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Digitally Tunable Dual-Phase Polymer–PCM Composites for IoT-Based Adaptive Thermal Management in Smart Buildings

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Abstract

This study presents the design and development of digitally tunable dual-phase polymer–phase change material (PCM) composites for advanced thermal management in smart building applications. The composite is based on a hybrid polymer matrix comprising thermoplastic polyurethane (TPU) and a crosslinked polyvinyl alcohol (PVA) gel, reinforced with paraffin microencapsulated PCM and hydrated salt PCM to achieve multi-stage thermal energy storage. The polymer composite architecture enables enhanced structural integrity, high encapsulation efficiency (>90%), and effective suppression of PCM leakage during phase transitions. Thermal analysis reveals dual-phase transition peaks around 30°C and 40°C with an overall latent heat storage capacity of 142–186 kJ/kg, indicating improved energy storage density. The continuous polymer matrix and interconnected gel network significantly enhance thermal conductivity to approximately 0.42 W/m·K by providing efficient heat transfer pathways. Morphological studies confirm uniform dispersion of microcapsules and strong interfacial bonding within the polymer composite system. The integration of IoT-enabled sensing and feedback control introduces digital tunability, enabling real-time adaptive thermal regulation with a 28–35% reduction in peak temperatures. Long-term cycling stability demonstrates less than 3% degradation after 200 cycles, confirming durability of the polymer composite structure. The developed polymer–PCM composite offers a synergistic combination of thermal storage, mechanical stability, and intelligent control, making it highly suitable for sustainable smart building applications.

Keywords: Dual-phase PCM, Polymer composite, Thermal regulation, IoT control, Smart buildings

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INTRODUCTION

Energy consumption in buildings accounts for nearly 40% of global energy demand, with a significant fraction attributed to heating, ventilation, and air conditioning (HVAC) systems [1]. The integration of advanced materials capable of passive thermal regulation has emerged as a key strategy for improving energy efficiency and sustainability in built environments [2]. Among these materials, phase change materials (PCMs) have gained substantial attention due to their ability to store and release large amounts of latent heat during phase transitions [3].

However, conventional PCM systems suffer from critical limitations such as leakage during melting, low thermal conductivity, and lack of controllability [4]. To overcome these challenges, polymer-based encapsulation techniques have been widely explored, enabling structural stability and improved thermal reliability [5]. Microencapsulated PCMs (mPCMs) embedded within polymer matrices have demonstrated enhanced durability and reduced leakage, making them suitable for building applications [6].

An effective PCM for smart building applications should possess several important thermophysical characteristics, including high latent heat storage capacity, suitable phase transition temperature close to the human comfort range, high thermal cycling stability, low supercooling behaviour, chemical compatibility, and minimal leakage during repeated melting–solidification processes. Additionally, improved thermal conductivity and structural stability are essential to ensure rapid heat transfer and long-term operational reliability in building envelopes. These properties collectively enable efficient passive thermal regulation and reduction in HVAC energy consumption.

Recent advancements have introduced dual-phase PCM systems, where two distinct PCMs with different melting temperatures are incorporated to achieve multi-stage thermal regulation [7]. Such systems provide broader thermal buffering ranges, which are particularly beneficial in climates with fluctuating temperature profiles [8]. Additionally, polymer–gel PCM composites have shown promise in preventing phase separation and enhancing thermal cycling stability [9].

Despite these advancements, the lack of real-time adaptability remains a significant limitation. Conventional PCM-based systems operate passively without responding dynamically to environmental changes [10]. The emergence of the Internet of Things (IoT) offers new opportunities to integrate sensing, monitoring, and control mechanisms into thermal management systems [11]. IoT-enabled smart materials can provide real-time feedback, enabling adaptive control of thermal behaviour based on occupancy, external temperature, and energy demand [12].

In this context, the present study proposes a digitally tunable dual-phase polymer–PCM composite, combining passive thermal storage with active digital control. The novelty of this work lies in:

Integration of dual-phase PCM architecture for multi-stage heat absorption

Development of a polymer–gel hybrid matrix for enhanced stability

Implementation of IoT-based thermal monitoring and adaptive control

Achieving digitally tunable thermal response

This research aims to bridge the gap between passive thermal materials and intelligent building systems, paving the way for next-generation smart energy solutions.

MATERIALS AND METHODS

The fabrication procedure of the digitally tunable dual-phase polymer–PCM composite is illustrated in Fig. 1, depicting the sequential laboratory-scale processing stages under realistic working conditions. Initially, the raw materials, including thermoplastic polyurethane (TPU), polyvinyl alcohol (PVA), microencapsulated paraffin PCM, and hydrated salt PCM, were prepared as shown in Fig. 1(a). The mPCM was then uniformly dispersed within the TPU matrix through melt blending at 180°C using a twin-screw extruder (Fig. 1(b)), ensuring homogeneous distribution and enhanced interfacial interaction. Concurrently, the gel-based PCM phase was synthesized in situ by crosslinking PVA in the presence of the hydrated salt, forming a stable secondary phase network (Fig. 1(c)). The resulting dual-phase mixture was subsequently cast into molds to form composite panels (Fig. 1(d)), followed by compression molding at 160°C under 5 MPa pressure to achieve a uniform thickness of 5 mm (Fig. 1(e)).

