Research Article

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Development of Adaptable Phase Change Material Composites for Advanced Passive Cooling of Processors

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ABSTRACT

Modern processors and data-centre modules often experience localized thermal spikes due to rapidly fluctuating computational loads, which can negatively affect device reliability, efficiency, and operational stability. Conventional cooling approaches, including air-based active cooling and conventional phase change materials (PCMs), face limitations such as low thermal conductivity, leakage during phase transition, and bulky packaging structures. In this work, a flexible PCM nanocomposite sheet was developed using paraffin wax as the base PCM reinforced with bio-carbon derived from agricultural waste, bentonite nanoclay, and cellulose fibres. The composite was fabricated using a controlled hot-press method to produce thin, adaptable PCM sheets suitable for direct processor surface integration. The hybrid filler system improves heat transfer pathways while suppressing leakage and enhancing mechanical stability. X-ray diffraction analysis confirmed the preservation of the crystalline structure of paraffin within the composite matrix. Differential scanning calorimetry showed a melting temperature of approximately 62.8 °C and a crystallization temperature near 59.1 °C, indicating stable phase-change behavior. Thermal conductivity measurements increased from about 0.25 W m^{-1} K^{-1} for pure paraffin to a maximum of 0.95 W m^{-1} K^{-1} in the optimized composite. Field emission scanning electron microscopy observations revealed uniform filler dispersion and an interconnected microstructure that enhances thermal transport. The developed sustainable PCM composite demonstrates promising potential for passive cooling of processors and advanced electronic thermal management systems.

Keywords: Phase change material composites; Paraffin; Bio-carbon nanosheets; Processor cooling; Data-centre thermal management.

1. INTRODUCTION

Modern high-performance computing systems, particularly processors, face significant thermal management challenges due to increasing transistor densities and power consumption, which can exceed 1 kW/cm^2 in advanced accelerators for artificial intelligence and machine learning applications (Navaux *et al.* 2023). This surge in power density leads to higher peak temperatures and transient heat spikes, which can severely degrade performance, shorten device lifespan, and compromise reliability (Hua *et al.* 2021; Zheng *et al.* 2025). Traditional cooling methods (Fig. 1), including conventional heat sinks and active cooling systems, often struggle to efficiently manage these rapid, localized, and non-stationary thermal loads (Ganatra *et al.* 2018; An, 2025). For instance, integrated heat spreaders in CPUs face challenges with distributed heat transfer coefficients due to non-uniform thermal loads (Elliott *et al.* 2022).

Phase change materials (PCMs) offer a promising passive cooling solution by exploiting their high latent heat capacity and nearly isothermal energy absorption during their solid-liquid phase transition (Li *et al.* 2023; Liu *et al.* 2011; Rubel *et al.* 2024). This makes them effective thermal buffers, capable of mitigating temperature fluctuations and preventing damaging localized heating effects, thereby improving the reliability of electronic packages and reducing thermal stress-induced failures (Kasitz *et al.* 2024). However, pure PCMs inherently suffer from several limitations that hinder their widespread adoption in high-performance electronics: predominantly low thermal conductivity (typically below 0.5 W/m·K for organic PCMs), leakage in their liquid phase, phase segregation over thermal cycling, and often poor mechanical stability (Zacharias *et al.* 2025; Kumar *et al.* 2021).

To overcome these intrinsic drawbacks, significant research efforts have focused on developing advanced PCM composites through various engineering strategies (Janumala *et al.* 2023; Radouane, 2022). One primary approach involves enhancing the thermal conductivity of PCMs by incorporating highly

conductive additives or structural supports (Yang *et al.* 2021). For instance, the use of carbon-based nano-additives, such as graphene nanoplatelets, graphene oxide, and carbon quantum dots, has shown considerable promise in boosting the effective thermal conductivity of nano-enhanced PCMs (Chen *et al.* 2024). Metal foams, including copper and aluminum foams, are also widely employed as high-conductivity matrices to create interconnected thermal pathways within the PCM, facilitating rapid heat transfer (Lin *et al.* 2018). Studies have explored paraffin wax combined with *Prosopis juliflora* biochar and aluminum powder, demonstrating improved thermal conductivity and sustainable passive cooling for electronic devices (Balasundaram and Sivaram, 2025). Similarly, the integration of graphite, graphene, and boron nitride with paraffin wax forms novel composite PCMs with enhanced heat absorption capabilities for battery thermal management (Yang *et al.* 2021).

