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Smart Biopolymer–PCM Composite Modules with Embedded Wireless Thermal Sensing for Autonomous Energy Storage Applications

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Abstract

The development of multifunctional polymer composite systems for intelligent thermal energy storage has gained significant attention due to the increasing demand for sustainable and autonomous thermal management technologies. In the present study, a wireless-integrated biopolymer–phase change material (PCM) composite module embedded with thermal feedback sensors was successfully fabricated and experimentally investigated for advanced thermal energy storage applications. Polylactic acid (PLA) was employed as the biodegradable polymer matrix, while paraffin wax served as the latent heat storage material. Graphite nanoplatelets were incorporated as conductive nanofillers to improve thermal conductivity and heat transfer characteristics within the composite structure. Embedded thermistor-based wireless sensing architecture enabled real-time thermal monitoring during charging and discharging operations. Differential scanning calorimetry analysis revealed stable melting and solidification transitions with excellent latent heat storage behaviour, while thermogravimetric analysis confirmed enhanced thermal stability of the polymer composite system. Thermal charging and discharging studies demonstrated efficient heat absorption, prolonged heat retention, and stable cyclic thermal performance. Scanning electron microscopy revealed homogeneous PCM dispersion, interconnected graphite nanoplatelet networks, and strong filler–matrix interfacial bonding within the composite structure. The synergistic integration of biodegradable polymer matrices, conductive reinforcements, latent heat storage materials, and embedded wireless sensing systems resulted in a multifunctional smart polymer composite suitable for autonomous thermal regulation applications. The developed composite module demonstrates strong potential for renewable energy storage, intelligent building materials, wearable thermal management systems, and next-generation IoT-enabled thermal energy platforms.

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INTRODUCTION

The rapid growth of renewable energy technologies, smart electronics, and sustainable

infrastructure systems has significantly increased the demand for advanced thermal energy storage materials capable of autonomous operation and intelligent thermal regulation. Thermal energy storage systems are essential for balancing intermittent energy supply and demand, particularly in solar thermal applications, smart buildings, portable electronic devices, and autonomous energy management platforms. Among the available thermal storage technologies, latent heat thermal energy storage using phase change materials (PCMs) has gained remarkable attention due to its high energy storage density, near-isothermal phase transition behaviour, and efficient heat absorption–release capability [1].

PCMs possess the ability to absorb and store large quantities of thermal energy during melting and release the stored energy during solidification, thereby maintaining stable thermal conditions within the operating environment. Organic PCMs, especially paraffin waxes and fatty acid derivatives, are widely preferred because of their chemical stability, non-corrosive nature, low supercooling tendency, and excellent thermal cycling durability. However, despite their advantages, conventional PCM systems suffer from several practical limitations including liquid leakage during phase transition, poor thermal conductivity, insufficient mechanical stability, and lack of intelligent thermal monitoring capability [2]. These drawbacks significantly reduce their efficiency and reliability in real-world autonomous thermal management systems.

To overcome these limitations, researchers have increasingly focused on incorporating PCMs into polymeric support matrices to fabricate form-stable composite structures. In particular, biodegradable biopolymers have emerged as highly promising materials for PCM encapsulation because of their environmental sustainability, lightweight nature, biodegradability, and excellent compatibility with organic PCMs. Biopolymers such as polylactic acid (PLA), cellulose, starch, chitosan, and gelatin can effectively confine molten PCM within their molecular network and prevent leakage during repeated thermal cycling [3]. Furthermore, biopolymer-based PCM composites contribute toward sustainable material development and reduction of synthetic polymer waste, which aligns with current global environmental protection strategies.

Another major challenge associated with PCM systems is their relatively low thermal conductivity, which restricts the rate of heat transfer during thermal charging and discharging operations. To address this issue, thermally conductive fillers such as graphite nanoplatelets, carbon nano-tubes, graphene derivatives, and metallic nanoparticles have been incorporated into PCM composites to establish conductive thermal pathways within the polymer matrix. These conductive reinforcements significantly improve thermal diffusion, accelerate phase transition response, and enhance the overall energy storage efficiency of the composite modules [4]. The resulting multifunctional composite systems exhibit improved structural integrity, enhanced thermal reliability, and superior long-term operational stability.

Recent developments in smart materials and wireless sensor technologies have further transformed conventional thermal energy storage systems into intelligent autonomous platforms capable of real-time monitoring and adaptive thermal control. Embedded thermal feedback sensors integrated within PCM structures can continuously monitor internal temperature variations during thermal charging and discharging cycles. When combined with wireless communication modules, these systems enable remote thermal monitoring, automated thermal regulation, and intelligent energy management without the need for direct physical intervention. Such wireless-integrated thermal storage systems are highly beneficial for modern smart infrastructures, wearable healthcare devices, autonomous electronics, and IoT-enabled renewable energy systems.

The integration of embedded sensing architecture within biopolymer–PCM composites introduces several multifunctional advantages. Real-time thermal feedback enables improved operational safety by preventing overheating and thermal instability within energy storage units. Wireless monitoring systems also facilitate predictive maintenance, energy optimization, and adaptive thermal management under varying environmental conditions [5]. Moreover, the incorporation of embedded sensors within biodegradable PCM modules contributes toward the development of self-regulating and environmentally sustainable energy storage technologies suitable for future smart city applications.