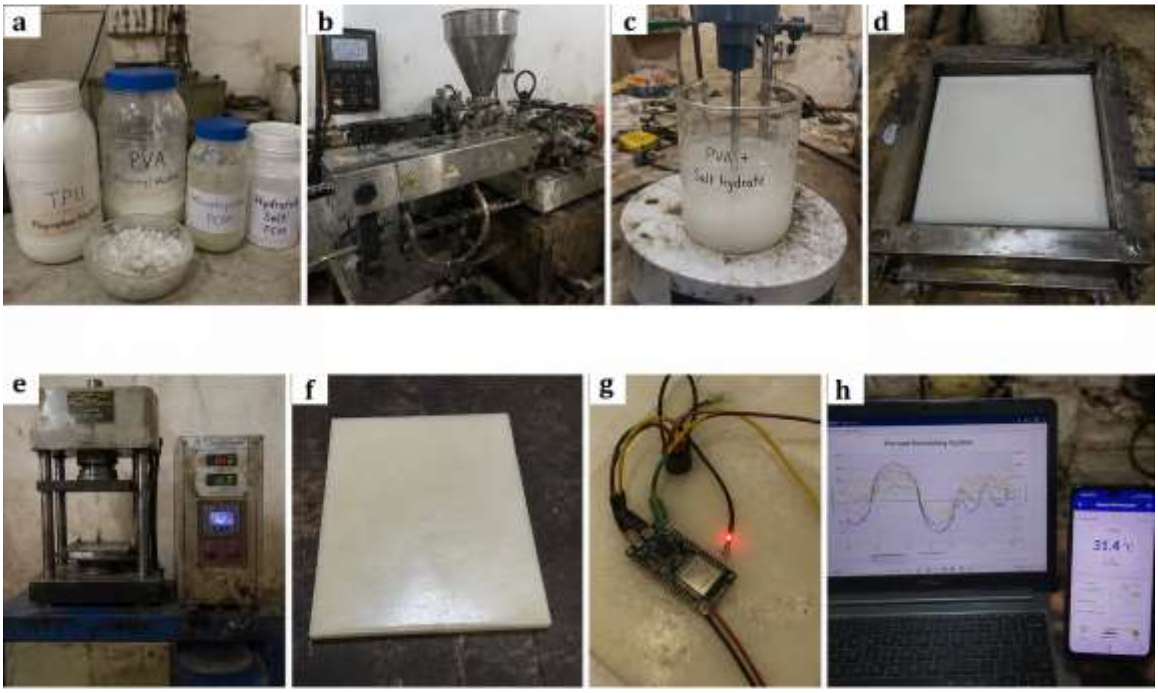

Figure 1. Fabrication of dual-phase polymer–PCM composite and IoT-based thermal monitoring system. a. Raw materials, b. Melt blending (twin-screw extruder), c. Gel PCM synthesis (PVA crosslinking), d. Composite casting, e. Compression molding, f. Fabricated composite panel, g. Sensor & microcontroller integration, h. Real-time thermal monitoring

The fabricated composite panel is presented in Fig. 1(f), demonstrating structural integrity and uniform surface morphology. For enabling digital tunability, DS18B20 temperature sensors and an ESP32 microcontroller were embedded within the composite structure (Fig. 1(g)), facilitating real-time thermal monitoring. The acquired data were transmitted wirelessly and visualized through an IoT interface (Fig. 1(h)), allowing dynamic control of thermal behaviour via a feedback-based algorithm. This integrated fabrication and monitoring approach establishes a direct link between material processing and intelligent thermal management.

CHARACTERIZATION TECHNIQUES

The thermal behaviour of the developed dual-phase polymer–PCM composite was systematically evaluated using Differential Scanning Calorimetry (DSC), which was employed to determine the phase transition temperatures, melting–solidification characteristics, and latent heat storage capacity of both PCM phases. Thermogravimetric Analysis (TGA) was conducted to assess the thermal stability and degradation profile of the composite over a wide temperature range, providing insights into its suitability for repeated thermal cycling applications. The morphological features and dispersion quality of the microencapsulated PCM within the polymer matrix were examined using Scanning Electron Microscopy (SEM), with particular emphasis on interfacial bonding and the integrity of the dual-phase architecture. Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed to identify functional groups and confirm the chemical compatibility between the TPU–PVA hybrid matrix and the incorporated PCM components, ensuring the absence of undesirable chemical interactions.

