

Article

Study on Preparation and Performance Testing of Silica-Composite Organic Phase Change Material Microcapsules

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Abstract

This study employs a mono-caprylate waterborne polyurethane microencapsulation technique to construct a core-shell phase-change microcapsule system with a structured composite core material. By integrating a silica network with phase change materials (ethyl palmitate/paraffin), a stable core material is formed. The silica not only acts as a physical framework to prevent leakage but also regulates the phase change temperature and latent heat through molecular interactions at its surface active sites. The shell layer polyurethane, derived from a fatty acid monoglyceride prepolymer, exhibits a structure highly similar to that of the core material, ensuring efficient and complete encapsulation, while the aqueous system aligns with green manufacturing requirements. The system successfully achieves two types of performance-tunable microcapsules: the silica-ethyl palmitate type exhibits a broad phase change temperature range near room temperature, while the silica-paraffin type demonstrates high latent heat of phase change in the medium-temperature range. This diversity in performance broadens the material's application scenarios. Its broad temperature range characteristic is particularly suitable for building energy efficiency and electronic thermal management fields, effectively mitigating temperature fluctuations and reducing energy consumption, demonstrating significant application value and innovative potential.

Keywords: phase change microcapsules; polyurethane; silicon dioxide

1. Introduction

Amid the dual pressures of global climate change and the depletion of fossil fuels, establishing a modern energy system that is clean, low-carbon, secure, and efficient has become a global consensus [1]. Energy scarcity is not only a bottleneck constraining economic development but also a core issue affecting geopolitical dynamics and sustainable human development [2]. In this macro context, energy technology innovation has adopted a dual approach of “opening new sources” and “conserving existing flows”: on one hand, the large-scale development of renewable energy is reshaping the energy supply structure; on the other hand, improving energy efficiency and reducing energy waste are critical pathways to achieving carbon neutrality goals [3,4].

Breakthroughs in materials science play a decisive role in this endeavor. As the “energy storage hub” connecting energy production and consumption, the performance of energy storage materials directly determines the efficiency and reliability of energy systems [5]. Traditional sensible heat storage faces inherent limitations in energy density and temperature control precision, while latent heat storage, due to its unique advantage of achieving high-density energy storage at constant temperatures, has emerged as a strategic



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direction to address energy mismatches in time and space [6,7]. Phase change materials (PCMs), as ideal carriers for latent heat storage, are transitioning from laboratory research to engineering applications. The optimization and application expansion of their performance hold transformative significance for key areas such as smart grid peak shaving, industrial waste heat recovery, building energy efficiency, and electronic thermal management [8,9].

From a materials science perspective, the PCM system exhibits a complex technological evolution path: organic PCMs, despite their excellent cyclic stability, are limited by inherent low thermal conductivity and mechanical brittleness, which constrain the rate of energy storage and release; inorganic PCMs, while superior in thermal properties, face challenges such as supercooling, phase separation, and corrosion [10]. This complementary performance highlights the inevitable trend toward material hybridization—achieving synergistic “ $1 + 1 > 2$ ” effects through multi-scale structural design, which represents the forefront of current scientific research [11,12].

Microencapsulation technology provides an elegant engineering solution to this scientific challenge [13]. It not only constructs a “core-shell” protective structure at the microscale but also creates novel multifunctional interfaces at the mesoscale: the shell material can prevent PCM leakage while serving as a functional modification carrier, such as incorporating thermal conductivity enhancers; core material hybridization can optimize phase change temperature and enthalpy through multi-component tuning. This integrated “material-structure-function” design philosophy represents a new paradigm for the development of advanced energy storage materials [14–17].

This study focuses on the ethyl palmitate-paraffin/silica hybrid system, with its scientific value reflected in three dimensions: at the fundamental research level, it explores the interaction mechanisms of organic-inorganic hybrid materials at the nanoscale through interface engineering; at the technological development level, it innovatively employs glycerol monocaprylate-derived waterborne polyurethane as an environmentally friendly shell material, achieving a balance between efficient encapsulation and performance enhancement; at the application level, it constructs microcapsule arrays with broad-temperature-range response characteristics, providing a material foundation for developing intelligent adaptive thermal control systems [18,19].

