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Stretchable Elastomer–PCM Composites with Bluetooth-Enabled Temperature Monitoring for Wearable Healthcare IoT Devices

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Abstract

The rapid advancement of wearable healthcare technologies has created a growing demand for multifunctional polymer composites capable of simultaneously providing mechanical flexibility, thermal energy management, electrical conductivity, sensing capability, and wireless communication. In this study, a stretchable elastomer-based polymer composite integrated with a phase-change material and a Bluetooth Low Energy temperature monitoring system was developed for wearable healthcare Internet-of-Things applications. The polymer composite was fabricated using an Ecoflex silicone elastomer matrix containing microencapsulated paraffin phase-change material, multi-walled carbon nano-tubes, and carbon black nanoparticles to create a multifunctional polymer nano-composite with combined thermal and electrical functionalities. Morphological characterization revealed uniform dispersion of PCM microcapsules and conductive nano-fillers, promoting effective interfacial adhesion and stable conductive pathways throughout the polymer composite matrix. Differential scanning calorimetry confirmed retention of latent heat storage behaviour, exhibiting melting and crystallization peaks near 33.4°C and 31.2°C, respectively. Mechanical testing demonstrated excellent flexibility and stretchability, with elongation exceeding 250%, while cyclic loading-unloading studies verified outstanding durability and elastic recovery under repeated deformation. Electrical conductivity increased significantly because of synergistic percolation networks formed between carbon nanotubes and carbon black particles. Integration of a DS18B20 sensor and ESP32 BLE module enabled accurate real-time wireless temperature monitoring with accuracy exceeding 98%. Thermal regulation experiments demonstrated slower heating and more gradual cooling than neat elastomer, highlighting effective latent heat storage. This polymer composite shows strong potential for healthcare.

Keywords: Stretchable elastomer, PCM composite, temperature monitoring, wearable devices, nano-fillers

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INTRODUCTION

The rapid growth of wearable electronics and smart healthcare technologies has accelerated the development of advanced polymer-based composites, elastomeric composites, and multifunctional polymer nanocomposites capable of integrating sensing, thermal regulation, and wireless communication functionalities into compact systems. Wearable healthcare IoT devices are increasingly utilized for continuous monitoring of physiological parameters such as body temperature, heart rate, respiration rate, and perspiration levels [1]. Among these parameters, skin temperature monitoring plays a crucial role in disease diagnosis, metabolic assessment, and remote patient care [2]. Consequently, the design of flexible polymer composites with integrated sensing capabilities has become a major focus in wearable biomedical engineering.

Stretchable elastomer–PCM composites are a class of multifunctional materials that combine the high deformability of elastomeric polymers with the thermal energy storage capability of phase change materials (PCMs). In such composites, the elastomer matrix provides excellent flexibility, softness, elasticity, and conformability, enabling intimate contact with complex human body surfaces without restricting natural movement. Simultaneously, the embedded PCM domains provide thermal regulation by absorbing and releasing latent heat during reversible phase transitions. The synergistic combination of mechanical compliance and thermal management makes stretchable elastomer–PCM composites highly suitable for wearable healthcare applications. In wearable biomedical devices, prolonged skin contact and continuous operation of embedded electronic components often cause localized heat accumulation, leading to discomfort, perspiration, and reduced sensing accuracy. By integrating PCM within stretchable elastomeric matrices, excess heat can be temporarily absorbed during heating and gradually released during cooling, thereby improving user comfort, maintaining thermal equilibrium, and enhancing overall wearable device performance.

Traditional wearable devices often suffer from poor thermal comfort due to heat accumulation at the skin–device interface, resulting in discomfort during prolonged usage [3]. To overcome this limitation, polymer composite phase change materials (PCM composites) have gained considerable attention because of their ability to absorb and release latent heat during phase transitions, thereby maintaining thermal equilibrium [4]. Paraffin-based PCMs are widely employed in polymer composite systems owing to their high latent heat capacity, chemical stability, and tunable melting temperature range [5]. However, leakage during phase transition and inadequate structural stability restrict the direct incorporation of PCM into wearable polymer and elastomer systems [6].

Microencapsulation of PCM within polymeric shells has emerged as an effective strategy for enhancing shape stability and preventing leakage in PCM-polymer composites [7]. Simultaneously, elastomeric polymers such as polydimethylsiloxane (PDMS), Ecoflex, and thermoplastic polyurethane (TPU) have attracted significant interest as matrix materials for stretchable polymer composites because of their excellent flexibility, biocompatibility, elasticity, and mechanical durability [8]. The incorporation of PCM microcapsules into these elastomeric polymers results in multifunctional polymer composites capable of combining thermal energy storage, thermal regulation, and mechanical deformability within a single material platform [9]. Such elastomer-based composites are particularly attractive for next-generation wearable healthcare devices where both user comfort and material performance are critical.

Recent advancements in conductive nanofillers have further expanded the capabilities of wearable polymer nanocomposites. Carbon nanotubes (CNTs), graphene nanoplatelets, carbon black nanoparticles, and other conductive fillers are frequently incorporated into polymer composite matrices to enhance electrical conductivity and sensing performance [10]. The formation of interconnected conductive networks within the polymer composite structure enables efficient electron transport while preserving the flexibility of the elastomer matrix [11]. As a result, conductive polymer-elastomer composites have emerged as promising materials for wearable sensing applications, including temperature monitoring, strain sensing, and physiological signal detection [12].