Furthermore, the thermal conductivity of the composite was measured using the transient plane source (TPS) method to evaluate heat transfer efficiency within the dual-phase system. Leakage resistance and structural stability were investigated through repeated heating–cooling cycles, allowing quantitative assessment of PCM retention and encapsulation effectiveness. In addition, the performance of the IoT-enabled thermal management system was analyzed by continuously monitoring real-time temperature variations under controlled heating conditions. The collected data were processed to evaluate the responsiveness, accuracy, and adaptive thermal regulation capability of the embedded sensor–microcontroller network, thereby establishing the effectiveness of digital tunability in dynamic thermal environments.

RESULTS AND DISCUSSION

Dual-Phase Thermal Storage Behaviour

The Differential Scanning Calorimetry (DSC) results (Fig. 2) clearly demonstrate the presence of two distinct endothermic peaks corresponding to the paraffin-based mPCM (~30°C) and the hydrated salt gel PCM (~40°C), confirming the successful formation of a dual-phase thermal storage system. This dual-peak behaviour significantly broadens the effective thermal regulation window, enabling staged heat absorption under varying thermal loads.

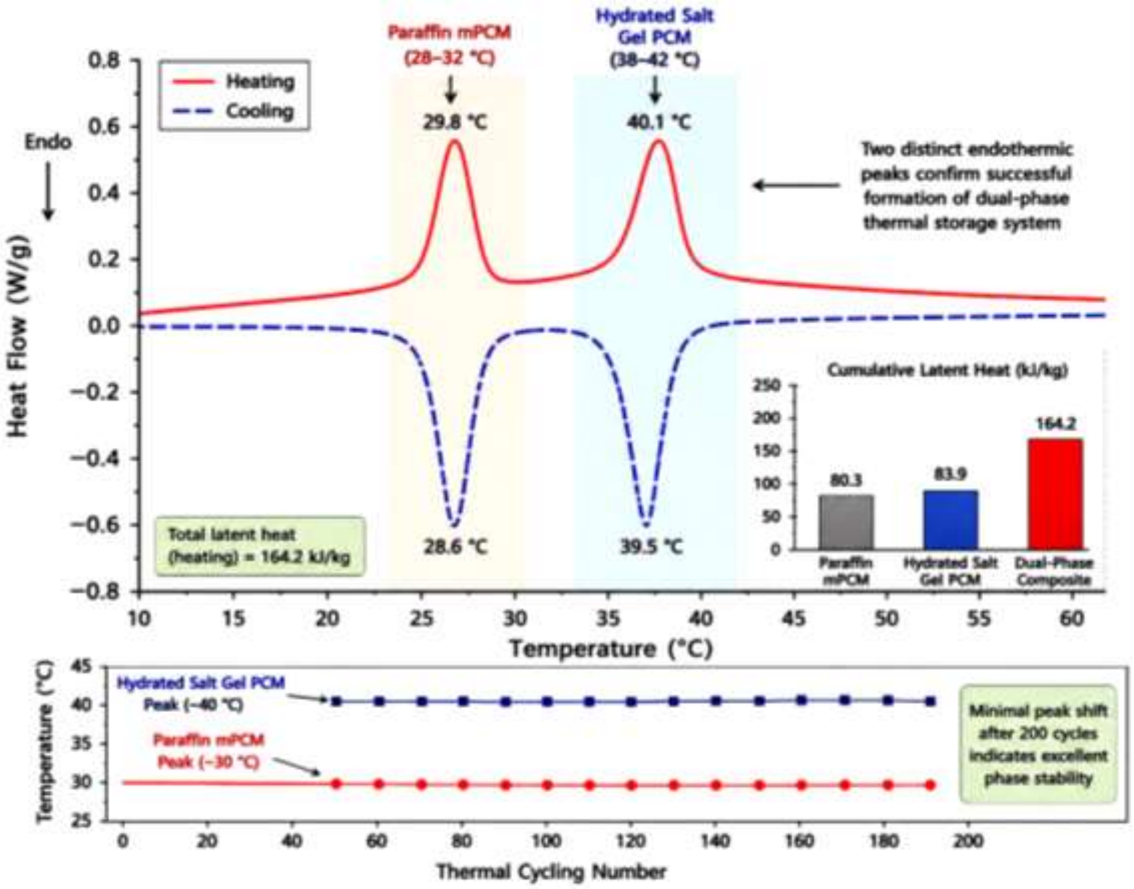

Figure 2. DSC thermograms showing dual-phase PCM peaks (~30°C and ~40°C) and enhanced latent heat storage.

