042.

[30] S. Harikrishnan, S. Magesh, S. Kalaiselvam, Thermochimica acta preparation and thermal energy storage behaviour of stearic acid – TiO2 nanofluids as a phase change material for solar heating systems, Thermochim. Acta. 565 (2013) 137–145, https://doi.org/10.1016/j.tca.2013.05.001.

[31] M. Chieruzzi, G.F. Cerritelli, A. Miliozzi, J.M. Kenny, Effect of nanoparticles on heat capacity of nanofluids based on molten salts as PCM for thermal energy storage, Nanoscale Res. Lett. 8 (2013) 448, https://doi.org/10.1186/1556-276X-8-448.

[32] A.M. Tiara, S. Chakraborty, I. Sarkar, A. Ashok, S.K. Pal, S. Chakraborty, Heat transfer enhancement using surfactant based alumina nanofluid jet from a hot steel plate, Exp. Therm. Fluid Sci. 89 (2017) 295–303, https://doi.org/10.1016/j. expthermflusci.2017.08.023.

[33] L. Chen, H. Xie, Y. Li, W. Yu, Nanofluids containing carbon nanotubes treated by mechanochemical reaction, Thermochim. Acta. 477 (2008) 21–24, https://doi.org/ 10.1016/j.tca.2008.08.001.

[34] L. Kong, J. Sun, Y. Bao, Preparation, characterization and tribological mechanism of nanofluids, RSC Adv. 7 (2017) 12599–12609, https://doi.org/10.1039/ c6ra28243a.

[35] Z. Mingzheng, X. Guodong, L. Jian, C. Lei, Z. Lijun, Analysis of factors influencing thermal conductivity and viscosity in different kinds of surfactant solutions, Exp. Therm. Fluid Sci. 36 (2012) 22–29, https://doi.org/10.1016/j.expthermflusci.2011.07.014.

[36] M.A. Neouze, U. Schubert, Surface modification and functionalization of metal and metal oxide nanoparticles by organic ligands, Monatsh. Chem. 139 (2008) 183–195, https://doi.org/10.1007/s00706-007-0775-2.

[37] I.M. Mahbubul, E.B. Elcioglu, R. Saidur, M.A. Amalina, Optimization of ultra- sonication period for better dispersion and stability of TiO2–water nanofluid, Ultrason. Sonochem 37 (2017) 360–367, https://doi.org/10.1016/j.ultsonch.2017.01.024.

[38] D. Dey, P. Kumar, S. Samantaray, A review of nanofluid preparation, stability, and thermo-physical properties, Heat Transf. Asian Res. 46 (2017) 1413–1442, https:// doi.org/10.1002/htj.21282.

[39] X.F. Peng, X.L. Yu, L.F. Xia, X. Zhong, Influence factors on suspension stability of nanofluids, J. Zhejiang Univ. 41 (2007) 577–580.

[40] R. Choudhary, D. Khurana, A. Kumar, S. Subudhi, Stability analysis of Al2O3/water nanofluids, J. Exp. Nanosci. 12 (2017) 140–151, https://doi.org/10.1080/17458080.2017.1285445.

[41] R. Azizian, E. Doroodchi, B. Moghtaderi, Influence of controlled aggregation on thermal conductivity of nanofluids, J. Heat Transf. (2016) 138, https://doi.org/10. 1115/1.4031730.

[42] C.J. Ho, J.Y. Gao, Preparation and thermophysical properties of nanoparticle-in- paraf fi n emulsion as phase change material, Int. Commun. Heat Mass Transf. 36 (2009) 467–470, https://doi.org/10.1016/j.icheatmasstransfer.2009.01.015.

[43] F.L. Tan, S.C. Fok, Cooling of helmet with phase change material, Appl. Therm. Eng. 26 (2006) 2067–2072, https://doi.org/10.1016/j.applthermaleng.2006.04.022.

[44] S. Ghani, E. Mohame, A. Ahmed, F. Bakochristou, S. Mahmoud, A. Gamaledin,M.M. Rashwan, The effect of forced convection and PCM on helmets' thermal performance in hot and arid environments, Appl. Therm. Eng. 111 (2017) 624–637, https://doi.org/10.1016/j.applthermaleng.2016.09.142.

[45] A. Karaipekli, A. Biçer, A. Sarı, V.V. Tyagi, Thermal characteristics of expanded perlite/paraffin composite phase change material with enhanced thermal con- ductivity using carbon nanotubes, Energy Convers. Manag. 134 (2017) 373–381, https://doi.org/10.1016/j.enconman.2016.12.053.

[46] A. Sari, A. Karaipekli, Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material, Appl. Therm. Eng. 27 (2007) 1271–1277, https://doi.org/10.1016/j. applthermaleng.2006.11.004.

[47] A. Chelliah, B. Karthick, A. Vimalkodeeswaran, V.R. Hariram, Helmet cooling system using phase change material for long drive, ARPN J. Eng. Appl. Sci. 10 (2015) 1770–1773.