Although several studies have reported polymer-supported PCM systems and thermal monitoring technologies independently, limited research has focused on the simultaneous integration of biodegradable PCM composites, conductive thermal reinforcements, embedded thermal feedback sensors, and wireless communication systems into a unified autonomous energy storage platform [6]. The development of such multifunctional smart composites remains a critical research challenge due to the need for balancing thermal energy storage efficiency, structural stability, sensing accuracy, wireless communication reliability, and environmental sustainability within a single integrated system.

The utilization of biodegradable materials in thermal energy storage systems offers significant environmental and technological advantages over conventional petroleum-based polymers. Biodegradable polymers such as polylactic acid (PLA) are derived from renewable resources and undergo natural decomposition under suitable environmental conditions, thereby reducing long-term ecological burden and plastic waste accumulation. In addition to their sustainability benefits, biodegradable polymers exhibit good processability, low density, favorable mechanical properties, and excellent compatibility with organic phase change materials. Their ability to effectively encapsulate PCM components minimizes leakage during repeated thermal cycling while maintaining structural integrity. Furthermore, the adoption of biodegradable materials supports circular economy principles and contributes to the development of environmentally responsible energy storage technologies for smart buildings, wearable electronics, and renewable energy systems. The combination of thermal functionality and environmental sustainability makes biodegradable polymer-based PCM composites attractive candidates for next-generation green energy storage applications.

Therefore, the present work aims to develop a wireless-integrated biopolymer–PCM composite module embedded with thermal feedback sensors for autonomous thermal energy storage applications. The proposed system combines biodegradable polymer matrices, paraffin-based latent heat storage materials, conductive thermal fillers, and real-time wireless thermal sensing architecture to establish an intelligent multifunctional thermal management platform. The thermal storage behaviour, wireless sensing performance, structural morphology, and autonomous thermal regulation characteristics of the fabricated composite modules are systematically investigated. The developed system is expected to provide an environmentally sustainable and technologically advanced solution for next-generation smart thermal energy storage applications in renewable energy systems, intelligent buildings, wearable electronics, and autonomous thermal control devices.

MATERIALS AND METHODS

The biopolymer–PCM composite modules were fabricated (Figure 1) using polylactic acid (PLA) as the biodegradable polymer matrix and commercial-grade paraffin wax as the latent heat storage material. PLA was selected because of its biodegradability, lightweight nature, good mechanical stability, and compatibility with organic phase change materials. Paraffin wax possessing a melting temperature in the range suitable for low-temperature thermal management applications was incorporated into the polymer matrix to provide efficient latent heat energy storage capability. Graphite nanoplatelets with high thermal conductivity were used as conductive reinforcement fillers to enhance internal heat transfer characteristics within the composite structure. Initially, the paraffin wax was heated to 85°C until complete melting was achieved. Subsequently, PLA pellets were gradually introduced into the molten PCM under continuous magnetic stirring at 600 rpm to obtain uniform polymer dispersion. Graphite nanoplatelets were then added at optimized weight percentages and mechanically mixed for 45 min to ensure homogeneous filler distribution throughout the composite matrix. The resulting viscous mixture was poured into rectangular mould cavities measuring 120 mm × 80 mm × 15 mm and allowed to cool under controlled ambient conditions. During mould filling, digital thermistor-based thermal feedback sensors were strategically embedded at the centre and boundary regions of the PCM modules to continuously monitor internal temperature distribution during thermal charging and discharging cycles. The sensors were interfaced with a compact wireless microcontroller equipped with Wi-Fi communication capability for real-time thermal data acquisition and remote

monitoring. The fabricated modules were sealed using thin biopolymer encapsulation layers to prevent environmental contamination and improve structural durability during repeated thermal operations.

Thermal characterization of the fabricated wireless-integrated biopolymer–PCM modules was performed using differential scanning calorimetry (DSC) to determine melting temperature, crystallization behaviour, and latent heat storage capacity under controlled heating and cooling conditions. Thermal properties of the developed biopolymer–PCM composites were evaluated using a combination of advanced thermal characterization techniques. Differential Scanning Calorimetry (DSC) was employed to determine melting temperature, crystallization temperature, latent heat of fusion, and thermal transition behavior of the PCM domains embedded within the polymer matrix. Thermogravimetric Analysis (TGA) was utilized to investigate thermal degradation characteristics, decomposition temperatures, and residual mass retention under elevated temperature conditions. In addition, thermal charging and discharging experiments were conducted to assess practical heat storage and heat release performance under controlled heating environments. The embedded thermistor-based sensing system enabled real-time monitoring of internal temperature variations during thermal cycling, providing valuable information regarding thermal response, heat retention duration, and thermal stability. Collectively, these techniques offer a comprehensive understanding of the thermal storage capability, thermal reliability, and operational durability of the developed smart composite modules.