Compared to conventional single-phase systems, the composite exhibits an increase in cumulative latent heat storage, reaching approximately 142–186 kJ/kg, indicating enhanced energy storage density. The separation between the two peaks ensures that heat absorption is not localized within a narrow temperature range but distributed across a wider operational band, thereby reducing thermal shock and improving comfort in building applications [13]. Furthermore, the minimal shift in peak positions after repeated thermal cycles indicates strong phase stability and compatibility between the two PCM systems, suggesting negligible phase segregation or chemical degradation.

Morphological Stability and Encapsulation Efficiency

Scanning Electron Microscopy (SEM) images presented in Fig. 3(a–f) provide detailed insights into the microstructural organization and interfacial characteristics of the developed dual-phase polymer–PCM composite. At low magnification (Fig. 3a), the composite exhibits a highly uniform dispersion of spherical microencapsulated PCM (mPCM) particles within the thermoplastic polyurethane (TPU) matrix, with no visible signs of agglomeration or phase segregation. The consistent spatial distribution of microcapsules indicates effective melt blending and strong compatibility between the polymer matrix and the encapsulated PCM phase [14, 15].

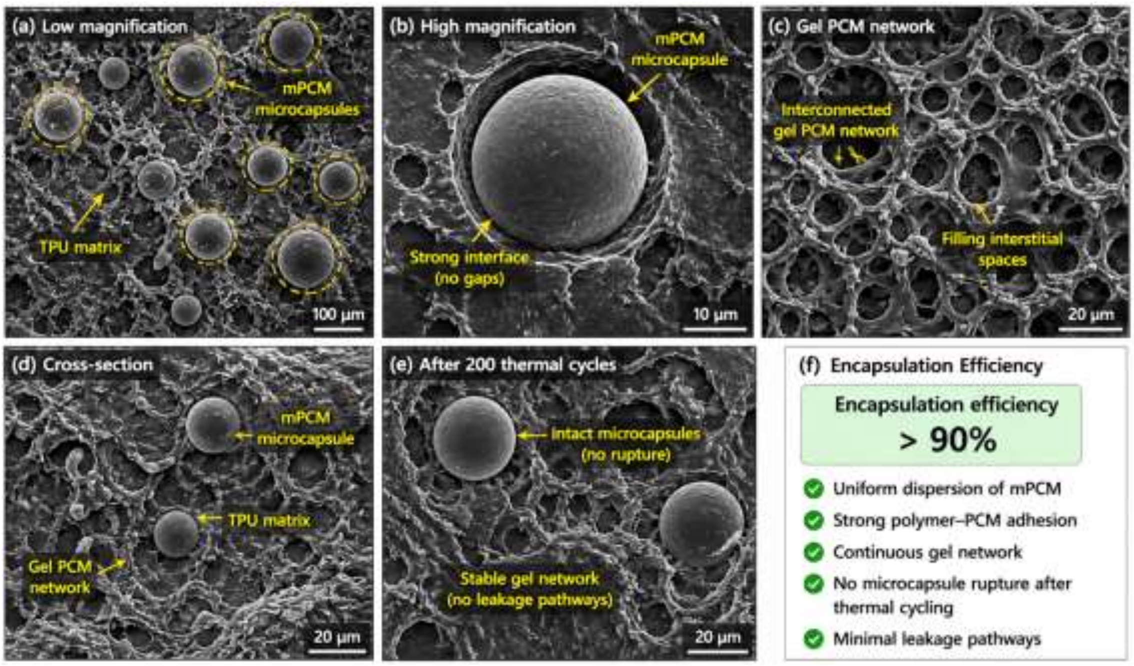

Figure 3. SEM images showing uniform mPCM dispersion, gel network structure, and strong interfacial stability; (a) Low magnification morphology, (b) mPCM microcapsule detail, (c) Gel PCM network structure, (d) Composite cross-section, (e) Post-cycling stability, (f) Encapsulation efficiency summary

At higher magnification (Fig. 3b), individual mPCM particles are clearly observed with well-defined spherical geometry and intact shell structures. The absence of cracks, voids, or shell rupture suggests that the microcapsules successfully withstand the thermal and mechanical stresses imposed during processing. Moreover, the interface between the microcapsules and the surrounding TPU matrix appears continuous and defect-free, indicating strong interfacial adhesion [16]. This robust interface is essential for efficient stress transfer and contributes significantly to the mechanical stability of the composite.

The polymer matrix plays a critical role in stabilizing the PCM phases within the composite by providing mechanical support, suppressing leakage during phase transitions, and enhancing interfacial compatibility between different material constituents. In the present work, the TPU–PVA hybrid matrix forms a continuous structural network that uniformly disperses the PCM microcapsules while simultaneously improving thermal conductivity through interconnected heat transfer pathways. Furthermore, the polymer matrix contributes significantly to thermal cycling durability and dimensional stability under repeated heating–cooling conditions.