The integration of conductive nanofillers into elastomeric polymer composites also facilitates seamless interfacing with electronic components and wireless communication systems. Flexible temperature sensors embedded within stretchable polymer composite substrates can continuously monitor physiological conditions while maintaining intimate skin contact and unrestricted body movement [13]. Furthermore, the mechanical compliance of elastomeric polymer composites ensures stable sensor performance under repeated bending, stretching, and cyclic deformation encountered during daily activities [14].

Bluetooth Low Energy (BLE) communication has become one of the most widely adopted wireless technologies for wearable healthcare applications owing to its low power consumption, compact architecture, and compatibility with smartphones and cloud-based healthcare platforms [15]. The integration of BLE-enabled electronics with multifunctional polymer composites enables real-time physiological monitoring, remote patient care, and IoT-driven healthcare analytics [16]. In particular, the combination of thermally responsive PCM-polymer composites, conductive polymer nanocomposites, and wireless sensing electronics represents a highly promising approach for the development of intelligent wearable healthcare systems capable of simultaneously managing thermal comfort and physiological monitoring [17].

Despite significant advances in wearable electronics and flexible materials, relatively few studies have focused on the development of multifunctional polymer composites that integrate thermal regulation, electrical conductivity, sensing capability, and wireless communication within a single stretchable elastomer composite platform. Challenges related to nanofiller dispersion, polymer–filler interfacial compatibility, thermal conductivity optimization, mechanical durability, and conductive network stability under repeated deformation remain important research concerns [18]. Moreover, maintaining sensing accuracy and electrical stability within highly deformable polymer composite materials subjected to cyclic stretching and thermal fluctuations is essential for practical healthcare applications [19].

In the present work, a novel multifunctional elastomer-based polymer composite integrated with a Bluetooth-enabled temperature sensing system was developed for wearable healthcare IoT applications. Microencapsulated paraffin PCM was incorporated into an Ecoflex elastomer matrix together with conductive carbon nano-fillers to fabricate a thermally responsive and electrically conductive polymer nano-composite. The resulting PCM-elastomer composite combines latent heat storage, mechanical flexibility, electrical conductivity, and wireless sensing capability within a unified polymer composite architecture. The developed polymer composite system was interfaced with a BLE module and a digital temperature sensor for real-time wireless monitoring. Comprehensive characterization including morphological analysis, thermal behaviour, tensile properties, cyclic durability, electrical conductivity, and wireless sensing performance was performed to evaluate the suitability of the developed multifunctional polymer composite for advanced wearable healthcare and biomedical IoT applications.

MATERIALS AND METHODS

Materials

Microencapsulated paraffin-based phase change material (PCM) with a melting temperature range of 32–35°C was selected as the thermal energy storage medium for wearable thermal regulation applications. Ecoflex 00-30 silicone elastomer was used as the stretchable polymer matrix due to its excellent flexibility, biocompatibility, and low elastic modulus. Multi-walled carbon nanotubes (MWCNTs) and conductive carbon black nanoparticles were incorporated as conductive fillers to enhance electrical conductivity and electromechanical stability. Ethanol was used as the dispersion medium during composite preparation. For wireless sensing and IoT integration, a DS18B20 digital temperature sensor, ESP32 microcontroller with integrated Bluetooth Low Energy (BLE) functionality, conductive connecting wires, and a compact lithium-polymer battery were employed. The complete step-by-step fabrication process of the stretchable elastomer–PCM composite and wearable healthcare monitoring device is illustrated in Figure 1.

Figure 1. Fabrication process of stretchable elastomer–PCM composite and wearable IoT temperature monitoring device.(a) Microencapsulated paraffin PCM material, (b) Dispersion of PCM with conductive fillers, (c) Addition of silicone elastomer and mixing, (d) Vacuum degassing of composite slurry,(e) Casting and curing of composite sheet, (f) Final wearable device with BLE temperature sensor integration.

Preparation of Stretchable Elastomer–PCM Composite

The fabrication procedure was carried out through a sequential solution-assisted mechanical mixing process as presented in Figure 1. Initially, the microencapsulated PCM particles shown in Figure 1(a) were weighed and dispersed in ethanol to facilitate uniform particle distribution. The PCM suspension was mechanically stirred and ultrasonicated to reduce particle agglomeration and improve dispersion homogeneity. Subsequently, MWCNTs and conductive carbon black nanoparticles were gradually added into the suspension as illustrated in Figure 1(b). The mixture was continuously stirred under controlled conditions to promote the formation of a stable conductive network throughout the composite matrix.

Following conductive filler incorporation, Ecoflex 00-30 silicone elastomer base resin was introduced into the dispersion system as shown in Figure 1(c). Mechanical stirring was performed using a high-speed laboratory stirrer for approximately 45 min to ensure uniform distribution of PCM microcapsules and conductive nanofillers within the elastomeric matrix. The silicone curing agent was then added in a 10:1 weight ratio and further mixed thoroughly to initiate crosslinking reactions and obtain a homogeneous composite slurry.The prepared composite mixture was subsequently transferred into a vacuum degassing chamber, as presented in Figure 1(d), to eliminate entrapped air bubbles generated during high-speed mixing. Degassing was conducted for approximately 20 min until bubble formation was minimized, thereby improving structural uniformity and minimizing internal defects in the cured composite.

After degassing, the composite slurry was poured into rectangular molds for casting and curing, as shown in Figure 1(e). The cast samples were initially cured at room temperature for 24 h followed by post-curing at 60°C for 2 h to enhance crosslinking density and mechanical stability. After complete curing, the elastomeric composite sheets were demolded and cut into required dimensions for characterization and wearable device fabrication.