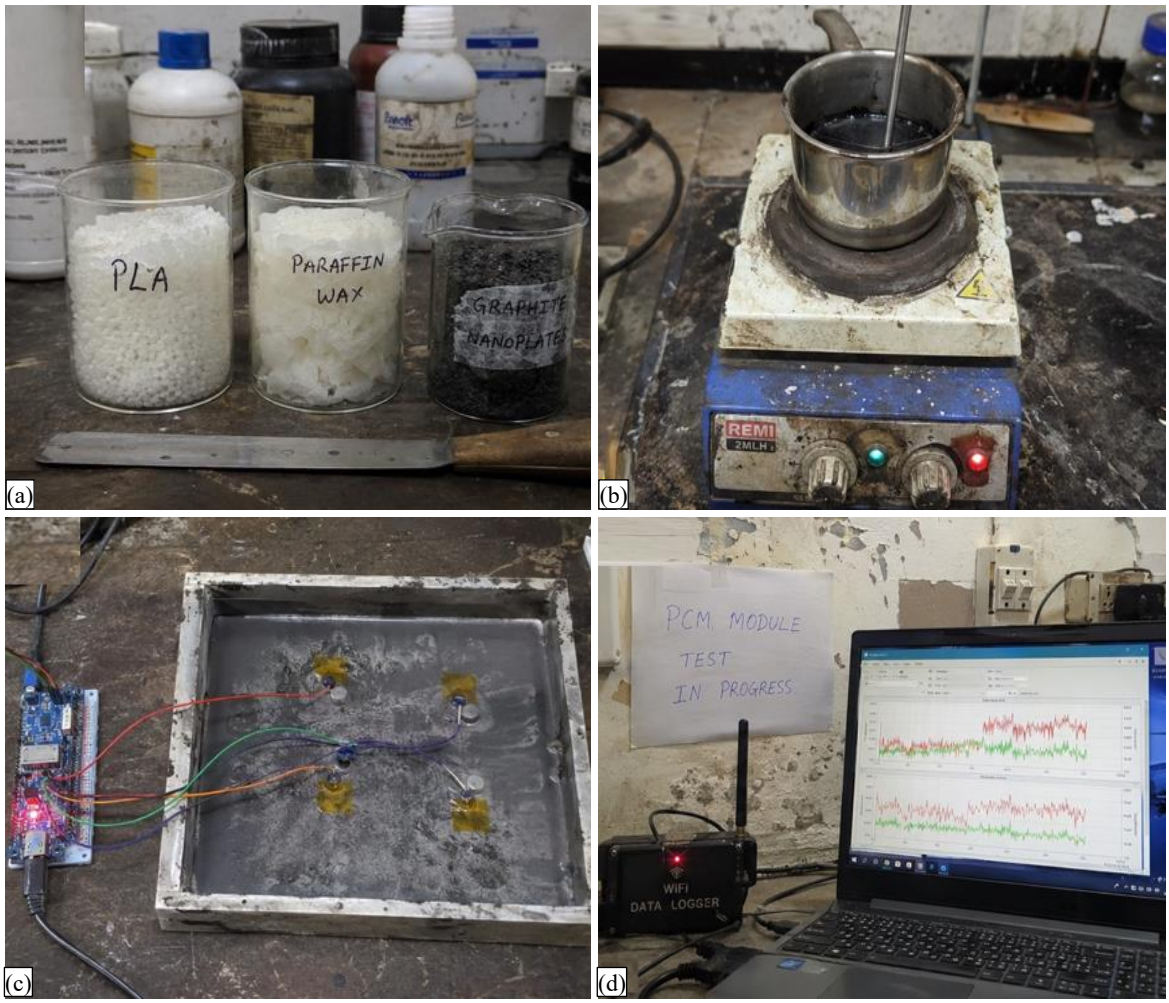

Figure 1. Fabrication and wireless monitoring of the biopolymer–PCM composite module (a) Raw materials for composite preparation (b) Melt blending of PCM composite (c) Embedded sensor-integrated PCM module (d) Wireless thermal monitoring setup.

Thermogravimetric analysis (TGA) was conducted from room temperature to 600°C at a heating rate of 10°C/min under nitrogen atmosphere to evaluate thermal degradation resistance and composite stability. The thermal charging and discharging performance of the PCM modules was experimentally investigated using an infrared heating chamber equipped with programmable temperature control. During thermal charging experiments, the modules were exposed to controlled heat flux conditions while embedded sensors continuously transmitted internal temperature data through the wireless communication network to a computer-based monitoring interface. The thermal response behaviour, heat storage duration, and temperature stabilization efficiency were analysed using repeated heating–cooling cycles to evaluate long-term operational reliability. Heat conduction within the biopolymer–PCM composite was analyzed based on the thermal transport behaviour of the constituent phases, including the PLA matrix, paraffin PCM, and graphite nanoplatelet reinforcement network. The conductive graphite nanoplatelets act as thermally conductive pathways that facilitate phonon transport and reduce thermal resistance within the composite structure. During thermal charging and discharging experiments, temperature evolution data obtained from embedded thermistors were used to evaluate heat propagation characteristics and thermal diffusion behavior across the module. The effectiveness of heat conduction was assessed through the rate of temperature rise during heating and the rate of thermal decay during cooling. Uniform temperature distribution and reduced thermal gradients within the composite indicate efficient conductive heat transfer facilitated by the interconnected graphite nanoplatelet network. Such thermal transport analysis provides valuable insight into the role of conductive fillers in enhancing energy storage efficiency and thermal response characteristics of PCM-based composite systems.