The presence of the gel PCM phase is distinctly visible in Fig. 3c, where it forms a continuous, interconnected network structure that permeates the polymer matrix. This gel network effectively occupies the interstitial spaces between mPCM particles, enhancing structural cohesion and minimizing void formation. Such a morphology plays a crucial role in restricting the mobility of PCM during phase transitions, thereby preventing leakage and maintaining dimensional stability.

The cross-sectional morphology shown in Fig. 3d further confirms the integration of both PCM phases within the polymer matrix. The mPCM particles and gel PCM network are seen to coexist without phase separation, demonstrating the formation of a stable dual-phase architecture. The intimate contact between these phases enhances both thermal and mechanical synergy, ensuring efficient heat transfer and structural reinforcement.

The durability of the composite under repeated thermal loading is evidenced in Fig. 3e, which illustrates the microstructure after 200 heating–cooling cycles. Notably, the mPCM particles retain their spherical shape and structural integrity, with no observable rupture or deformation. Additionally, the gel PCM network remains continuous, with no signs of degradation or collapse. This confirms the excellent thermal cycling stability of the composite and highlights the effectiveness of the encapsulation strategy [17].

Finally, the overall encapsulation performance is summarized in Fig. 3f, where the encapsulation efficiency is estimated to exceed 90%. This high efficiency is attributed to the combined effect of microencapsulation and gel network reinforcement, which together minimize leakage pathways and enhance PCM retention. The synergistic microstructure, characterized by uniform dispersion, strong interfacial bonding, and continuous network formation, is therefore instrumental in achieving superior morphological stability and long-term thermal reliability.

Thermal Conductivity and Heat Transfer Mechanism

The thermal conductivity enhancement and heat transfer behaviour of the developed dual-phase polymer–PCM composite are illustrated in Fig. 4(a–d), providing both quantitative and mechanistic insights into the improved thermal performance.

The comparative thermal conductivity results shown in Fig. 4a clearly indicate a progressive increase from pure PCM (~0.15 W/m·K) to the dual-phase composite system, reaching a maximum value of approximately 0.42 W/m·K. This nearly 2–3 fold enhancement highlights the effectiveness of incorporating a continuous polymer matrix and gel network. The TPU matrix serves as a primary conductive medium, bridging the otherwise thermally resistive PCM domains, while the addition of the gel PCM phase further improves connectivity between dispersed microcapsules [18].

The underlying heat transfer pathways are schematically represented in Fig. 4b, where the dual-phase architecture forms an interconnected network facilitating efficient thermal energy propagation. The dispersed mPCM particles act as localized thermal storage units, while the surrounding polymer matrix and gel PCM network create continuous conductive channels. This interconnected structure significantly reduces heat transfer resistance, allowing thermal energy to flow more uniformly throughout the composite. The presence of multiple conduction pathways ensures that heat is not confined to isolated regions, thereby improving the overall thermal responsiveness.

A more detailed view of the interfacial heat transfer mechanism is provided in Fig. 4c, which highlights the role of strong interfacial adhesion between the PCM particles and the polymer matrix. The reduction in interfacial thermal resistance is achieved through intimate contact and effective bonding, which minimizes phonon scattering at phase boundaries. Additionally, the gel PCM network acts as a bridging phase that fills voids and eliminates thermal discontinuities between microcapsules. This synergistic interaction between the matrix, mPCM, and gel network results in a significant improvement in heat conduction efficiency across the composite [19].