Fabrication of Bluetooth-Enabled Wearable Temperature Monitoring Device

The cured composite specimens were integrated with a DS18B20 digital temperature sensor and an ESP32 Bluetooth Low Energy microcontroller to develop a wearable healthcare IoT monitoring platform, as illustrated in Figure 1(f). The temperature sensor was embedded near the skin-contact surface of the stretchable composite to ensure accurate physiological temperature measurement. Flexible conductive wiring was utilized to electrically connect the sensor to the ESP32 module while maintaining overall flexibility and stretchability of the device. The ESP32 module transmitted real-time temperature data wirelessly to a smartphone interface through BLE communication. A rechargeable lithium-polymer battery was employed to power the sensing module and wireless communication system. The final integrated wearable device demonstrated conformability, flexibility, and real-time wireless temperature monitoring capability suitable for healthcare IoT applications.

RESULTS AND DISCUSSION

Morphological Characteristics of Elastomer–PCM Composite

The morphological characteristics and filler dispersion behaviour of polymer composites play a decisive role in determining the overall thermal, mechanical, and electromechanical performance of wearable functional materials. In the present study, the stretchable elastomer–PCM composite exhibited a highly uniform microstructure with excellent compatibility between the Ecoflex elastomer matrix, microencapsulated paraffin PCM, and conductive nanofillers. The morphology and particle size distribution characteristics of the composite system are presented in Figure 2.

The fabricated composite displayed a homogeneous black appearance without visible phase separation, filler sedimentation, or PCM leakage, indicating successful processing and effective filler incorporation within the polymer matrix.As illustrated in Figure 2, the PCM microcapsules predominantly exhibited particle sizes within the 1–10 μm range, while the conductive nanofillers were primarily distributed below 5 μm. The narrow particle size distribution and uniform filler dispersion observed in the composite indicate that the combined ultrasonication and mechanical stirring process effectively minimized agglomeration of carbon nano-tubes and carbon black particles. In polymer composite systems, agglomeration of conductive nano-fillers often results in localized stress concentration, poor electrical conductivity, and non-uniform thermal transport behaviour. However, the homogeneous dispersion achieved in the present work enabled the formation of stable conductive pathways throughout the elastomeric network, thereby improving multifunctional performance characteristics.

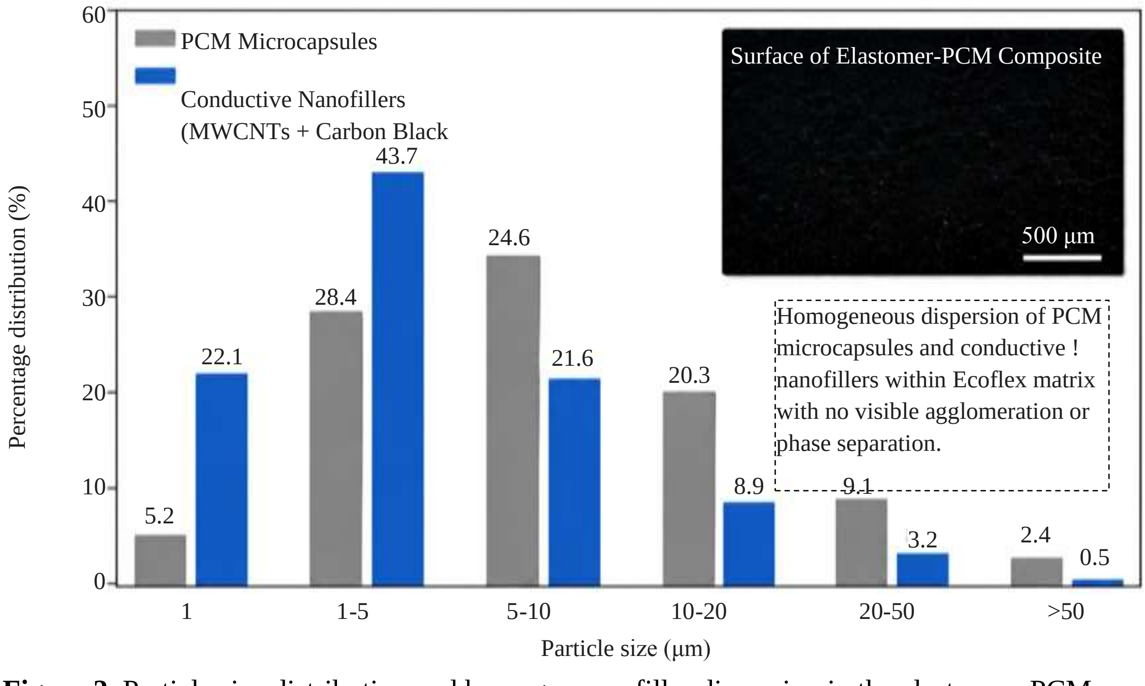

Figure 2. Particle size distribution and homogeneous filler dispersion in the elastomer–PCM composite.

The Eco-flex silicone elastomer acted as a continuous polymeric phase capable of uniformly encapsulating PCM microcapsules and conductive fillers. The flexible polymer chains of the elastomer facilitated strong interfacial interaction with the PCM shell material, thereby improving filler–matrix adhesion and structural integrity. The PCM microcapsules remained embedded within the elastomeric matrix without visible rupture or shell degradation, confirming the chemical compatibility between the paraffin PCM and silicone elastomer. Such stable encapsulation behaviour is particularly important in polymer composite-based thermal energy storage systems because PCM leakage during repeated thermal cycling can significantly deteriorate thermal efficiency and mechanical durability.