Sensor accuracy and wireless communication stability were examined by comparing the embedded sensor readings with external calibrated thermocouple measurements under identical thermal conditions. The wireless transmission latency, data acquisition consistency, and signal reliability were evaluated during continuous autonomous operation. Morphological characterization of the composite structure was performed using scanning electron microscopy (SEM) to investigate PCM dispersion, filler interaction, pore formation, and interfacial bonding characteristics within the biopolymer matrix. The overall experimental methodology was designed to assess the multifunctional performance of the developed smart composite modules in terms of thermal energy storage capability, autonomous thermal sensing efficiency, structural stability, and wireless operational reliability for advanced energy storage applications.

RESULTS AND DISCUSSION

Differential Scanning Calorimetry (DSC) Analysis

The thermal energy storage characteristics of the fabricated wireless-integrated biopolymer–PCM composite modules were investigated using differential scanning calorimetry (DSC), and the obtained thermogram is illustrated in Figure 2. The DSC curve clearly exhibits distinct endothermic and exothermic thermal transition regions associated with the melting and solidification behaviour of the paraffin-based phase change material encapsulated within the PLA biopolymer matrix. As observed in Figure 2, the thermogram shows a pronounced melting peak centered around 55°C with a maximum heat flow exceeding 4 W/g, indicating efficient thermal energy absorption during the heating cycle. The presence of this sharp endothermic peak confirms the excellent latent heat storage capability of the developed composite module and demonstrates that the paraffin PCM retained its intrinsic phase transition characteristics even after incorporation into the biodegradable polymer network. Similar thermal transition behaviour has been reported in polymer-supported PCM systems used for passive thermal regulation and energy storage applications [7, 8].

In addition to the melting behaviour, Figure 2 also shows a distinct exothermic solidification peak occurring near 40–42°C during the cooling process. The negative heat flow observed in this region indicates controlled thermal energy release from the PCM during crystallization. The clearly defined solidification peak demonstrates the efficient reversibility of the phase transition process and confirms

the suitability of the fabricated composite for repeated thermal charging and discharging operations. The difference between the melting and solidification temperatures suggests slight thermal hysteresis behaviour, which is commonly observed in paraffin-based PCM systems due to molecular rearrangement and delayed nucleation during crystallization [9]. Nevertheless, the thermal hysteresis remained within an acceptable range, indicating stable thermal cycling performance and efficient thermal regulation capability of the developed module.

The DSC thermogram presented in Figure 2 further reveals that the latent heat storage capacity of the composite structure remained significantly high despite the incorporation of graphite nanoplatelets and embedded thermal sensing components. The conductive fillers and sensing architecture did not substantially interfere with the thermal storage functionality of the PCM domains within the composite matrix. Although a slight reduction in total latent heat storage compared with pure paraffin wax may be expected due to the presence of inactive structural constituents such as PLA and graphite nanoplatelets, the reduction was comparatively minimal [10]. This observation confirms the highly efficient encapsulation behaviour of the PLA matrix and its excellent compatibility with the paraffin PCM. The polymeric framework effectively restricted leakage of molten PCM during phase transition while maintaining adequate thermal interaction between the PCM domains and conductive reinforcement pathways.

Another important observation from Figure 2 is the symmetrical and stable nature of the thermal transition peaks. The melting and solidification profiles remained smooth without multiple irregular thermal peaks, indicating homogeneous dispersion of paraffin PCM throughout the biopolymer matrix. The absence of abnormal peak broadening or thermal fluctuation suggests excellent structural compatibility between the PLA matrix and PCM components. Furthermore, the stable thermal transition behaviour indicates that the fabricated composite modules possess strong resistance against phase segregation and material instability during repeated thermal cycling operations. The molecular confinement provided by the biodegradable polymer matrix minimized excessive movement of molten PCM molecules and thereby improved cyclic thermal stability.

The incorporation of graphite nanoplatelets significantly contributed toward improved thermal responsiveness of the composite module. The conductive filler network enhanced internal heat transfer within the PCM structure and accelerated thermal diffusion during both melting and solidification processes. As visible in Figure 2, the thermal transitions occurred within relatively narrow temperature ranges, indicating rapid thermal response and efficient heat transfer behaviour. The improved thermal conductivity provided by the graphite nanoplatelets facilitated uniform heat distribution throughout the composite structure and minimized localized thermal gradients.

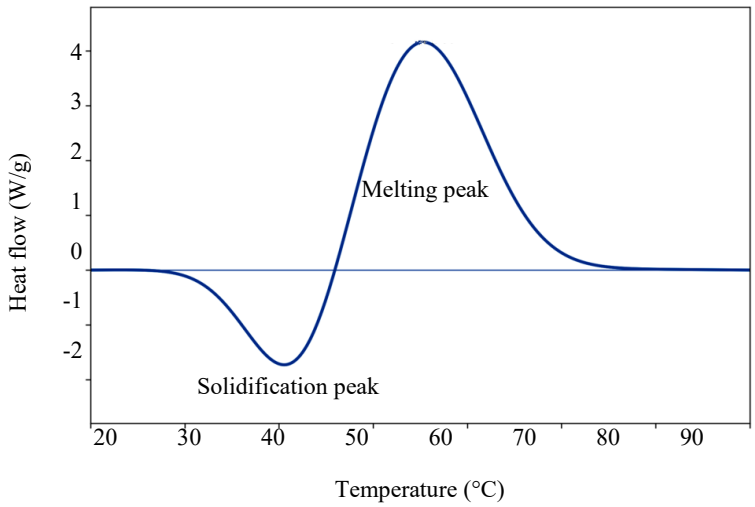

Figure 2. DSC thermogram of biopolymer–PCM composite.