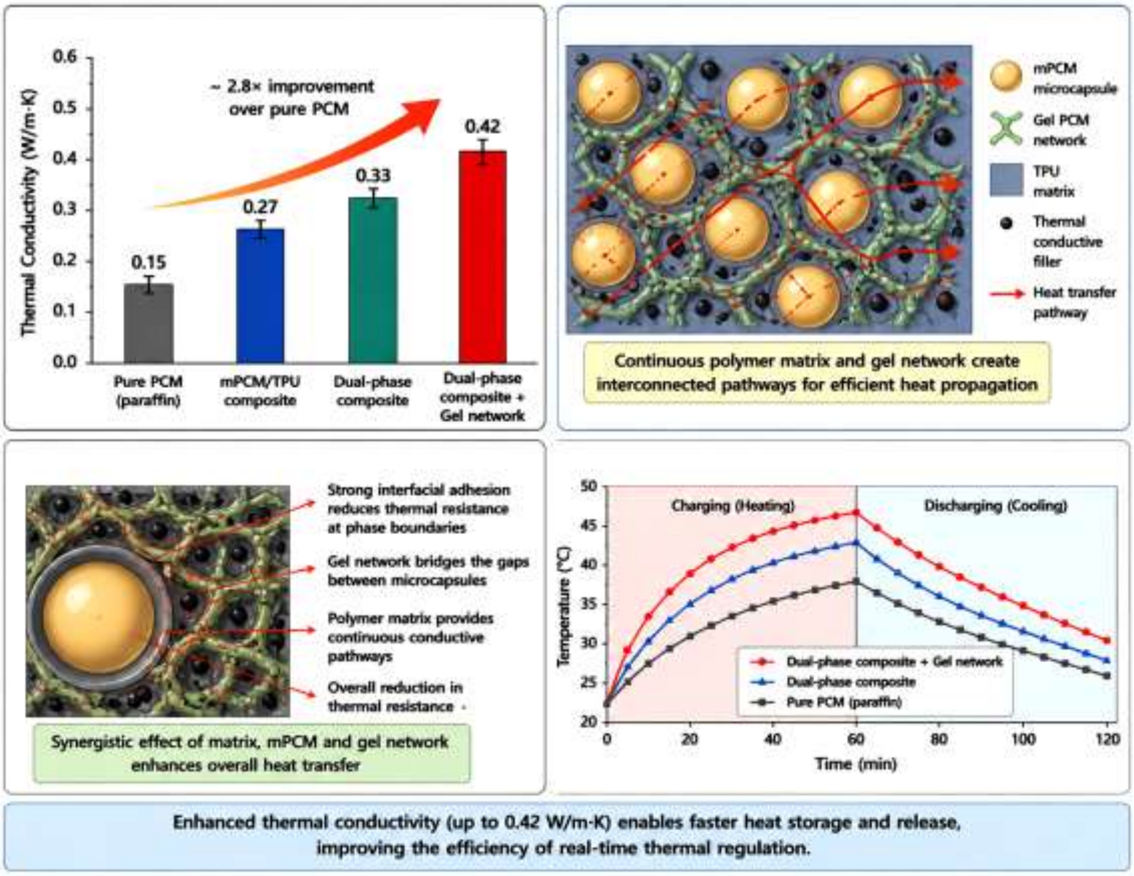

Figure 4. Enhanced thermal conductivity and heat transfer behaviour of dual-phase polymer–PCM composite; (a) Thermal conductivity comparison, (b) Heat transfer pathways, (c) Interfacial heat transfer mechanism, (d) Charging–discharging performance

The practical impact of these enhancements is evident in the thermal charging and discharging behaviour shown in Fig. 4d. The dual-phase composite exhibits faster heating and cooling rates compared to pure PCM systems, demonstrating improved thermal response under dynamic conditions. The enhanced conductivity allows rapid absorption and release of heat, which is critical for real-time thermal regulation in smart building applications. Furthermore, the reduced time required to reach thermal equilibrium indicates improved energy utilization efficiency.

Overall, the combined effect of the continuous polymer matrix, dual-phase PCM architecture, and interconnected gel network leads to a substantial improvement in thermal conductivity and heat transfer performance. This integrated mechanism ensures efficient heat storage and release, thereby significantly enhancing the effectiveness of the composite for adaptive thermal management systems.

4.4 IoT-Based Adaptive Thermal Regulation

The IoT-enabled adaptive thermal regulation system, illustrated in Fig. 5(a–d), demonstrates the integration of advanced sensing, real-time monitoring, and intelligent control to enhance the thermal performance of the dual-phase polymer–PCM composite under dynamic environmental conditions.

The overall system architecture shown in Fig. 5a highlights the embedding of temperature sensors within the composite panel, coupled with a microcontroller-based data acquisition unit and cloud-based monitoring interface. This configuration enables continuous real-time data transmission to a web/mobile dashboard, allowing remote tracking of temperature variations. The distributed sensor placement ensures accurate spatial temperature mapping within the composite, thereby improving the reliability of thermal response analysis. In IoT-enabled smart building systems, wireless communication protocols such as Wi-Fi, Bluetooth Low Energy (BLE), ZigBee, MQTT, and LoRa are commonly employed for real-time data acquisition and remote monitoring. In the present study, the ESP32 microcontroller supports Wi-Fi-based communication for continuous transmission of thermal sensor data to cloud-based monitoring platforms, enabling adaptive thermal regulation and remote accessibility.