The conductive carbon nanotubes and carbon black nanoparticles formed interconnected percolative conductive networks surrounding the PCM domains within the polymer matrix. The high aspect ratio of MWCNTs enabled long-range electron transport pathways, while the smaller carbon black particles occupied the interstitial regions between nanotube junctions, thereby enhancing conductive network continuity. This synergistic filler interaction significantly improved electron mobility and electromechanical stability within the elastomeric composite structure. Similar conductive network formation mechanisms have been widely reported in advanced polymer nanocomposites designed for flexible electronics and wearable sensing applications [16].

Another important observation from Figure 2 is the absence of large particle clusters beyond 50 µm, indicating highly efficient dispersion stability during composite processing. In polymer nanocomposites, uniform filler distribution is strongly associated with improved stress transfer capability between the polymer matrix and reinforcing fillers. The homogeneous dispersion observed in the present composite therefore contributed not only to electrical conductivity enhancement but also to improved tensile flexibility and cyclic mechanical durability. The conductive fillers additionally acted as reinforcing agents within the elastomer matrix by restricting excessive polymer chain mobility under deformation, thereby improving structural stability during stretching and bending operations.

The morphology of the composite also strongly influenced thermal transport characteristics. Uniformly distributed PCM particles enabled effective latent heat absorption and thermal buffering throughout the elastomer matrix, while the conductive carbon nano-fillers improved heat distribution by facilitating phonon transport pathways. The simultaneous presence of thermal storage domains and conductive networks therefore created a multifunctional polymer composite system capable of achieving both thermal regulation and stable electrical performance. Such multifunctional morphology is highly desirable in next-generation wearable healthcare materials because it enables simultaneous flexibility, thermal comfort, and wireless sensing functionality within a single integrated composite structure.

Furthermore, the elastomeric polymer matrix contributed significantly to deformability and shape recoverability of the composite. The flexible crosslinked silicone network allowed reversible deformation under tensile loading while maintaining conductive pathway integrity. The PCM microcapsules were effectively accommodated within the soft polymer matrix without inducing significant brittleness or rigidity. Consequently, the composite exhibited excellent flexibility and dimensional stability suitable for wearable biomedical applications involving repeated body movement and continuous skin contact.

Thermal Energy Storage and Phase Change Behaviour

The thermal energy storage capability of the developed elastomer–PCM composite is a critical parameter for wearable healthcare applications because it directly influences thermal comfort during prolonged skin contact. The differential scanning calorimetry (DSC) thermograms of the pure microencapsulated PCM and the elastomer–PCM composite are presented in Figure 3. The pure PCM exhibited a distinct melting transition within the temperature range of 32–35°C, which closely corresponds to the normal human skin temperature range. After incorporation into the Ecoflex elastomer matrix, the composite retained the phase transition characteristics of the PCM, indicating that the encapsulation process and composite fabrication procedure did not adversely affect the latent heat storage mechanism.

The DSC curve presented in Figure 3 demonstrates a melting peak centered around 33.4°C and a crystallization peak near 31.2°C during cooling. The latent heat of fusion was slightly reduced compared with pure PCM because the elastomer matrix and conductive fillers contributed additional non-phase-change mass. Nevertheless, the composite retained substantial thermal energy storage capability, enabling efficient absorption of excess body heat during temperature fluctuations.

The retention of phase-change behaviour observed in Figure 3 confirms the structural integrity of the PCM microcapsules after composite processing. Furthermore, the conductive nanofillers facilitated heat distribution toward PCM domains, thereby improving thermal buffering efficiency. Consequently, the elastomer–PCM composite offers an effective thermal management platform suitable for wearable healthcare systems [17].

Tensile Behaviour and Stretchability Analysis

The tensile properties of wearable polymer composites significantly influence their durability and comfort under repeated body movement. The tensile stress–strain characteristics of the elastomer–PCM composite are presented in Figure 4.