From a broader socio-economic perspective, the significance of this research extends beyond mere laboratory breakthroughs: the industrialization of high-performance phase change microcapsules will directly advance building energy efficiency from passive insulation to active temperature regulation, potentially reducing building energy consumption by 20–30%; in the field of electronic device thermal management, it offers lightweight thermal control solutions for high-heat-flux scenarios such as 5G base stations and data centers; in the new energy vehicle sector, it provides novel technological pathways for the thermal safety management of power battery packs [20,21]. This integrated research, spanning from microscopic material design to macroscopic energy system optimization, not only demonstrates the pivotal role of materials science in addressing global energy challenges but also highlights the practical pathways for driving sustainable development through technological innovation [22].

In this study, we adopt an oil-in-water (O/W) emulsification and interfacial polymerization strategy to fabricate phase change microcapsules with a core-shell architecture. The shell is composed of a waterborne polyurethane synthesized from glyceryl monocaprylate (GMC), which introduces hydrophobic alkyl segments into the polymer network, thereby improving interfacial compatibility with the organic phase change core. The core material consists of ethyl palmitate or paraffin blended with trace amounts of nano-silica, which not only enhances structural stability but also modulates the phase transition behavior. This method was selected due to its ability to produce uniform, defect-free microcapsules

under mild, aqueous conditions, offering both high encapsulation efficiency and scalability. Moreover, the use of bio-based monomers and solvent-free processing aligns with the principles of green and sustainable materials engineering.

2. Experiment

2.1. Materials

All materials were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China) and used without further purification. These included isophorone diisocyanate (IPDI), polyethylene glycol monomethyl ether, polyether triol, glyceryl monocaprylate (GMC), ethyl palmitate, paraffin, nano-silica, methyl ethyl ketone, triethylamine, diethylenetriamine (DETA), and 2,2-dimethylolpropionic acid (DMPA).

2.2. Preparation of Phase Change Microcapsules

This study employed 2,2-dimethylolpropionic acid (DMPA), poly(ethylene glycol) methyl ether (MPEG1000), polyether triol (N303), and glyceryl monocaprylate (GMC) as primary raw materials to prepare composite phase-change microcapsules through a multi-step process with precise control. After high-temperature dehydration pretreatment, isophorone diisocyanate (IPDI) was added dropwise into the cooled system, and the amount of butanone was dynamically adjusted in real-time based on changes in the viscosity of the reaction mixture, ultimately synthesizing polyurethane prepolymer. Building on this, an innovative silica modification process was introduced: nanometer-sized silica particles, treated with surface silanization, were dispersed into the organic phase-change material, forming a homogeneous silica–phase-change material composite core system.

Surface modification of nano-silica: Prior to use, nano-silica was treated to introduce hydrophobic groups, thereby enhancing its dispersibility in organic phase change materials (ethyl palmitate or paraffin).

Preparation of the composite core dispersion: The modified nano-silica was weighed at a specific mass fraction (1–5 wt% relative to the core material) and ultrasonically dispersed into the molten phase change material at 50 °C for 30 min to form a homogeneous suspension.

Integration into the emulsification system: This silica–PCM composite suspension was precisely metered using a microsyringe pump and added dropwise into the polyurethane prepolymer system under high-speed shear stirring, followed by the slow addition of deionized water to form a stable oil-in-water emulsion.

Subsequently, the prepolymer was cooled, followed by the sequential addition of triethylamine (TEA) for carboxyl group neutralization. Using a microinjection pump, the composite core material was precisely dripped into the system. Leveraging charge regulation and interfacial tension matching mechanisms, synergistic dispersion of the nanometer-sized silica and phase-change material was achieved. Under high-speed shear stirring, deionized water was slowly introduced, successfully producing a stable composite emulsion with a submicron-scale, uniform droplet structure.

An innovatively adopted dual-stage chain extension–demulsification coupled process further optimized the microcapsule structure: first, diethylenetriamine (DETA), dissolved in deionized water, initiated interfacial polymerization at the oil–water interface, forming a dense polyurethane shell. The emulsion was then dripped into a dilute hydrochloric acid solution, utilizing a pH-responsive phase separation mechanism to induce solidification and precipitation of the microcapsules. Finally, through post-treatment, composite phase-change microcapsule powder with regular sphericity, high encapsulation efficiency, and excellent thermal cycling stability was obtained [23].

2.3. Characterization

All characterizations were performed on representative samples, and key quantitative analyses (e.g., particle size, enthalpy, core content) were based on at least three independent measurements to confirm reproducibility.

2.3.1. Fourier Transform Infrared Spectroscopy

FT-IR spectroscopy was used to analyze ethyl palmitate, paraffin, nano-silica, the polyurethane prepolymer, the polyurethane shell material, and the phase-change microcapsules.