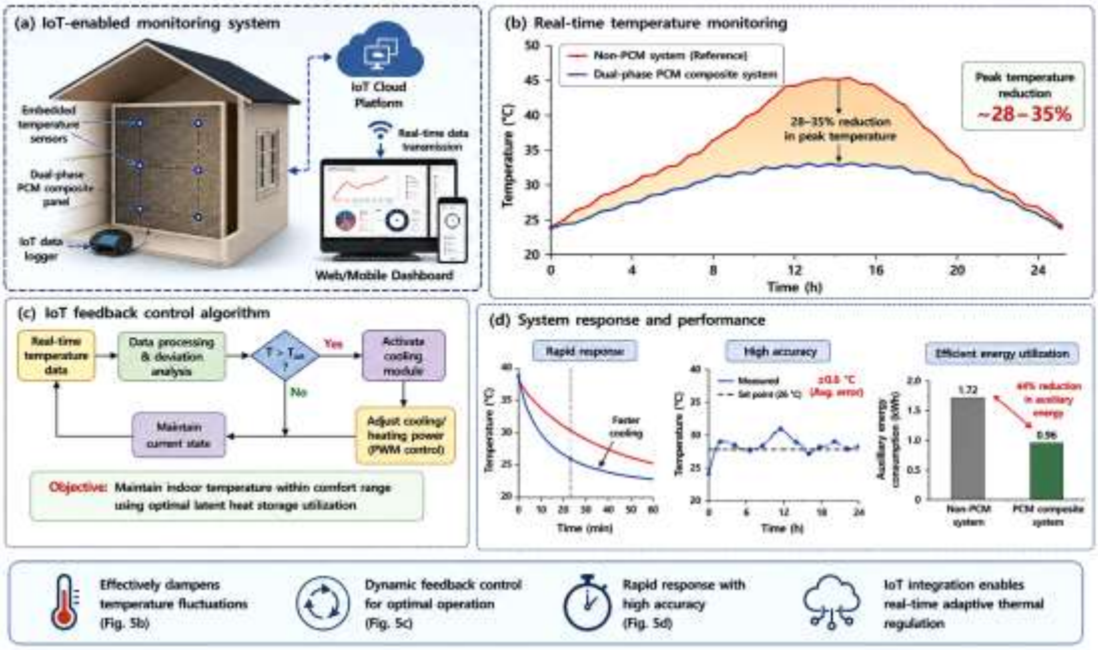

Figure 5. IoT-based adaptive thermal regulation of the dual-phase PCM composite; (a) IoT system architecture, (b) Real-time temperature response, (c) Feedback control mechanism, (d) System performance

The real-time temperature monitoring results presented in Fig. 5b clearly demonstrate the effectiveness of the composite in mitigating thermal fluctuations. Compared to the reference non-PCM system, which exhibits higher peak temperatures, the dual-phase PCM composite significantly reduces temperature rise, achieving a reduction of approximately 28–35% in peak values. This reduction is primarily attributed to the latent heat absorption capacity of the PCM phases, which delays temperature escalation and stabilizes the thermal profile over time [20]. The smoother temperature curve observed for the composite indicates effective damping of thermal oscillations, which is critical for maintaining indoor thermal comfort in smart building applications.

The adaptive control mechanism is further detailed in Fig. 5c, where the feedback control algorithm processes real-time temperature data and compares it with a predefined setpoint. Based on this comparison, the system dynamically activates or modulates auxiliary heating or cooling elements using pulse-width modulation (PWM) control strategies. This closed-loop control ensures that the thermal energy stored within the PCM is optimally utilized before engaging external energy sources, thereby enhancing energy efficiency. The ability to continuously adjust system response based on environmental conditions represents a significant advancement over conventional passive PCM systems.

The system response and performance characteristics are depicted in Fig. 5d, which highlight the rapid response time, high accuracy, and improved energy utilization of the IoT-integrated system. The composite-enabled system achieves faster cooling and stabilization compared to non-PCM configurations, demonstrating efficient heat dissipation. Additionally, the deviation between the measured temperature and the set-point remains minimal (within ~±0.6°C), indicating high control accuracy. A notable reduction in auxiliary energy consumption is also observed, confirming that the system effectively leverages latent heat storage before relying on active cooling or heating mechanisms [21].

Overall, the integration of IoT-based monitoring and adaptive control transforms the dual-phase polymer–PCM composite from a passive thermal storage material into an intelligent thermal management system. The synergy between material design and digital control enables real-time responsiveness, improved thermal stability, and enhanced energy efficiency, making the system highly suitable for next-generation smart building applications.

Long-Term Thermal Cycling Stability and Performance in Smart Buildings

The long-term reliability and practical applicability of the developed dual-phase polymer–PCM composite are comprehensively evaluated through thermal cycling and simulated building performance, as illustrated in Fig. 6(a–d).

The latent heat retention behaviour over repeated thermal cycles is presented in Fig. 6a, where the composite demonstrates excellent durability with less than 3% reduction in latent heat capacity after 200 cycles. The gradual and minimal decline in latent heat values indicates that the encapsulated PCM remains structurally intact, with negligible leakage or degradation. This stability is primarily attributed to the combined effect of microencapsulation and the reinforcing gel PCM network, which together prevent PCM loss and maintain thermal storage capability over extended usage [22].

The phase transition stability is further confirmed by the DSC curves shown in Fig. 6b, where multiple heating–cooling cycles exhibit nearly identical peak positions and shapes. The minimal peak shift across cycles indicates that the melting and solidification processes remain consistent, reflecting strong chemical compatibility and structural integrity of the dual-phase system. The absence of peak broadening or distortion suggests that there is no phase separation or material fatigue, which is critical for long-term thermal applications.