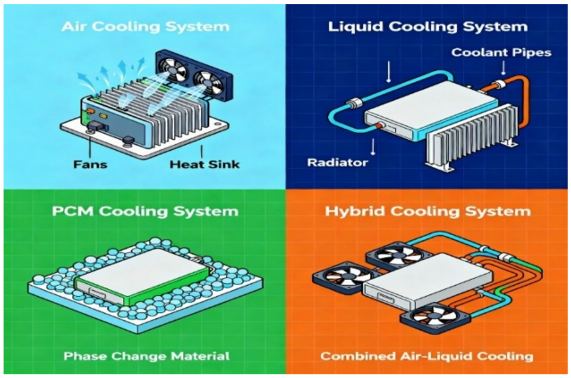


Fig. 1: Conventional cooling technologies

Another critical aspect of PCM composite development is microencapsulation, which addresses the leakage issue of liquid PCMs and improves their mechanical stability (Wang *et al.* 2023). Microencapsulated PCMs allow for better integration into thermal interface materials and other cooling architectures. For instance, micro-encapsulated PCM slurry saturated in metal foam has been developed for passive thermal management, mitigating problems of low thermal conductivity, supercooling, volume expansion, and corrosion. The use of eutectic gallium-indium liquid metal to immerse carbon-based PCM capsules has resulted in scalable, thermally stable, mechanically reliable, highly conductive, and leakage-free composites for CPU cooling.

The design of PCM heat sinks is complex due to the non-linear interactions between heat flow and phase change during melting and solidification (Kim *et al.* 2024). Computational fluid dynamics simulations are extensively used to investigate the thermal performance of PCM-based cooling systems, considering various materials, geometries, and operating conditions (Omi, 2025). These simulations help optimize parameters such as metal foam porosity, nanoparticle volume fractions, and fin configurations to enhance heat transfer rates. For example, studies have explored hybrid nanocomposite PCM dispersed metal-foam heat sinks for passive cooling enhancement, showing that dispersing hybrid nanoparticles like GO-Ag into PCMs can improve thermal performance (Arshad *et al.* 2021).

Fig. 2 shows a decade-long publication trend (2015–2025) based on searches through Google Scholar, Dimensions, and publisher databases shows a continuous rise in research on PCM-based cooling system. Publications increased from fewer than 20 per year in 2015 to nearly 100 per year by 2024, indicating growing scientific interest in transient thermal management for high-performance electronics. The upward trend reflects increasing power densities in processors, the expansion of data-centres, and the shift toward nanocomposite and sustainable PCM technologies.

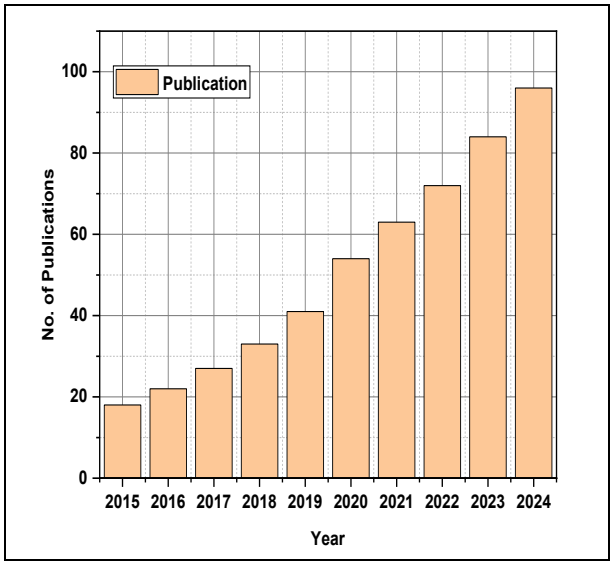


Fig. 2: Estimated annual research publications (2015–2025) related to phase change materials for processor

To the best of our knowledge, limited studies have explored a hot-pressed, paper-like composite PCM sheet constructed from paraffin, waste-derived bio-carbon nanosheets, and bentonite nano clay, specifically engineered for processor hot-spot cooling. The combination of bio-carbon and nano clay provides a sustainable, low-cost pathway to enhance thermal conductivity and shape stability, while the paper-like sheet geometry enables direct mounting on integrated heat spreaders or other processor hot-spot regions without the need for complex encapsulation.