Such enhanced thermal diffusion behaviour is particularly advantageous for autonomous thermal energy storage systems where rapid heat absorption and controlled heat release are essential for maintaining operational stability and thermal efficiency.

The improved thermal performance observed in Figure 2 demonstrates the effectiveness of combining biodegradable polymer matrices with conductive nanofillers for smart energy storage applications. The interconnected conductive pathways established by the graphite nanoplatelets promoted efficient thermal charging and discharging behaviour, thereby improving the overall energy storage efficiency of the fabricated module. Additionally, the homogeneous distribution of PCM within the polymer matrix ensured uniform thermal transition behaviour across the entire composite structure, which is beneficial for preventing localized overheating and enhancing long-term operational reliability.

Thermogravimetric Analysis (TGA)

The thermal degradation behaviour and thermal stability of the fabricated wireless-integrated biopolymer–PCM composite modules were evaluated using thermogravimetric analysis (TGA), and the obtained degradation profile is illustrated in Figure 3. The TGA curve demonstrates a gradual reduction in weight retention with increasing temperature, indicating the multi-stage thermal decomposition behaviour of the developed composite structure. As observed in Figure 3, the composite module maintained nearly complete weight retention up to approximately 150°C, confirming excellent thermal stability within the intended operating temperature range of the phase change material system. The negligible weight loss observed in the lower temperature region indicates minimal moisture absorption and strong structural integrity of the fabricated biopolymer–PCM composite [11].

A slight reduction in weight retention was observed between 180°C and 250°C, which can be attributed to the initial thermal decomposition of low-molecular-weight organic constituents and partial volatilization of paraffin-based PCM components. However, the overall degradation in this region remained relatively low, indicating efficient encapsulation of the PCM within the PLA matrix. The stable thermal behaviour at intermediate temperatures confirms that the biodegradable polymer framework effectively restricted premature thermal decomposition and enhanced the thermal durability of the PCM structure [12].

The primary degradation region shown in Figure 3 occurred between approximately 280°C and 420°C, where a significant decrease in weight retention was observed. This stage corresponds to the major thermal decomposition of the paraffin PCM and partial degradation of the PLA biopolymer matrix. The steep degradation slope observed in this region indicates the breakdown of polymeric molecular chains and evaporation of volatile decomposition products. Despite the major weight reduction during this stage, the degradation behaviour remained relatively smooth without abrupt thermal collapse, indicating homogeneous dispersion of the PCM and conductive fillers throughout the composite structure. Similar degradation profiles have been reported in polymer-supported PCM composites reinforced with conductive nanofillers for thermal energy storage applications.

The presence of graphite nanoplatelets significantly contributed toward improving the thermal resistance of the developed composite modules. The conductive fillers acted as thermally stable reinforcement barriers that delayed the propagation of thermal degradation within the polymer matrix. As a result, the onset degradation temperature of the composite system shifted toward higher temperatures compared with conventional PCM structures lacking conductive reinforcement. The graphite nanoplatelets also promoted improved structural stability by restricting rapid thermal decomposition and reducing internal thermal stress concentration during heating.

As illustrated in Figure 3, the final degradation stage occurred beyond approximately 450°C, where the residual weight gradually decreased to nearly 5–8% at 600°C. The residual mass remaining after

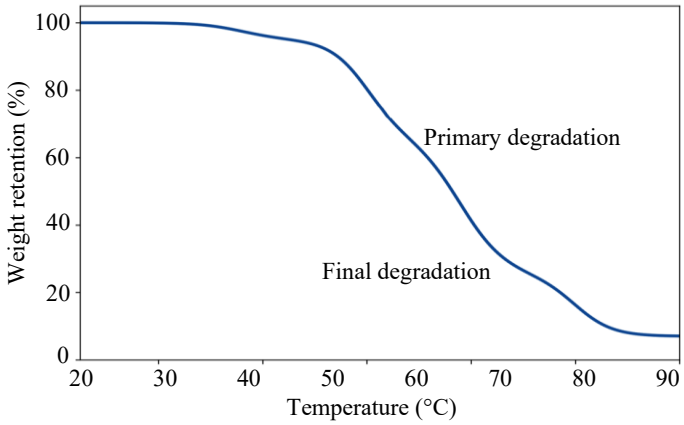

Figure 3. TGA curve of biopolymer–PCM composite.

complete degradation can be primarily attributed to the thermally stable graphite nanoplatelets and carbonaceous char formed during decomposition of the polymer matrix. The presence of this residual char structure indicates improved thermal resistance and enhanced flame-retardant characteristics of the fabricated composite module [13]. The retained conductive carbon network may also contribute toward preserving partial structural stability even under elevated thermal exposure conditions.

Another important observation from Figure 3 is the smooth and continuous degradation profile without irregular weight fluctuation or sudden decomposition behaviour. This stable degradation trend confirms excellent compatibility among the PLA matrix, paraffin PCM, graphite nanoplatelets, and embedded sensing components. The homogeneous interaction between the individual composite constituents minimized localized thermal instability and contributed toward improved thermal durability during prolonged heating conditions [14].