2.3.2. Microstructural Analysis of Polyurethane PCMs

The structure of the microcapsules was analyzed by an S-4800 field-emission scanning electron microscope (SEM) (Hitachi, Tokyo, Japan). Prior to observation, the microcapsule dispersion was diluted approximately 100-fold. The resulting sample was then secured using conductive adhesive and subjected to gold sputtering to enhance conductivity.

2.3.3. Particle Size Distribution of Polyurethane Phase-Change Microcapsules

Laser diffraction measurements were carried out using a Malvern ZEN3600 instrument (Malvern Panalytical, Malvern, UK) with its accompanying software (Version 7.12) to determine the particle size and distribution of the phase-change microcapsules. Following a 100-fold dilution, 7–8 drops of the emulsion aliquot were analyzed. The final particle size reported is the average of at least three independent measurements.

2.3.4. Thermogravimetric Analysis

The phase change material microencapsulation content in the microcapsules was determined using a NETZSCH TG 209 F3 Tarsus thermogravimetric analyzer (NETZSCH-Gerätebau GmbH, Selb, Germany). The measurement was conducted by employing a heating rate of 20 K/min under a N₂ atmosphere over a temperature scope of 40–600 °C. To ensure comparability, all samples were analyzed simultaneously under identical conditions to minimize systematic errors.

By definition, the actual core content is the weight fraction of the phase-change material in the dried microcapsules, calculated via Equation (1). The encapsulation efficiency is subsequently calculated as the actual content divided by the theoretical value, with the supplied equation in Equation (2).

$$A_{TG} = \frac{W_{core}}{W_{PU-PCMs}} \times 100\% \quad (1)$$

where, W_{core} (%) is defined as the weight fraction of the core material, and $W_{PU-PCMs}$ (%) is the total weight fraction of the phase-change microcapsule specimen.

$$\eta_{TG} = \frac{\text{Actual Core Content}}{\text{Theoretical Core Content}} \quad (2)$$

where, η_{TG} as the encapsulation efficiency determined by TG; $\omega_{core,actual}$ as the actual core mass fraction obtained from TG; $\omega_{core,theoretical}$ as the theoretical core mass fraction based on the initial feed ratio. Theoretical Core Material Content: The mass ratio of artificially added core material to the total mass of “core material + shell material raw materials” during experimental preparation (precisely calculable before the experiment).

Actual Core Material Content: The actual proportion of core material calculated from the aforementioned TGA test.

2.3.5. Thermal Performance of the Phase-Change Microcapsules

The enthalpies of phase transition of the microcapsules were analyzed by differential scanning calorimetry (DSC, PE Diamond) from -20 to 120 °C at a rate of temperature increase of 10 °C/min under a N_2 atmosphere. All samples were tested concurrently under identical conditions to ensure direct comparability. The actual core content (η) was calculated from the DSC data using the following formula:

$$A_{DSC} = \frac{\Delta H_{m, PU - PCMs} + \Delta H_{c, PU - PCMs}}{\Delta H_{m, core} + \Delta H_{c, core}} \quad (3)$$

where, $\Delta H_{m, PU - PCMs}$ (J/g) denotes the latent heat of fusion of the phase-change microcapsules; $\Delta H_{c, PU - PCMs}$ (J/g) is the latent heat of solidification for the phase change microcapsules; and $\Delta H_{m, core}$ (J/g) is the latent heat of fusion of the core material. $\Delta H_{c, core}$ (J/g) is the crystallization latent heat of the core material. The coating efficiency (η_{DSC}) of the phase change material is defined as the ratio of the actual core content to the theoretical core content, and its the required formula is:

$$\eta_{DSC} = \frac{\text{Actual Core Content}}{\text{Theoretical Core Content}} \times 100\% \quad (4)$$

where, Actual Core Content: The actual core material content, calculated from the aforementioned DSC enthalpy value;

Theoretical Core Content: The designed mass proportion of core material added during experimental preparation (fixed value).

3. Results and Discussion

3.1. Preparation Process of Polyurethane PCMs

The synthesis of polyurethane phase-change microcapsules primarily involved the following steps: First, a waterborne polyurethane was synthesized using fatty acid monoglyceride as the raw material to serve as the encapsulation substrate. By incorporating the lipophilic long-chain alkane structure from the monoglyceride into the polyurethane backbone, the affinity for the phase-change material was effectively enhanced, thereby improving encapsulation efficiency. The polyurethane prepolymer was blended with the organic phase-change material, and by leveraging the self-emulsifying property of the prepolymer, a stable dispersion was formed upon the addition of water. Subsequently, a chain extension reaction was initiated by adding an alkaline solution, during which the isocyanate groups on the surface of the prepolymer particles reacted with diethylenetriamine at the particle-water interface, ultimately constructing the complete polyurethane shell.