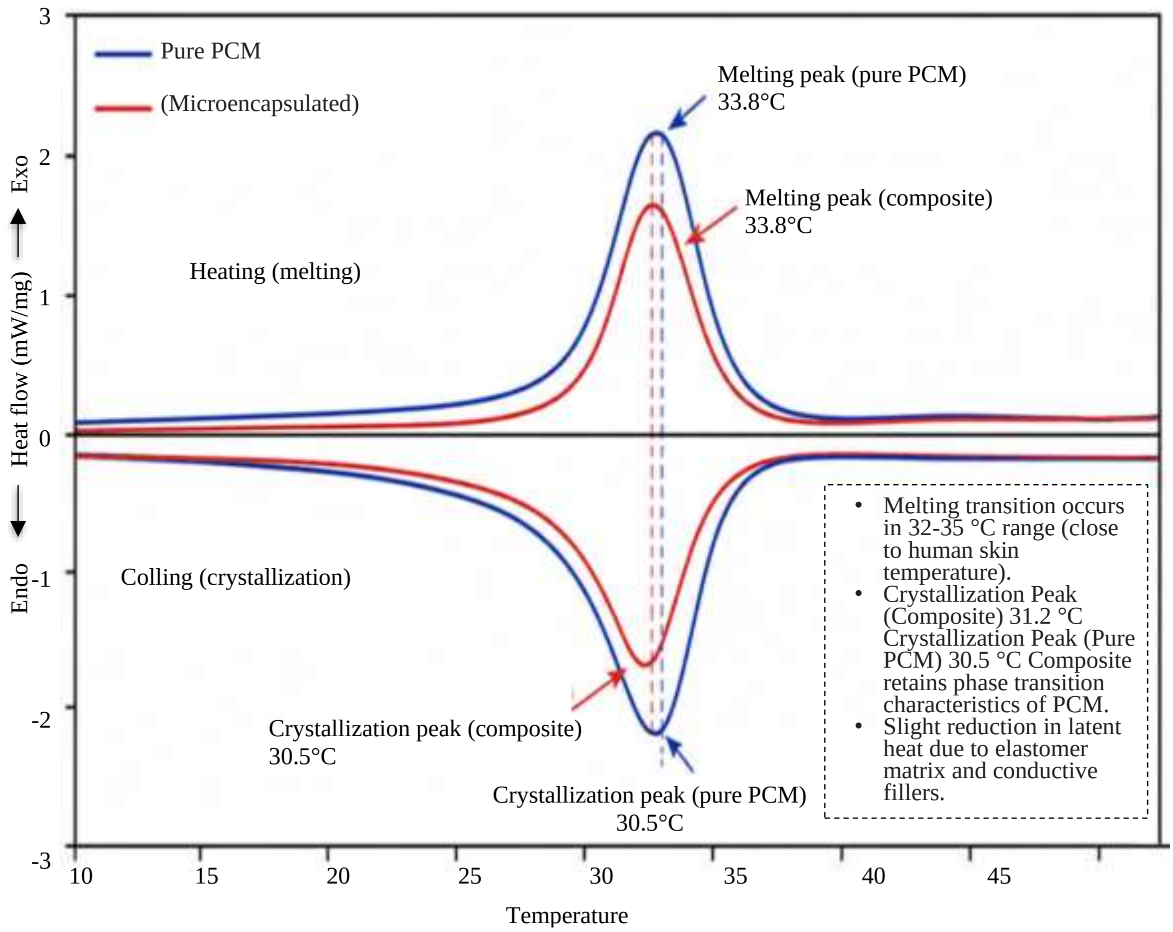

Figure 3. DSC thermograms of pure PCM and elastomer–PCM composite showing melting and crystallization transitions.

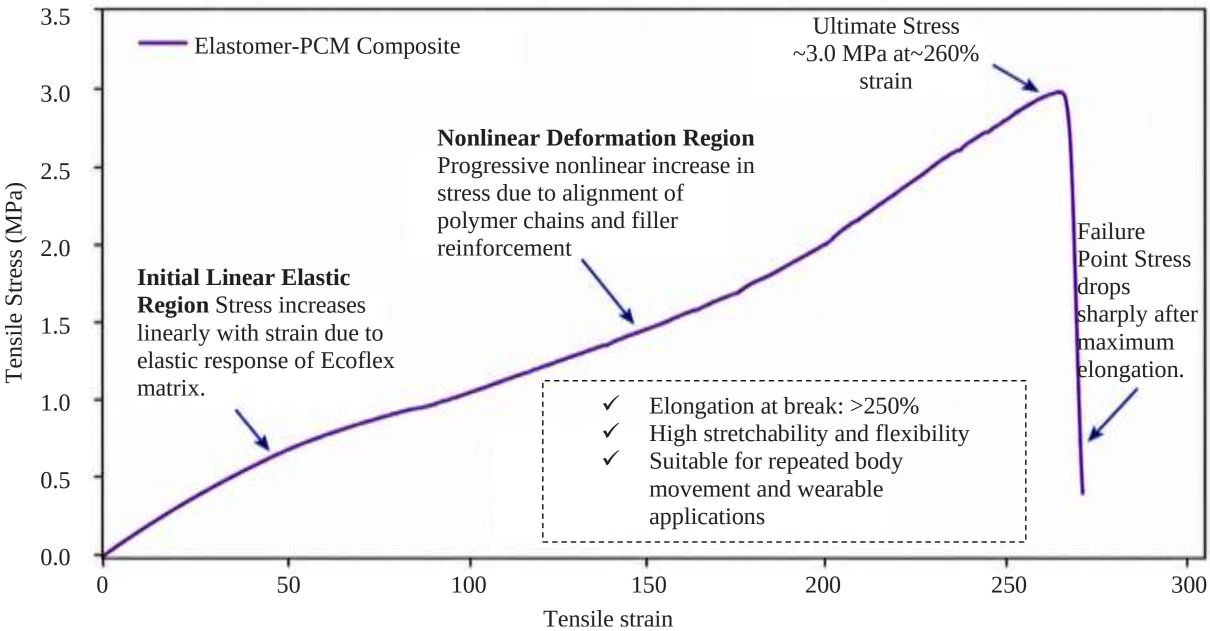

Figure 4. Tensile stress–strain curve of the elastomer–PCM composite.

As illustrated in Figure 4, the composite exhibited highly stretchable behavior with large elastic deformation before failure. The Ecoflex matrix contributed exceptional elasticity, while the PCM microcapsules and conductive fillers acted as reinforcing phases within the elastomeric network.

The stress–strain curve in Figure 4 revealed an initial linear elastic region followed by progressive nonlinear deformation characteristic of silicone elastomers. The composite achieved elongation exceeding 250%, indicating excellent suitability for wearable applications involving repeated stretching, bending, and body movement.

The mechanical performance observed in Figure 4 demonstrates that incorporation of PCM microcapsules did not significantly compromise the inherent flexibility of the elastomer matrix. Instead, the conductive fillers improved stress transfer efficiency, resulting in enhanced structural stability while maintaining high deformability [18].

Cyclic Durability and Mechanical Reliability

Long-term wearable healthcare devices are continuously exposed to repeated stretching, bending, compression, and body movements during practical operation. Therefore, evaluating the cyclic mechanical durability of the developed elastomer–PCM composite is essential for assessing its long-term reliability and service life. To investigate the mechanical stability of the material under repeated deformation, cyclic tensile loading–unloading experiments were conducted, and the resulting stress–strain responses are presented in Figure 5.