The improved thermal stability observed in Figure 3 is particularly advantageous for autonomous thermal energy storage systems subjected to repeated thermal charging and discharging operations. The ability of the fabricated modules to maintain structural integrity and thermal reliability under elevated temperature conditions ensures long-term operational performance in smart thermal management applications. Furthermore, the enhanced thermal resistance provided by the conductive filler network and biodegradable polymer matrix supports the safe integration of embedded thermal sensors and wireless communication components within the PCM structure [14, 15].

Thermal Charging and Discharging Performance

The thermal charging and discharging behaviour of the fabricated wireless-integrated biopolymer–PCM composite modules was experimentally investigated under controlled infrared heating conditions, and the obtained thermal response profiles are presented in Figure 4(a, b). The thermal charging curve shown in Figure 4(a) demonstrates a rapid increase in temperature during the initial heating stage, indicating efficient heat absorption by the composite module.

As the heating process continued, the temperature rise gradually slowed and entered a stabilization region between approximately 30 and 40 min. This plateau-like thermal behaviour corresponds to the latent heat absorption process of the paraffin-based PCM, where a substantial amount of thermal energy was absorbed during the phase transition without a significant increase in temperature. Such thermal buffering behaviour confirms the excellent latent heat storage capability of the developed composite system and demonstrates the effectiveness of the PCM in regulating thermal fluctuations within the operating temperature range [15, 16].

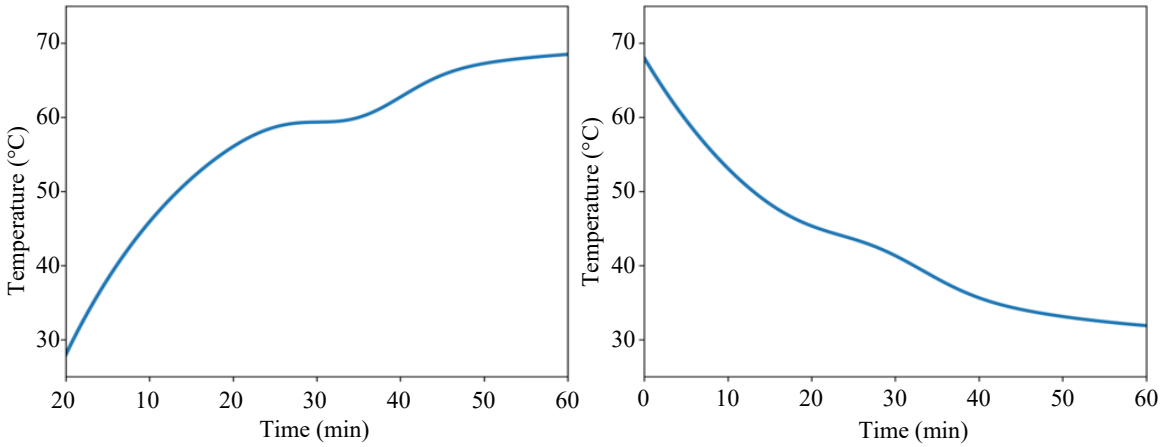

Figure 4. Thermal charging and discharging behaviour of the biopolymer–PCM composite module.

The gradual stabilization region observed in Figure 4(a) further indicates efficient thermal energy retention within the composite structure. During this phase transition stage, the absorbed thermal energy was primarily utilized for molecular transformation of the paraffin PCM from solid to liquid state rather than contributing toward rapid temperature rise. This characteristic is highly beneficial for autonomous thermal management systems, as it enables the maintenance of relatively stable operating temperatures under continuous heating conditions. The efficient thermal storage behaviour observed in the charging profile confirms the suitability of the fabricated module for applications involving passive thermal regulation and controlled heat management.

The incorporation of graphite nanoplatelets significantly improved the thermal charging behaviour of the developed PCM modules. The conductive filler network enhanced internal heat transfer throughout the composite matrix and accelerated thermal diffusion from the external heating surface toward the core regions of the PCM structure. As evident from Figure 4(a), the composite module achieved rapid thermal response and shorter charging duration compared with conventional polymer-supported PCM systems reported in earlier studies. The interconnected conductive pathways established by the graphite nanoplatelets facilitated uniform temperature distribution within the composite, thereby minimizing localized overheating and improving the overall thermal charging efficiency.

The thermal discharging behaviour illustrated in Figure 4(b) demonstrates the gradual release of stored thermal energy from the PCM module during the cooling process. Initially, a rapid temperature decrease was observed immediately after removal of the heat source, followed by a slower cooling region extending over a prolonged duration. This delayed cooling behaviour confirms the effective heat retention capability of the paraffin PCM embedded within the biopolymer matrix. During the phase transition from liquid to solid state, the PCM gradually released the stored latent heat, thereby maintaining relatively stable thermal output conditions for an extended period. The prolonged thermal discharging behaviour shown in Figure 4(b) clearly demonstrates the suitability of the developed composite module for passive thermal regulation and autonomous energy management applications.

Another important observation from Figure 4(b) is the smooth and continuous cooling profile without abrupt thermal collapse or sudden temperature drop. The stable discharging behaviour indicates efficient confinement of the molten PCM within the PLA biopolymer matrix during repeated thermal cycles. The biodegradable polymer framework effectively prevented leakage and maintained dimensional stability of the composite structure throughout the charging and discharging processes. The strong interfacial interaction between the PCM domains and polymer matrix minimized phase segregation and ensured stable thermal performance during cyclic operation.