The synthetic route is summarized in Figure 1.

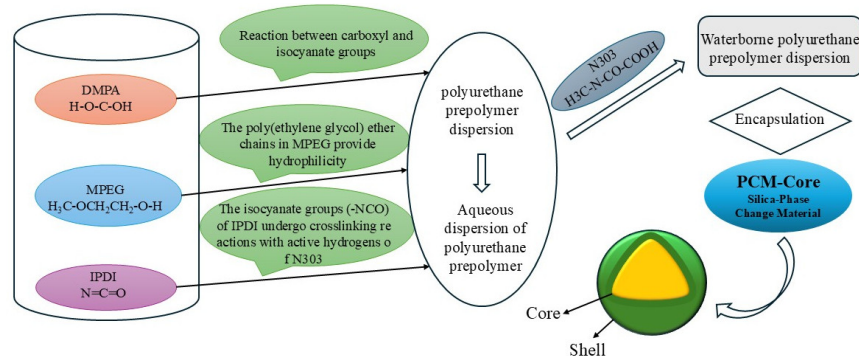


Figure 1. Schematic diagram of the synthesis route for polyurethane-based phase change microcapsules (PU-PCMs).

3.2. Morphologies of PU-PCMs

Figure 2a is a low-magnification image (scale bar: 10 μm) showing the overall morphology and dispersion of the microcapsule population. The fundamental characteristics of the synthesized product can be clearly observed. The image reveals numerous independent and uniformly dispersed spherical particles, which directly confirms the successful formation of a stable core-shell structure during the emulsification and interfacial polymerization of the waterborne polyurethane prepolymer. The absence of significant agglomeration or fracture among particles indicates the effectiveness of the preparation process. Introducing lipophilic long-chain alkane segments into the polyurethane backbone enhanced its affinity for the core material, facilitating the formation of emulsion droplets with suitable interfacial tension and structural stability, ultimately yielding well-defined particles upon solidification.