Fig. 3 illustrates the comparison between active, passive, and PCM-based cooling clearly highlighting why next-generation processors and data-centre hardware require an alternative thermal management

pathway. Active cooling systems (relying on fans, pumps, and refrigeration) are effective but energy-intensive, complex, and increasingly insufficient for handling localized, fast-rising heat spikes in modern CPUs. Passive methods such as heat sinks and natural convection offer simplicity but struggle to maintain stable temperatures under fluctuating workloads. Phase change material-based cooling, by contrast, provides a latent-heat absorption mechanism capable of maintaining more uniform temperatures with less power consumption. This combination of safety, energy efficiency, and transient heat-buffering capability makes PCM technology a strong candidate for future electronics thermal regulation, creating a clear motivation for the development of advanced PCM nanocomposites tailored for processor hot-spot cooling.

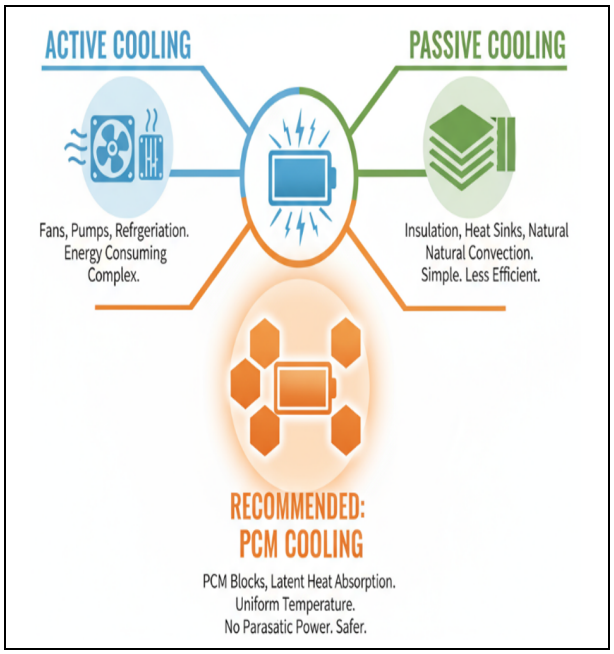


Fig. 3: Comparison of thermal management strategies for electronic systems

The ultimate goal in developing adaptable PCM composites is to achieve ultrafast thermal response, reversible adaptability to variable heat spike amplitude and frequency, integration-compatible form factors (e.g., thin-film, conformal coating), and long-term cyclability under thermal-mechanical stress. While PCMs offer advantages such as improved reliability and reduced system volume and weight, their effectiveness is often limited to a narrow temperature range around their melting point, posing a challenge for designing systems with broad operating conditions. Therefore, ongoing research focuses on materials and designs that can dynamically modulate thermal conductivity, offer self-healing encapsulation, or enable on-demand solidification kinetics tailored to processor duty cycles. Such innovations are critical for the sustainable thermal management of electronic devices, particularly in the face of ever-increasing power densities and the resulting thermal challenges.

Therefore, to design, fabricate, and evaluate an eco-friendly PCM-paper nanocomposite capable of absorbing and delaying heat spikes in processor environments. The present work aims to develop a scalable, low-temperature hot-press method to produce thin PCM sheets, characterize their phase-change behaviour, microstructure, and thermal transport, and experimentally assess their transient cooling performance using a processor-equivalent hot-spot simulation.