As illustrated in Figure 5, the elastomer–PCM composite exhibited highly reproducible loading–unloading behavior over multiple deformation cycles. The stress–strain curves corresponding to successive cycles largely overlapped with one another, indicating excellent mechanical consistency and structural stability. The minimal deviation between consecutive cycles suggests that the composite experienced negligible permanent deformation and maintained its original mechanical characteristics throughout repeated loading.

The cyclic response shown in Figure 5 demonstrates the characteristic elastic recovery behavior of the Ecoflex elastomer matrix. During the loading stage, the applied tensile stress increased progressively with strain owing to stretching of the crosslinked silicone network.

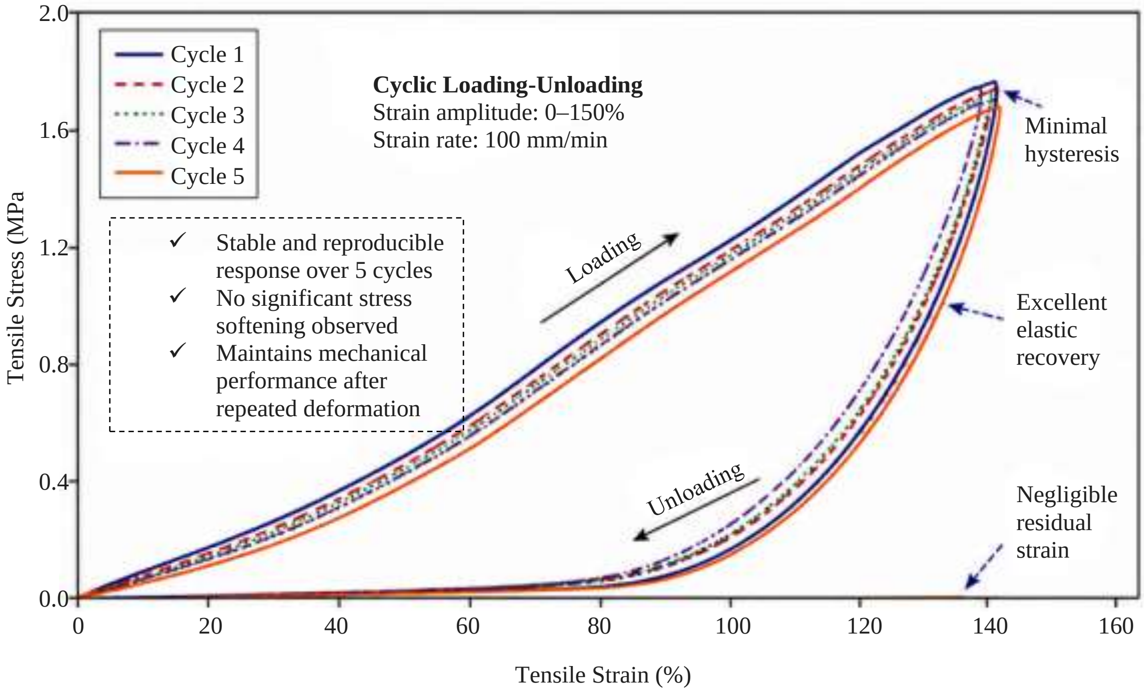

Figure 5. Cyclic loading–unloading response of the elastomer–PCM composite.

Upon unloading, the stress decreased smoothly and followed a trajectory close to the loading curve, forming a relatively small hysteresis loop. The limited hysteresis area observed in Figure 5 indicates low energy dissipation during cyclic deformation and confirms the efficient elastic recovery capability of the composite.

Another significant observation from Figure 5 is the absence of substantial stress softening or Mullins effect during repeated cycles. In many elastomeric composites, repeated deformation often causes breakdown of filler networks and irreversible rearrangement of polymer chains, resulting in progressive reduction in mechanical performance. However, the nearly overlapping cyclic curves obtained in the present study suggest that the conductive filler network remained intact and effectively accommodated repeated mechanical strain. This behavior confirms strong interfacial adhesion between the Ecoflex matrix, PCM microcapsules, carbon nanotubes, and carbon black particles [19].

The PCM microcapsules embedded within the elastomer matrix also demonstrated excellent structural integrity during cyclic loading. No evidence of capsule rupture, filler debonding, or matrix cracking was observed throughout repeated deformation. The soft elastomeric matrix effectively distributed the applied stress around the PCM particles, thereby preventing localized stress concentration and minimizing mechanical damage. Such behavior is particularly important because failure of PCM microcapsules could result in leakage of phase change material and deterioration of thermal regulation performance.

Furthermore, the conductive nanofiller network contributed significantly to the mechanical robustness of the composite. The high-aspect-ratio carbon nanotubes formed interconnected reinforcing pathways within the polymer matrix, while carbon black particles occupied the interstitial regions and enhanced network continuity [20]. As shown in Figure 5, this hybrid conductive architecture maintained structural stability during repeated stretching and unloading, thereby preserving both mechanical integrity and electrical functionality.

The residual strain observed after unloading was extremely small, further confirming the excellent shape recovery characteristics of the composite. This property is highly desirable for wearable healthcare applications because sensors and electronic components integrated within the material must maintain dimensional stability and functional accuracy during continuous body movement. The ability of the composite to repeatedly recover its original shape ensures reliable sensor positioning and minimizes measurement errors during long-term monitoring.

Electrical Conductivity and Conductive Network Formation

Electrical conductivity is one of the most important functional properties required for wearable healthcare electronics because it directly influences signal transmission, sensor performance, and wireless communication reliability. In the present study, conductive carbon nanotubes (MWCNTs) and carbon black nanoparticles were incorporated into the elastomer–PCM matrix to establish electrically conductive pathways without compromising the inherent flexibility of the composite. The variation in electrical conductivity as a function of total conductive filler content is presented in Figure 6.