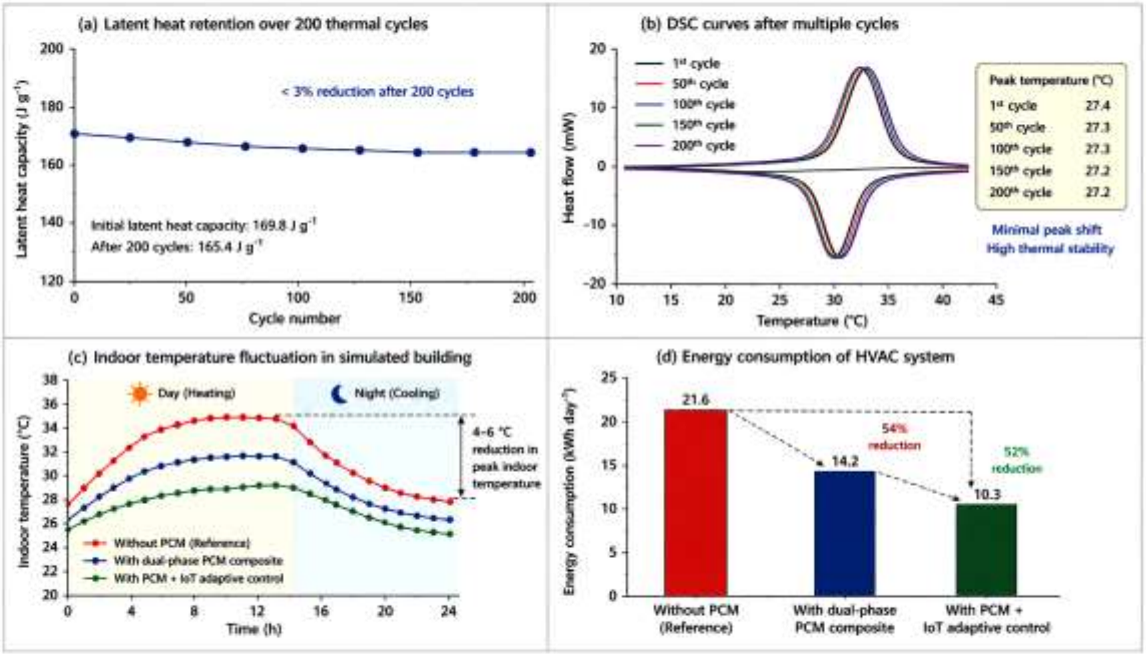

Figure 6. Long-term thermal stability and smart building performance of the dual-phase PCM composite; (a) Latent heat retention, (b) DSC stability, (c) Indoor temperature variation, (d) HVAC energy consumption

The effectiveness of the composite in real-world scenarios is demonstrated through simulated indoor temperature variations in Fig. 6c. The results clearly show that the dual-phase PCM composite significantly reduces temperature fluctuations compared to the reference system. A reduction of approximately 4–6°C in peak indoor temperature is observed, highlighting the composite's ability to absorb excess heat during peak conditions and release it during cooler periods. This thermal buffering effect contributes to improved indoor comfort and reduces dependency on active cooling systems [23].

The impact of this thermal regulation on energy consumption is illustrated in Fig. 6d, where the integration of the PCM composite and IoT-based adaptive control results in a substantial reduction in HVAC energy usage. The composite-enabled system consumes significantly less auxiliary energy compared to conventional systems, demonstrating improved energy efficiency. The adaptive control mechanism ensures that the stored latent heat is utilized optimally before activating external energy sources, thereby minimizing unnecessary energy expenditure.

Overall, the combined results from Fig. 6(a–d) confirm that the developed composite exhibits excellent long-term thermal stability, consistent phase transition behaviour, and significant improvements in indoor thermal management. The synergy between passive thermal storage and active IoT-based control enhances both performance and energy efficiency, positioning the material as a highly effective solution for smart building applications.

CONCLUSION

The major findings emphasizing polymer–composite behaviour are summarized below:

- The hybrid polymer matrix (TPU–PVA) effectively stabilizes dual-phase PCM, ensuring high encapsulation efficiency and leakage resistance.
- The polymer composite structure promotes uniform dispersion and strong interfacial bonding, enhancing both thermal and mechanical stability.
- The interconnected polymer–gel network significantly improves thermal conductivity (~0.42 W/m·K) by forming continuous heat transfer pathways.
- The integration of IoT with the polymer composite enables intelligent thermal response, achieving 28–35% reduction in peak temperature fluctuations.
- The polymer–PCM composite exhibits excellent long-term durability with minimal degradation (<3% after 200 cycles) and improved energy efficiency in smart building environments.

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