2. MATERIALS AND METHODS

2.1 Materials

Paraffin wax (melting temperature 55–60 °C, analytical grade, purity ≥99%, purchased from Sigma-Aldrich, Chemico Chemical, Erode, India) was used as the primary phase change material responsible for absorbing and releasing thermal energy during melting and solidification, thereby providing effective thermal regulation in the composite. Bio-carbon nanosheets derived from coconut shell biomass were used as high-surface-area thermally conductive fillers to enhance heat transfer pathways, improve structural stability, and reduce leakage during the phase transition of paraffin. Bentonite nano clay (analytical grade, purchased from Merck, India) served as a reinforcing agent that enhances the mechanical strength of the composite while preventing wax seepage by forming a stable intercalated network within the PCM matrix. Ethanol (analytical grade, purity ≥99.5%, purchased from Chemico Chemical, Erode, India) was used as a dispersion medium to uniformly mix paraffin, nano clay, and bio-carbon, ensuring homogeneous distribution of fillers and improving composite formation during processing. Cellulose fibres (analytical grade, purchased from Chemico Chemical, Erode, India) were incorporated to provide additional mechanical stability, improve shape retention, and support the formation of a conductive thermal network, resulting in a flexible and mechanically robust PCM composite. Fig. 4 shows the materials used in the work.

2.2 Preparation of Bio-carbon Nanosheets

Coconut shell biomass was used as the precursor material for producing bio-carbon. The raw coconut shells were first washed thoroughly with distilled water to remove soil particles and surface contaminants, followed by drying in a hot-air oven at 85 °C for 12 hours to eliminate moisture. The dried biomass was then placed in a ceramic crucible and subjected to slow pyrolysis in a muffle furnace under oxygen-limited conditions. The furnace temperature was increased at a controlled heating rate of 5 °C min^{-1} until reaching 450

℃, and the sample was maintained at this temperature for 2–3 hours to allow complete carbonization of the organic structure.

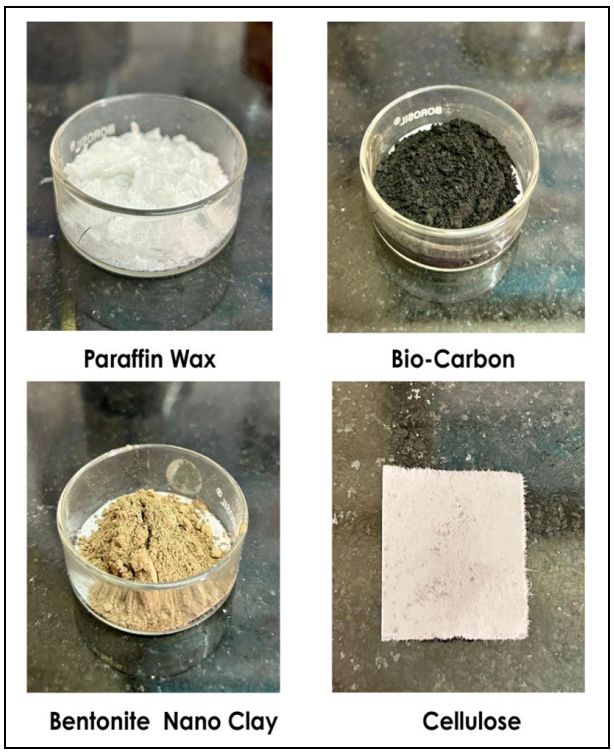


Fig. 4: Materials used for the preparation of composite

After pyrolysis, the furnace was allowed to cool naturally to room temperature. The obtained charred material was then ground manually using a mortar and pestle and further milled to reduce particle size. The powder was subsequently sieved through a 50 µm mesh to obtain a uniform fine bio-carbon powder. The resulting porous carbon particles provide thermally conductive pathways and act as reinforcing fillers within the PCM composite.

2.3 Composite Formulation

The PCM nanocomposite was formulated using paraffin wax as the base phase change material, reinforced with bio-carbon powder and bentonite nano clay to improve thermal conductivity and structural stability. Cellulose fibres (5 wt%) were incorporated in all formulations to enhance mechanical flexibility and facilitate the formation of a thin sheet structure during hot pressing.

Different compositions were prepared by varying the paraffin and bio-carbon content while keeping bentonite nano clay and cellulose constant. The detailed composition of each composite sample is presented in Table 1.