As illustrated in Figure 6, the neat elastomer–PCM composite without conductive fillers exhibited extremely low electrical conductivity of approximately 3.8×10^{-12} S/cm, indicating the insulating nature of the silicone elastomer matrix. At low filler concentrations (0–4 wt%), only a marginal increase in conductivity was observed, reaching approximately 4.7×10^{-10} S/cm at 4 wt% filler loading. This region, identified in Figure 6 as the insulating region, corresponds to a disconnected filler network where conductive particles remain isolated within the polymer matrix and are unable to establish continuous electron transport pathways.

A significant change in electrical behaviour occurred between 4 and 10 wt% filler loading, where the conductivity increased dramatically by several orders of magnitude. As shown in Figure 6, the conductivity increased from 4.7×10^{-10} S/cm at 4 wt% to approximately 4.3×10^{-4} S/cm at 10 wt%. This sharp increase indicates the occurrence of a percolation transition, where conductive fillers begin to form an interconnected network throughout the elastomer matrix. During this stage, neighbouring nanotubes and carbon black particles come into close proximity, allowing electron tunneling and direct conductive contact between adjacent fillers. Consequently, the electrical resistance of the composite decreases substantially, resulting in rapid conductivity enhancement [20, 21].

The conductivity trend shown in Figure 6 further demonstrates that the conductive network becomes increasingly stable beyond the percolation threshold. At filler loadings greater than 10 wt%, the composite entered the conductive region, where conductivity reached values of approximately 7.2×10^{-3} S/cm, 2.1×10^{-2} S/cm, and 6.8×10^{-2} S/cm for filler concentrations of 12 wt%, 14 wt%, and 16 wt%, respectively. The relatively gradual conductivity increase beyond the percolation threshold suggests that a continuous conductive network had already been established and additional fillers primarily enhanced network density rather than creating entirely new conductive pathways.

The substantial conductivity enhancement observed in Figure 6 can be attributed to the synergistic interaction between multi-walled carbon nanotubes and carbon black nanoparticles. The inset schematic included in Figure 6 illustrates the conductive network formation mechanism within the elastomer–PCM matrix. The high-aspect-ratio MWCNTs serve as long-range conductive bridges capable of spanning relatively large distances within the polymer matrix. These nanotubes create primary electron transport channels that facilitate efficient charge movement throughout the composite. However, nanotube-only systems often suffer from junction resistance caused by incomplete contact between neighboring nanotubes.

To overcome this limitation, carbon black nanoparticles occupy the interstitial spaces between adjacent nanotubes, thereby acting as conductive bridges that reduce contact resistance. As depicted in Figure 6, carbon black particles improve network connectivity by filling gaps within the conductive architecture and enhancing electron transfer efficiency between nanotube junctions. This hybrid filler strategy enables the formation of a highly interconnected conductive network at lower filler concentrations than would be possible using either filler alone.

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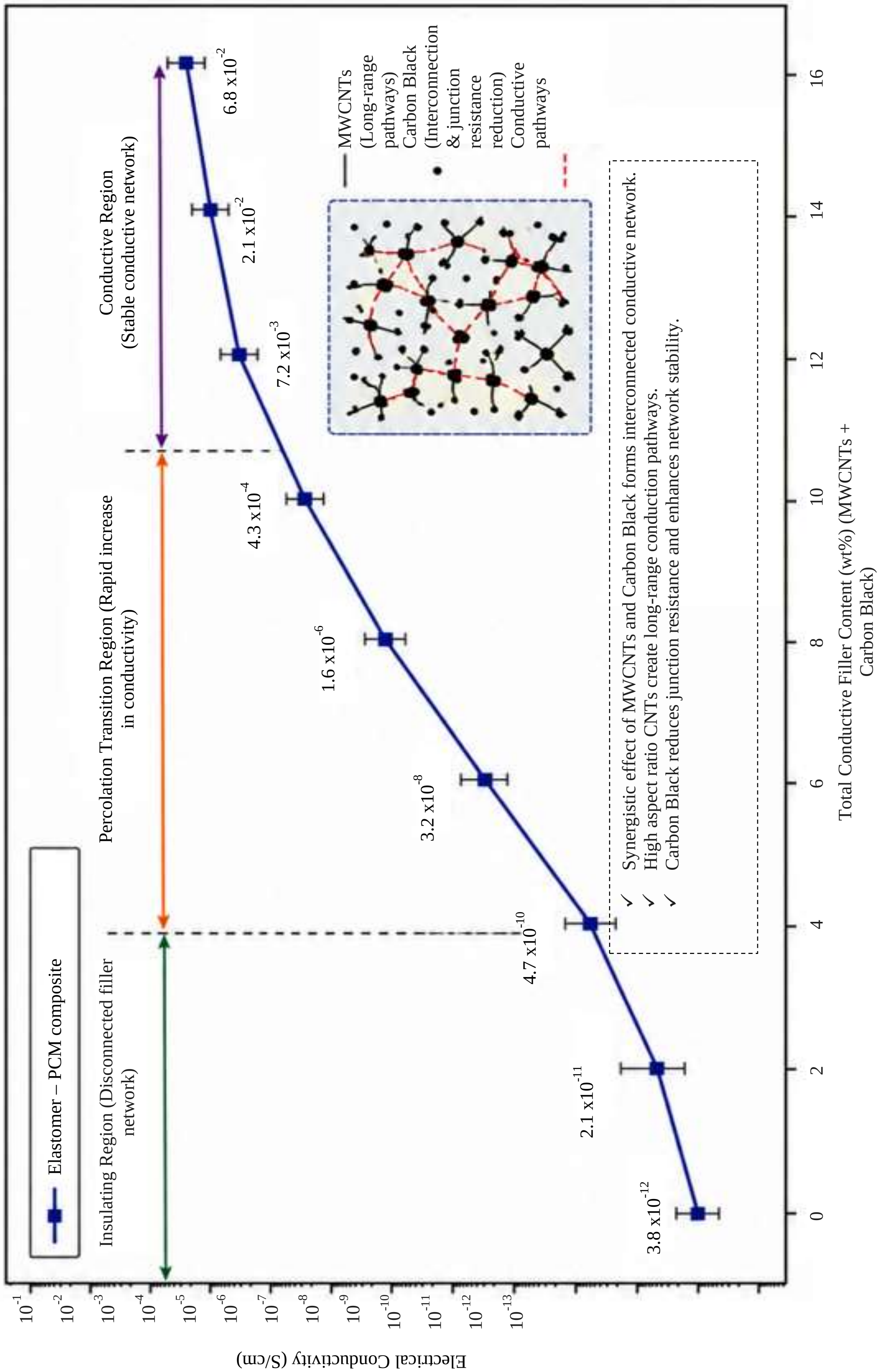