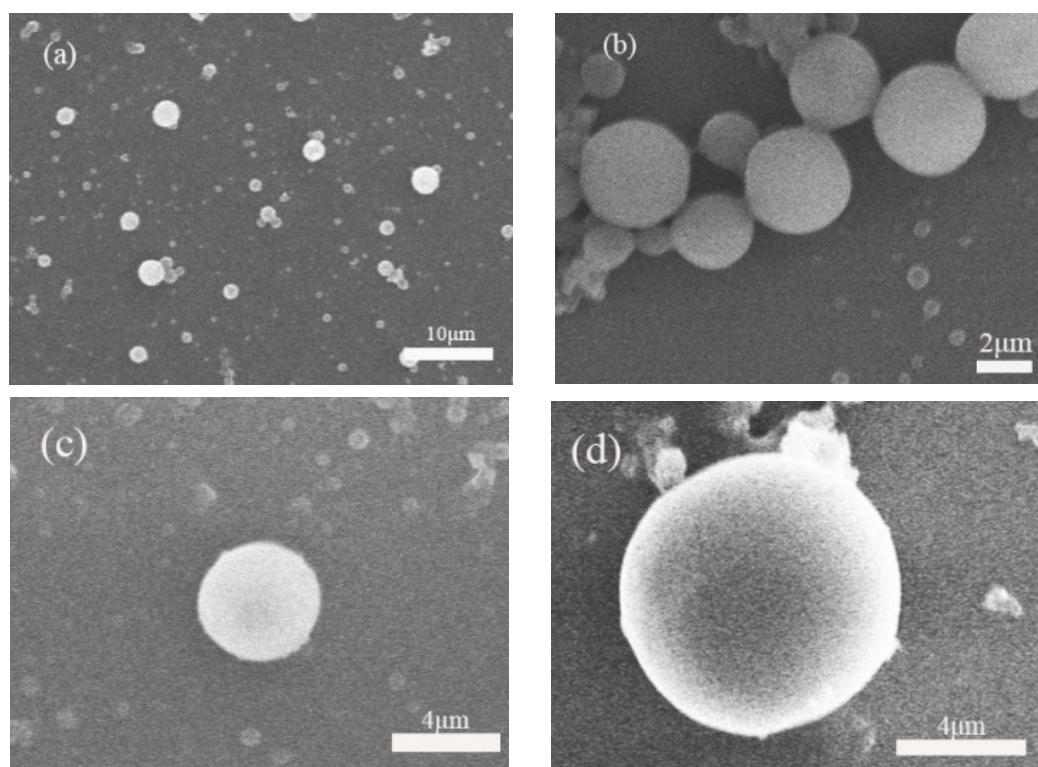


Figure 2. The SEM images of (a) EP@SiO₂-PU-PCMs, (b) PW@SiO₂-PU-PCMs, (c) A single EP@SiO₂-PU-PCMs, and (d) A single PW@SiO₂-PU-PCMs.

Figure 2b is a high-magnification image (scale bar: 2 μm) focusing on the surface details of individual or a small number of microcapsules. The shell surface appears smooth, dense, and defect-free. Such a continuous and smooth surface implies uniform cross-linking and curing of the polyurethane shell during interfacial polymerization, which can effectively prevent leakage of the internal liquid ethyl palmitate during phase transition. In contrast, a rough, porous, or wrinkled surface might indicate uneven polymerization rates or insufficient compatibility between the core and shell materials, potentially leading to performance degradation over long-term thermal cycling.

Figure 2c,d present comparative analyses under different conditions (scale bar: 4 μm), with Figure 2c,d representing products synthesized under distinct experimental setups. Figure 2c corresponds to ethyl palmitate-based microcapsules with a trace amount of silica added, while Figure 2d shows paraffin-based microcapsules with a trace amount of silica added as a control group. By comparing the differences in morphology, dispersion, and

surface smoothness between the two, the effectiveness of trace silica addition in optimizing the microcapsule morphology can be visually demonstrated.

3.3. Infrared Spectra Analysis of PU-PCMs

To characterize the chemistry of the phase-change microcapsules, infrared spectroscopy was performed on ethyl palmitate, paraffin wax, ethyl palmitate-doped silica/polyurethane microcapsules, and paraffin wax-doped silica/polyurethane microcapsules. The results are presented in Figure 3.

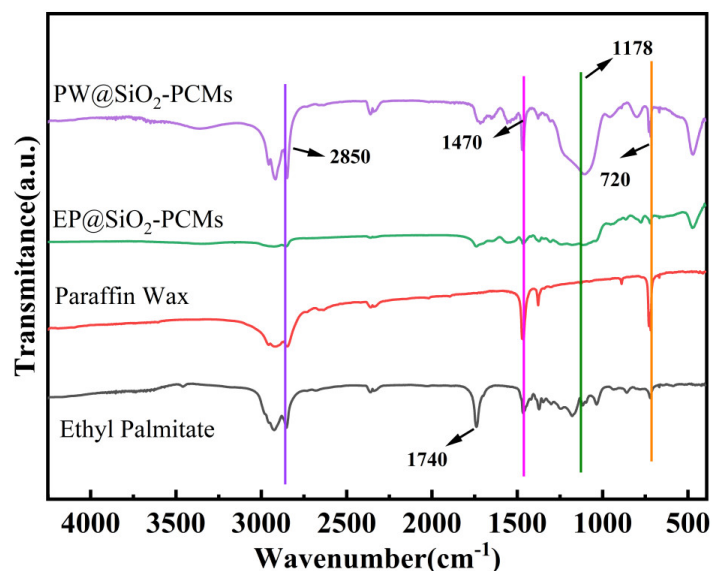


Figure 3. Fourier transform infrared (FT-IR) spectra of ethyl palmitate, paraffin wax, ethyl palmitate-doped silica/polyurethane phase change microcapsules, and paraffin wax-doped silica/polyurethane phase change microcapsules (PU-PCMs).

In both the palmitic acid ethyl ester and microcapsule spectra, characteristic peaks corresponding to the ester carbonyl ($\text{C}=\text{O}$) stretching vibration at 1740 cm^{-1} and the $\text{C}-\text{O}-\text{C}$ stretching vibration at 1178 cm^{-1} were observed, confirming the presence of ethyl palmitate within the microcapsules. Similarly, in the spectra of paraffin wax and the corresponding microcapsules, the peak at 720 cm^{-1} , attributed to $\text{C}-\text{C}$ stretching vibration, was detected.

Furthermore, the absence of the characteristic isocyanate ($-\text{NCO}$) stretching vibration peak at 2258 cm^{-1} in the microcapsule spectra indicates complete reaction between the isocyanate groups in the prepolymer and diethylenetriamine (DETA).