Table 1. Composition of the PCM–bio-carbon–nano clay composite

Composite ID	Paraffin wt%	Bio-Carbon wt%	Bentonite wt%	Cellulose wt%
PCM70_Comp	70	15	10	5
PCM60_Comp	60	25	10	5
PCM75_Comp	75	10	10	5
PCM80_Comp	80	5	10	5
PCM65_Comp	65	20	10	5

In the composite system, paraffin acts as the thermal energy storage medium, while bio-carbon introduces thermally conductive pathways that improve heat transport within the PCM matrix. Bentonite nano clay serves as a shape-stabilizing material that suppresses leakage of molten paraffin, and cellulose fibres contribute to mechanical strength and flexibility, enabling the formation of a paper-like composite sheet suitable for processor surface cooling.

2.4 Fabrication of PCM-paper (Hot-press Method)

The PCM composite sheets were fabricated using a hot-press consolidation method. Paraffin wax was first heated to approximately 80 ℃ in a thermostatically controlled heating bath until it completely melted. In a separate container, the prepared bio-carbon powder was dispersed in a small quantity of ethanol and subjected to ultrasonic agitation for 30 min to improve particle dispersion and prevent agglomeration.

Bentonite nano clay and cellulose fibres were then gradually added to the suspension while stirring continuously to ensure uniform mixing. The dispersed filler mixture was subsequently combined with molten paraffin and mixed using mechanical stirring to obtain a homogeneous slurry. During this process, ethanol was allowed to evaporate gradually due to the elevated temperature.

The resulting mixture was poured into a pre-heated stainless-steel mold and placed in a hydraulic hot press. The composite was compressed at 80 ℃ under a pressure of 5–12 MPa for 10 min, which enabled the formation of a dense and uniform sheet structure. After pressing, the mold was allowed to cool under pressure to minimize void formation and maintain structural stability. A schematic representation of composite preparation is given in Fig. 5.

The final product was obtained in the form of a thin flexible PCM sheet, which can be directly applied to processor heat-spreading surfaces for passive thermal management experiments.

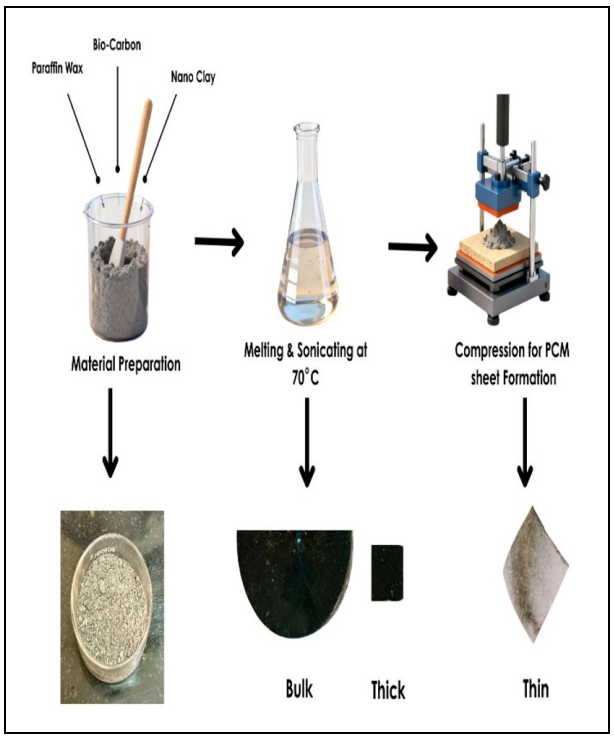


Fig. 5: Schematic representation of composite preparation and the final adaptable forms of composites

2.5 Characterization Techniques

The structural, thermal, and performance characteristics of the prepared PCM composites were evaluated using several characterization techniques. Differential Scanning Calorimetry (DSC) was used to investigate the phase change behavior and latent heat characteristics of the composites. Approximately 5 mg of the composite sample was sealed in an aluminium pan and subjected to controlled heating and cooling cycles over a temperature range of 20–80 ℃ at a heating and cooling rate of 5 ℃ min^{-1}. The DSC analysis provided information on the melting temperature, crystallization temperature, and latent heat of fusion of the composite. The thermal conductivity of the samples was measured using the transient hot-wire method at room temperature, and measurements were repeated at least three times to ensure reproducibility and accuracy. These measurements allowed comparison between the thermal conductivity of pure paraffin and the enhanced conductivity of the PCM composites containing bio-carbon and bentonite nano clay fillers. In addition, a laboratory-scale thermal performance test was conducted to evaluate the practical heat absorption capability of the composite. The PCM samples were subjected to repeated heating and cooling cycles using a controlled hot plate setup, simulating transient heat loading conditions. Temperature variations during the charging and discharging processes were monitored using thermocouples connected to a data logger, allowing analysis of phase change behavior and heat buffering performance of the PCM composites under laboratory conditions.