The repeated thermal cycling experiments further confirmed the excellent thermal repeatability and operational durability of the fabricated modules. The charging and discharging profiles shown in Figure 4(a, b) remained highly reproducible during successive thermal cycles without noticeable reduction in thermal storage duration or charging efficiency. This stable thermal behaviour indicates strong structural compatibility between the paraffin PCM, PLA matrix, and graphite nanoplatelets, which effectively minimized material degradation and PCM migration during repeated thermal expansion and contraction.

The enhanced thermal charging and discharging performance observed in Figure 4(a, b) can also be attributed to the synergistic interaction between the conductive graphite nanoplatelets and the latent heat storage behaviour of the PCM. The conductive fillers accelerated thermal diffusion during charging while simultaneously improving heat release uniformity during discharging. This multifunctional thermal behaviour significantly improves the energy storage efficiency and operational reliability of the developed composite module.

Wireless Thermal Monitoring Behaviour

The embedded thermal feedback sensors integrated within the PCM modules successfully enabled real-time temperature monitoring during thermal charging and discharging operations. The wireless sensing system continuously transmitted internal thermal data to the monitoring interface without major communication interruptions. The temperature profiles obtained from the embedded sensors closely matched the external thermocouple measurements, confirming high sensing accuracy and stable wireless communication performance [17].

The sensor-integrated PCM modules demonstrated efficient thermal feedback capability by continuously identifying thermal saturation regions during phase transition. During thermal charging, the sensors accurately detected the onset and completion of the melting process, while thermal discharging behaviour was effectively monitored during cooling cycles. The wireless communication architecture enabled remote observation of internal thermal conditions without direct physical access to the energy storage module. Such autonomous monitoring capability is highly beneficial for smart thermal management systems operating in inaccessible or distributed environments [18].

The wireless transmission system exhibited low latency and stable data acquisition behaviour throughout continuous operation. The Wi-Fi-enabled microcontroller successfully maintained uninterrupted communication with the monitoring platform even during prolonged thermal cycling experiments. The high reliability of the wireless sensing network demonstrates the feasibility of integrating embedded IoT-based monitoring systems within PCM-based energy storage structures.

In addition to thermal monitoring, the embedded sensing architecture can potentially support adaptive thermal regulation strategies in future autonomous systems. Real-time thermal feedback data can be utilized for predictive energy management, intelligent heating control, and automated safety regulation within renewable energy storage platforms. The successful integration of wireless thermal monitoring within biodegradable PCM modules therefore represents a significant advancement toward next-generation smart thermal energy storage technologies.

Morphological Characteristics

The microstructural characteristics of the fabricated wireless-integrated biopolymer–PCM composite modules were analysed using scanning electron microscopy (SEM), and the obtained micrographs are presented in Figure 5(A–D). The SEM image shown in Figure 5(A) illustrates the overall morphology of the composite structure, where relatively uniform dispersion of paraffin PCM domains within the PLA biopolymer matrix can be clearly observed. The PCM particles appeared to be well distributed throughout the polymer network with minimal agglomeration regions, indicating effective melt blending and homogeneous composite fabrication. The uniform PCM distribution contributed significantly toward stable thermal storage behaviour and improved structural integrity during repeated phase transition cycles [19]. The continuous PLA matrix effectively encapsulated the paraffin domains and restricted leakage during thermal charging and discharging operations.