The Fourier transform infrared (FT-IR) analysis thus verifies the successful encapsulation of ethyl palmitate as the core material within the polyurethane-based shell in the synthesized phase-change microcapsules.

3.4. Thermal Degradation Behavior of Polyurethane Phase-Change Microcapsules

As shown in Figure 4, two well-separated mass loss stages were observed in the GMC-based PU-PCMs. The first stage, occurring between 124 and $242\text{ }^{\circ}\text{C}$, originates from the volatilization and degradation of the ethyl palmitate core. The second stage, between 250 and $455\text{ }^{\circ}\text{C}$, results from the decomposition of the polyurethane shell. These two stages closely correspond to the volatilization temperature (116 – $248\text{ }^{\circ}\text{C}$) and decomposition temperature (255 – $463\text{ }^{\circ}\text{C}$) of the individual core and shell materials, respectively.

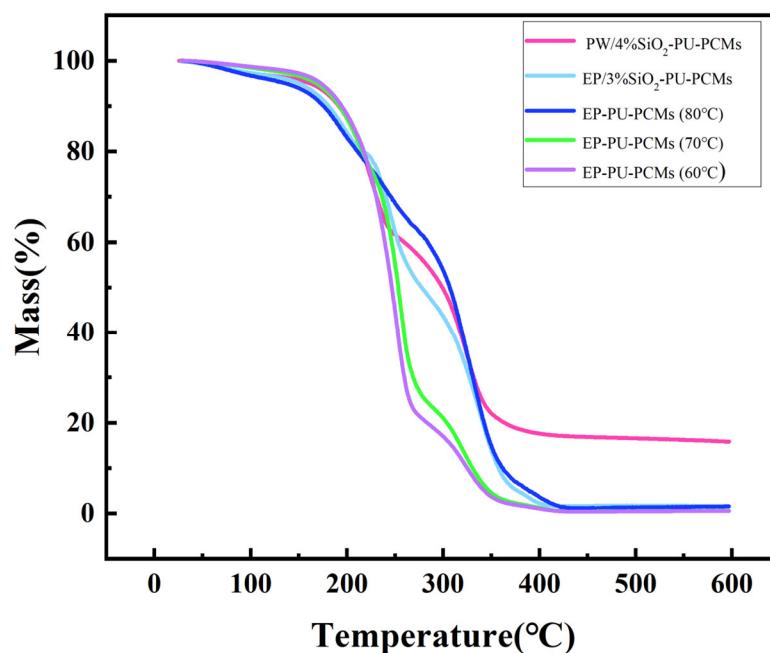


Figure 4. Thermogravimetric Analysis (TGA) curves of ethyl palmitate microcapsules, ethyl palmitate-doped silica/polyurethane phase change microcapsules, and paraffin wax-doped silica/polyurethane phase change microcapsules (PU-PCMs).

3.5. Differential Scanning Calorimetry (DSC) Analysis of PU-PCMs

Figure 5 presents the differential scanning calorimetry (DSC) curves of ethyl palmitate/paraffin phase-change microcapsules encapsulated in fatty acid monoglyceride-based waterborne polyurethane. Under programmed temperature control, these curves directly reveal the thermal behavior of the encapsulated phase-change material (core). Analysis of the DSC curves clearly shows a sharp and symmetric endothermic melting peak, indicating that the ethyl palmitate core undergoes a first-order solid–liquid phase transition within the microcapsules, characterized by a concentrated and efficient process. The flat baseline and single peak shape, with no other significant thermal events observed, demonstrate high sample purity and confirm the successful encapsulation of the target phase-change material. Furthermore, the absence of noticeable glass transition or decomposition of the polyurethane shell or other additives within the tested temperature range validates the effectiveness of the material design.

The pronounced melting peak and quantifiable phase-change enthalpy directly confirm the successful encapsulation and retained phase-change capability of the core material. The magnitude of the phase-change enthalpy serves as a quantitative measure of the encapsulation efficiency of the microcapsules. Compared to the DSC curve of pure ethyl palmitate, the slight shift in phase-change temperature or minor broadening of the peak observed in the microcapsules can be attributed to the nanoconfinement effect—i.e., the subtle constraint exerted by the polyurethane shell on the crystallization behavior of the core material. This effect is typically minimal, further demonstrating that the long-chain alkane modification strategy effectively enhances shell-core interfacial compatibility and minimizes interference of the shell with the phase-change properties of the core.