3. RESULTS AND DISCUSSION

3.1 XRD ANALYSIS

The XRD patterns of pure paraffin wax (PFW) and the developed flexible PCM composite are shown in Fig. 6. Pure PFW exhibits sharp and intense diffraction peaks at 2θ values of approximately 21.4° and 23.8°, which correspond to the orthorhombic crystalline structure of long-chain paraffin molecules. These characteristic reflections confirm the highly crystalline nature of paraffin, which is responsible for its high latent heat storage capability.

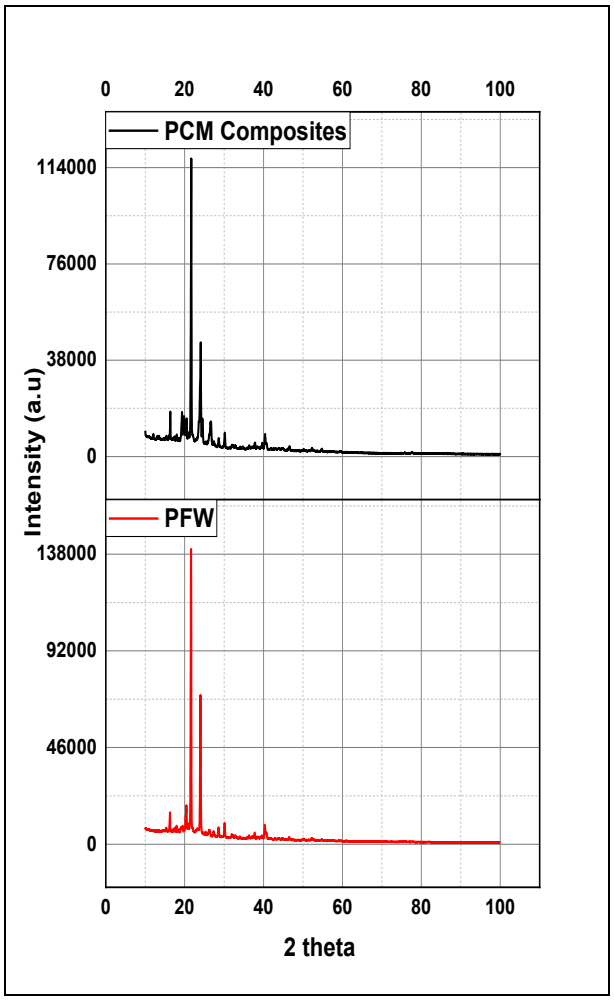


Fig. 6: XRD patterns of PFW and PCM nano composite

After incorporating bio-carbon particles, bentonite nano clay, and cellulose fibres, the PCM composite retains the dominant paraffin diffraction peaks, indicating that the crystalline phase of paraffin is preserved within the composite structure. However, a slight reduction in peak intensity and minor peak broadening are observed in the composite sample. This

behaviour suggests physical confinement of paraffin molecules within the porous filler network and interfacial interactions between the PCM matrix and the reinforcing fillers.

In addition, the absence of new diffraction peaks indicates that no chemical reactions occurred during composite fabrication and that the interaction between paraffin and the fillers is primarily physical. The presence of amorphous bio-carbon and layered bentonite structures contributes to enhanced thermal transport pathways and structural stability, while bentonite also assists in suppressing leakage during the phase transition process. The XRD results confirm that the composite maintains structural stability and phase change integrity, making it suitable for flexible passive cooling applications in processors and electronic devices.

3.2 DSC Results

The phase change behaviour of the PCM composite was analysed using DSC. The DSC thermogram shown in Fig. 7 illustrates the endothermic melting peak and exothermic crystallization peak of the composite during heating and cooling cycles.