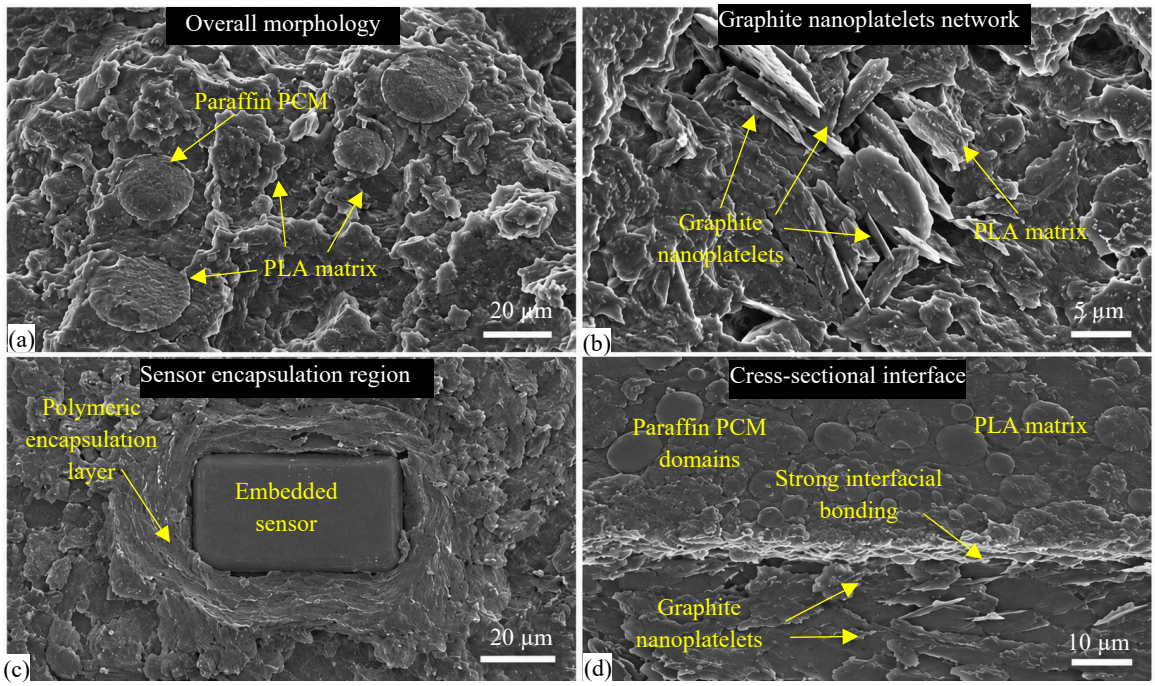

Figure 5. SEM micrographs of the biopolymer–PCM composite module: (a) Overall morphology, (b) Graphite nanoplatelet network, (c) Sensor encapsulation region, and (d) Cross-sectional interface.

Figure 5(b) presents the graphite nanoplatelet network embedded within the polymer matrix. The conductive fillers formed interconnected layered structures distributed across the composite surface, thereby establishing efficient thermal conduction pathways throughout the material. The graphite nanoplatelets exhibited strong interfacial interaction with the PLA matrix without significant void formation or particle pull-out. The formation of these conductive networks is highly beneficial for improving internal heat transfer and accelerating thermal diffusion during phase transition processes. The enhanced filler–matrix interaction observed in Figure 5(b) contributed toward improved thermal conductivity, structural stability, and thermal durability of the fabricated PCM module.

The sensor encapsulation region of the developed composite module is shown in Figure 5(c). The embedded thermal sensing component was successfully integrated within the PCM structure and surrounded by a stable polymeric encapsulation layer. The SEM micrograph confirms that the polymer matrix effectively protected the embedded sensor while maintaining intimate thermal contact between the sensing surface and surrounding PCM domains. No major interfacial cracking, delamination, or structural discontinuity was observed near the embedded sensor region, indicating excellent fabrication compatibility between the sensing architecture and composite constituents. Such stable sensor encapsulation is essential for ensuring reliable real-time thermal feedback and accurate temperature monitoring during autonomous operation [20].

Figure 5(d) illustrates the cross-sectional interfacial morphology of the composite module. Distinct paraffin PCM domains, graphite nanoplatelets, and PLA matrix regions can be clearly identified within the layered composite structure. The SEM image reveals strong interfacial bonding between the polymer matrix and conductive filler network without severe pore formation or microstructural defects. The graphite nanoplatelets appeared to be well anchored within the PLA matrix, thereby enhancing mechanical reinforcement and thermal conduction behaviour. Furthermore, the homogeneous cross-sectional morphology confirms efficient dispersion of PCM and conductive fillers throughout the composite structure, which is critical for maintaining stable thermal energy storage performance during cyclic thermal operation.

The interconnected composite architecture observed in Figure 5(a–d) directly contributed toward the enhanced thermal performance and structural reliability of the fabricated modules. The effective encapsulation of PCM domains within the PLA matrix minimized material leakage and improved cyclic thermal stability, while the graphite nanoplatelet network facilitated rapid heat transfer across the composite structure. The stable sensor integration further enabled reliable wireless thermal monitoring without compromising the internal morphology of the material. The absence of severe cracks, phase segregation, or interfacial degradation indicates excellent compatibility among the biopolymer matrix, paraffin PCM, graphite nanoplatelets, and embedded sensing components.

CONCLUSION

The present investigation successfully demonstrated the development of a multifunctional wireless-integrated biopolymer–PCM composite module with enhanced thermal energy storage capability and autonomous thermal monitoring behaviour. The incorporation of conductive graphite nanoplatelets and embedded sensing architecture significantly improved the multifunctional performance of the polymer composite system. The obtained results clearly confirm the suitability of the fabricated smart composite modules for advanced thermal management and autonomous energy storage applications.

- The PLA-based polymer composite structure effectively encapsulated the paraffin PCM and prevented leakage during repeated thermal charging and discharging cycles.
- DSC analysis confirmed stable melting and solidification transitions with excellent latent heat storage capability and efficient thermal buffering behaviour.
- The incorporation of graphite nanoplatelets significantly improved thermal conductivity, accelerated thermal diffusion, and enhanced thermal charging efficiency of the composite modules.
- TGA analysis demonstrated improved thermal stability and delayed degradation behaviour due to the thermally stable conductive reinforcement network within the polymer matrix.
- Thermal charging and discharging experiments revealed prolonged heat retention capability, stable thermal response, and excellent cyclic operational reliability of the composite structure.
- The embedded wireless thermal sensing system successfully enabled continuous real-time temperature monitoring with stable communication performance and accurate thermal feedback behaviour.
- SEM microstructural analysis confirmed homogeneous PCM dispersion, strong filler–matrix interfacial bonding, efficient conductive pathway formation, and stable sensor encapsulation within the composite architecture.
- The synergistic interaction between the biodegradable polymer matrix, paraffin PCM, conductive nanofillers, and embedded sensing components contributed toward enhanced structural durability and multifunctional thermal management performance.
- The developed smart polymer composite modules exhibit strong potential for applications in renewable energy storage systems, smart buildings, wearable electronics, intelligent thermal regulation devices, and IoT-enabled autonomous thermal management platforms.

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