As shown in Figure 5a,b, the endothermic and exothermic curves of the phase-change microcapsules are similar to those of silica-doped ethyl palmitate and silica-doped paraffin, all exhibiting two melting peaks and a relatively broad melting temperature range. Specifically, the melting temperature of ethyl palmitate-based phase-change microcapsules is close to room temperature, while that of paraffin-based phase-change microcapsules is around 50 °C. Thermal performance analysis revealed that the prepared composite microcapsules

exhibit excellent heat storage capacity. As shown in Figure 5a,b, the melting enthalpy of silica-doped ethyl palmitate-based phase-change microcapsules (EP/SiO₂-PU-PCMs) reached 89.77 J/g at a silica doping level of 3%, while that of silica-doped paraffin-based phase-change microcapsules (PW/SiO₂-PU-PCMs) reached 136.92 J/g at a silica doping level of 4%.

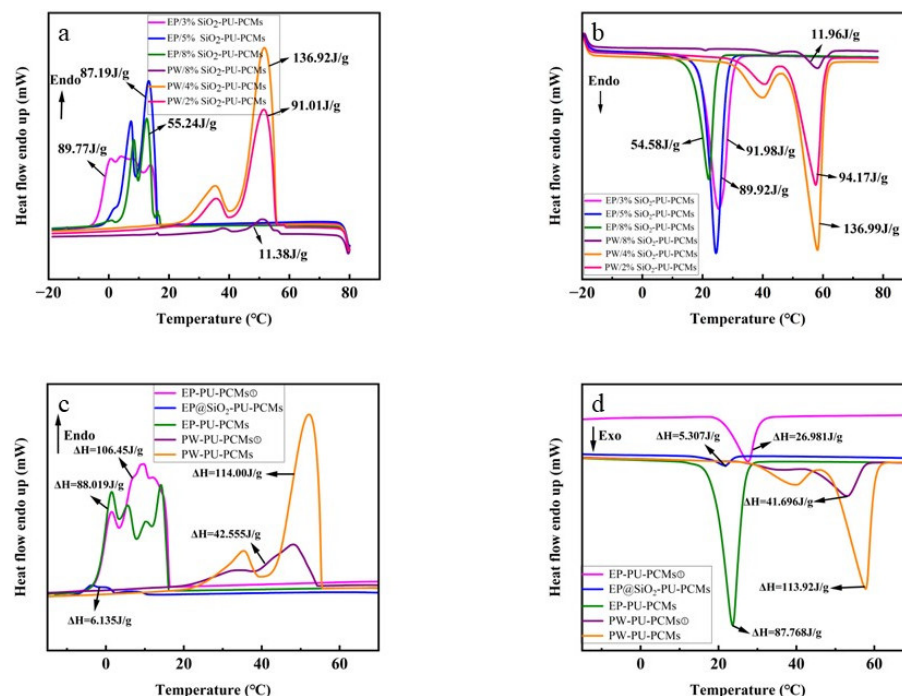


Figure 5. (a,b) are the DSC curves of optimized ethyl palmitate microcapsules, ethyl palmitate-doped silica/polyurethane phase change microcapsules, and paraffin-doped silica/polyurethane phase change microcapsules (PU-PCMs); (c,d) are the DSC curves of ethyl palmitate microcapsules, ethyl palmitate-doped silica/polyurethane phase change microcapsules, and paraffin-doped silica/polyurethane phase change microcapsules (PU-PCMs).

Notably, the symmetric and sharp melting peaks observed in Figure 5a indicate a rapid and concentrated thermal response, which is critical for real-time temperature regulation scenarios such as electronic device cooling or wearable thermal management. Moreover, the suppression of supercooling (evidenced by the reduced crystallization peak shift compared to pure ethyl palmitate) suggests improved energy release reliability under fluctuating ambient conditions. The thermal degradation onset above 240 °C (Figure 4) further ensures structural integrity during composite processing (e.g., extrusion, coating), demonstrating practical feasibility beyond laboratory scale.

3.6. Comprehensive Assessment of Application Potential

To bridge material characteristics and functional deployment, a comparison was made with representative phase-change microcapsules reported for building and electronic thermal management.

The comparison reveals that the silica-composite PU-PCMs exhibit a favorable combination of suitable phase-change temperature, high latent heat, and superior thermal stability. Notably, the degradation onset (>240 °C) exceeds typical processing temperatures of polymer-based composites (e.g., extrusion at 180–200 °C), suggesting practical feasibility for melt blending. Furthermore, the defect-free shell morphology implies low risk of core leakage during long-term service, although cyclic durability tests are required to validate this hypothesis.