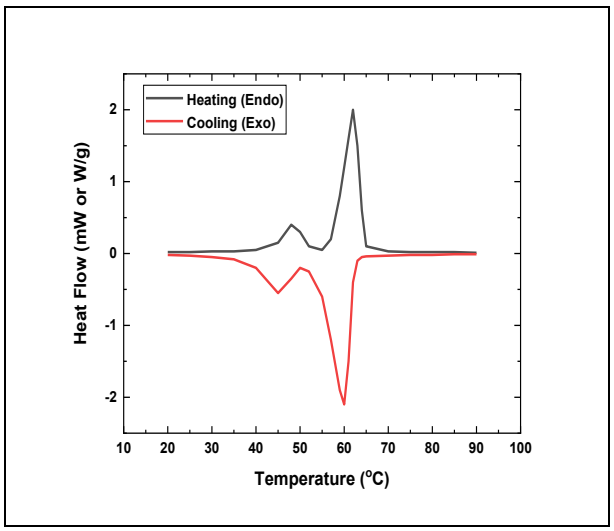


Fig. 7: DSC curve for the PCM nano composite

The DSC curve shows a distinct melting peak at approximately 62.8 °C and a crystallization peak at around 59.1 °C, confirming the stable phase change behaviour of the PCM composite. The temperature hysteresis between melting and crystallization is approximately 3.7 °C, which indicates good thermal reversibility and efficient heat storage–release capability during repeated thermal cycles. An endothermic enthalpy value of 197.7 J/g indicates heat absorption, whereas an exothermic value of −181.2 J/g indicates heat release.

The preservation of the melting temperature close to that of pure paraffin indicates that the addition of bio-carbon, bentonite, and cellulose does not significantly disrupt the intrinsic phase transition behaviour of the PCM. This result confirms that the composite retains the latent heat storage capability while improving thermal transport properties, making it suitable for thermal buffering of transient heat spikes in electronic components.

3.3 Thermal Conductivity

Thermal conductivity is an important parameter that determines the rate of heat transfer through a material. Pure paraffin wax typically exhibits a low thermal conductivity in the range of approximately 0.20–0.25 W m^{-1} K^{-1}, which limits its effectiveness in electronic cooling applications. Table 2 presents the measured thermal conductivity values for the developed PCM composites with varying filler compositions.

The results show that the incorporation of bio-carbon significantly improves the thermal conductivity of the PCM composites. The maximum thermal conductivity value of 0.95 W m^{-1} K^{-1} was obtained for the PCM60_Comp formulation, which represents approximately a four-fold increase compared with pure paraffin. This improvement can be attributed to the formation of conductive heat transfer pathways by bio-carbon particles and the layered structure of bentonite nano clay, which facilitates efficient heat transport within the composite matrix.

Table 2. Thermal conductivity of the PCM composites

Composite ID	Paraffin wt%	Bio-Carbon wt%	Bentonite wt%	Cellulose wt%	Thermal Conductivity (W/m·K)
PCM70_Comp	70	15	10	5	0.72
PCM60_Comp	60	25	10	5	0.95
PCM75_Comp	75	10	10	5	0.58
PCM80_Comp	80	5	10	5	0.40
PCM65_Comp	65	20	10	5	0.82

However, increasing filler concentration beyond an optimal level may reduce the overall PCM content, potentially affecting the latent heat storage capacity. Therefore, a balance between thermal conductivity enhancement and energy storage capability must be considered in the composite design.

3.4 FE-SEM

The Field Emission Scanning Electron Microscopy (FE-SEM) images illustrate the morphological differences between pure paraffin wax and the developed PCM composite.

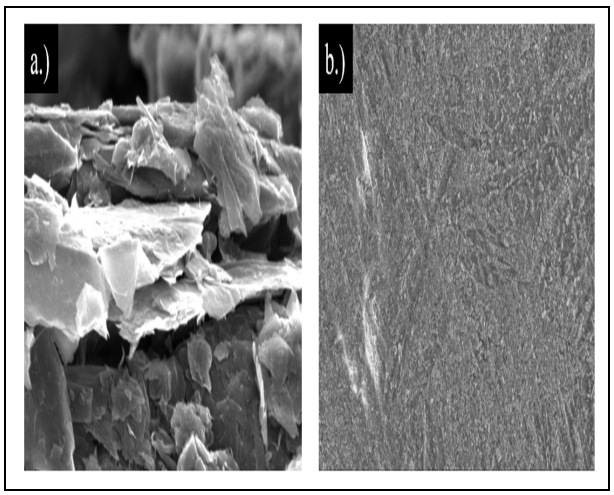


Fig. 8: (a) Morphological structure of paraffin wax and (b) Morphological structure of PCM composite