To further clarify the engineering application orientation of the material, this study, based on the phase change temperature window, enthalpy density, shell integrity, and processability of the microcapsules, has preliminarily established matching pathways for three typical application scenarios:

Building energy efficiency: The palmitate-based microcapsules ($T_m \approx 25\text{--}35\text{ }^\circ\text{C}$, $\Delta H_m = 89.77\text{ J/g}$) exhibit a phase change temperature close to the human comfort zone, making them suitable for incorporation as passive thermal storage fillers into building envelopes. Their broad phase transition response helps mitigate indoor temperature fluctuations and reduce the frequency of air conditioning cycling, rendering them particularly applicable to lightweight structures and the energy-efficient retrofitting of existing buildings [24]. **Electronic thermal management:** The paraffin-based microcapsules ($T_m \approx 50\text{ }^\circ\text{C}$, $\Delta H_m = 136.92\text{ J/g}$) possess high latent heat and excellent shell compactness, rendering them suitable for transient thermal buffering in high-power-density devices. It is proposed that they be dispersed within a flexible polymer matrix to fabricate thermally conductive buffer films or potting composites for localized overheating suppression in applications such as 5G macro base stations, blade servers, and lithium-ion battery modules [25]. **Smart textiles and wearable devices:** This microcapsule system can be stably dispersed in water and exhibits good compatibility between the polyurethane shell and fiber substrates, offering feasibility for integration into fabric carriers via coating or spinning processes. Its thermal response behavior in the $35\text{--}45\text{ }^\circ\text{C}$ range shows promise for applications in medical constant-temperature dressings, outdoor workwear, and sports rehabilitation equipment [26].

The proposal of the above application scenarios is grounded in quantitative characterization of the material's intrinsic properties, while also considering the constraints of processing techniques and actual service environments. This provides a clear direction for subsequent system-level validation studies.

4. Conclusions

This study successfully developed a novel phase-change microcapsule composite material based on fatty acid monoglyceride-derived waterborne polyurethane. By incorporating long-chain alkane structures into the polyurethane molecular backbone, the hydrophobicity of the shell material was systematically enhanced, thereby significantly improving its interfacial compatibility with hydrophobic phase-change core materials. This molecular design strategy effectively promoted the formation of a stable and uniform core-shell structure during emulsification, fundamentally ensuring the high encapsulation efficiency and structural integrity of the microcapsules.

Thermal performance analysis revealed that the prepared composite microcapsules exhibit excellent heat storage capacity. The melting enthalpy of silica-doped ethyl palmitate-based phase-change microcapsules reached 89.77 J/g , while that of silica-doped paraffin-based phase-change microcapsules reached an even higher value of 136.92 J/g . These values not only confirm that the microcapsule system successfully retained the high latent heat characteristics of the core materials but also indicate that the incorporation of silica may have further optimized energy storage performance by enhancing thermal pathways or suppressing core material flow.

Notably, while demonstrating high energy storage density, the material also exhibited significant thermal buffering capacity, as evidenced by its high latent heat and well-defined phase transition platform, which enables passive temperature regulation under transient thermal loads. This is primarily attributed to the low thermal conductivity of the polyurethane shell and the multiple thermal resistance effects created by the microcapsule structure. The synergistic interaction of these two factors effectively delays heat transfer.

For instance, when integrated as “thermal energy batteries” into building materials, the material can absorb or release heat through the phase-change process to automatically regulate indoor temperature, thereby reducing energy consumption for air conditioning and heating. Additionally, to address localized overheating issues in high-power chips, batteries, and other components, it leverages phase-change heat absorption to delay temperature rise, enhancing device stability and lifespan. Thus, this study provides new insights and technical pathways for the design and development of high-performance integrated thermal insulation and energy storage materials.

Based on its phase-change enthalpies of 89.77 J/g (near room temperature) and 136.92 J/g (50 °C), combined with a thermal decomposition temperature above 240 °C and a smooth, dense shell morphology, preliminary assessment indicates that this microcapsule system possesses the fundamental thermophysical properties and structural compatibility required for integration into gypsum boards, exterior wall insulation layers, or textile substrates. Its actual temperature regulation performance in simulated building environments or constant-temperature energy storage devices warrants further quantitative validation through infrared thermography or thermal cycling platforms in subsequent studies.

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