Fig. 8a shows the microstructure of pristine paraffin wax, characterized by a layered and plate-like morphology with loosely packed structures. This non-uniform arrangement creates interlamellar gaps that may contribute to leakage during melting and limit effective heat transfer. In contrast, Fig. 8b shows the PCM composite containing bio-carbon particles, bentonite nano clay, and cellulose fibres. The composite exhibits a dense, interconnected, and relatively homogeneous microstructure, indicating successful dispersion of the reinforcing fillers within the paraffin matrix. The porous network formed by bio-carbon particles provides thermal transport pathways, while bentonite nano clay contributes to structural stability and leakage suppression. This interconnected microstructure enhances heat conduction, improves shape stability, and helps maintain structural integrity during repeated melting and solidification cycles. The FE-SEM observations therefore confirm the successful formation of the composite and the synergistic effect of the fillers in improving both thermal and mechanical properties of the PCM.

3.5 Experimental Analysis

To evaluate the practical thermal performance of the PCM composite, a laboratory-scale heating experiment was conducted using a controlled hot-plate setup. The PCM composite samples were subjected to repeated heating and cooling cycles, simulating transient heat loading conditions similar to those experienced by electronic devices.

Temperature variations during the charging (heating) and discharging (cooling) cycles were monitored using thermocouples connected to a digital data-logging system. The recorded temperature–time profile shown in Fig. 9 demonstrates a clear phase change plateau region, which indicates the ability of the PCM composite to absorb and store thermal energy during melting and release it gradually during cooling.

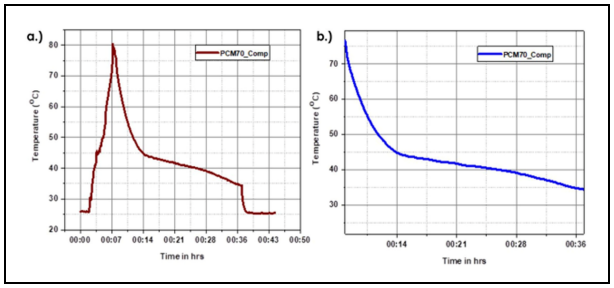


Fig. 9: Experimental analysis of PCM nanocomposite

The observed delay in temperature rise confirms that the PCM composite can effectively buffer sudden heat spikes, thereby reduce peak temperature and improve thermal regulation. These experimental results demonstrate the potential applicability of the developed PCM composite for passive thermal management in processor and electronic cooling systems.

4. CONCLUSION

In this study, a sustainable and flexible PCM nanocomposite was successfully developed for passive thermal management of processors and electronic devices. Paraffin wax was modified using a hybrid filler system consisting of bio-carbon particles derived from coconut shell biomass, bentonite nano clay, and cellulose fibres, which improved the structural stability and thermal performance of the PCM composite. The incorporation of bio-carbon significantly enhanced heat transfer within the composite, while bentonite nano clay and cellulose fibres provided mechanical reinforcement and leakage suppression, enabling the formation of thin flexible PCM sheets suitable for direct surface integration.

Structural and thermal characterization confirmed that the crystalline structure of paraffin was preserved, ensuring stable phase change behavior. The DSC analysis revealed a melting temperature of approximately 62.8 °C and a crystallization temperature near 59.1 °C, indicating good thermal reversibility during heating and cooling cycles. The thermal conductivity of the optimized composite reached 0.95 W m^{-1} K^{-1}, representing a substantial improvement compared with pure paraffin (~0.2–0.25 W m^{-1} K^{-1}). The FE-SEM analysis further demonstrated uniform filler dispersion and the formation of an interconnected microstructure, which enhances heat transport and improves structural

stability. The developed PCM composite demonstrates promising potential as an eco-friendly passive cooling material for next-generation processor and data-centre thermal management systems.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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