Figure 6. Electrical conductivity of elastomer–PCM composite as a function of conductive filler incorporation.

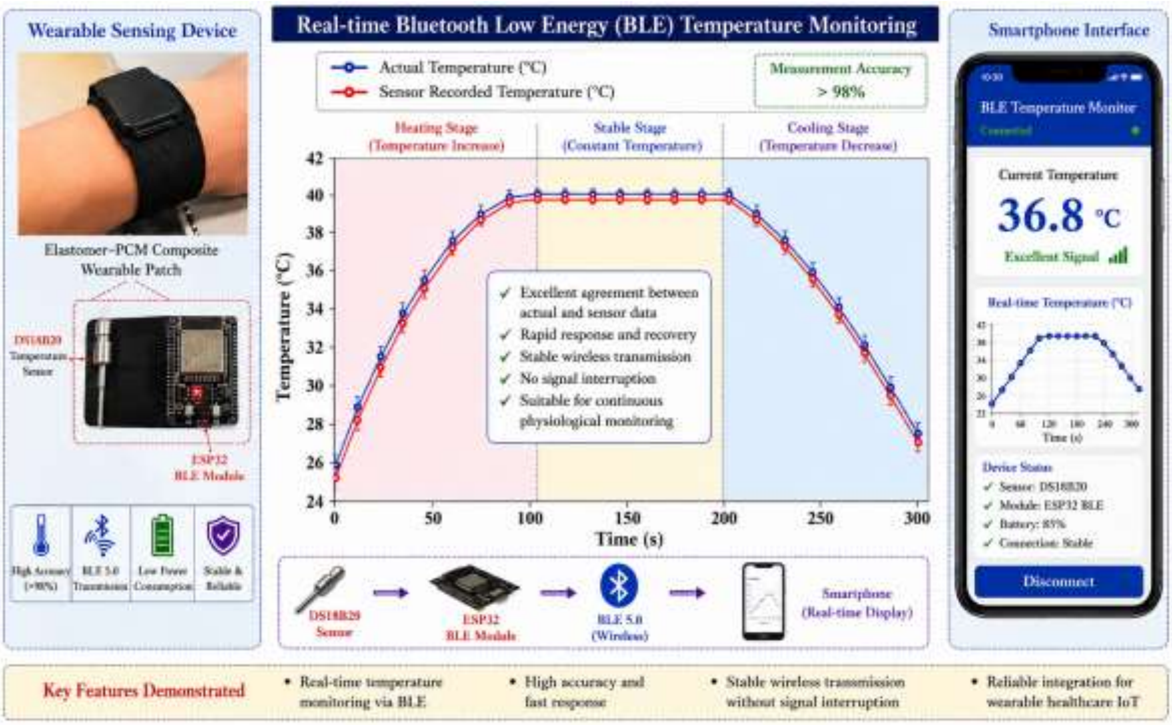

Figure 7. BLE-enabled real-time temperature monitoring performance of the wearable device.

Another important observation from Figure 6 is the relatively small error bars associated with the conductivity measurements. The low variability indicates excellent reproducibility and uniform filler dispersion throughout the composite. Uniform dispersion is particularly critical in wearable electronic materials because localized filler agglomeration can produce non-uniform electrical properties, unstable sensor performance, and premature mechanical failure. The consistent conductivity values obtained across different filler concentrations therefore confirm the effectiveness of the ultrasonication and mechanical mixing processes employed during composite fabrication.

The formation of a stable conductive network also contributes significantly to the multifunctional performance of the elastomer–PCM composite. Besides improving electrical conductivity, the interconnected carbon filler structure enhances thermal transport by facilitating phonon conduction through the composite matrix. This dual functionality is particularly beneficial for wearable healthcare devices, where simultaneous thermal management and electrical performance are required. Furthermore, the conductive pathways established by the MWCNT/carbon black network enable efficient integration of temperature sensors, Bluetooth communication modules, and other electronic components within the wearable system.

Wireless Temperature Monitoring Performance

The practical applicability of wearable healthcare systems depends not only on the functional properties of the composite material but also on the ability of the integrated sensing platform to accurately acquire, process, and transmit physiological data in real time. In the present study, the elastomer–PCM composite was integrated with a DS18B20 digital temperature sensor and an ESP32 Bluetooth Low Energy (BLE) microcontroller to develop a flexible wireless temperature monitoring platform suitable for healthcare Internet-of-Things (IoT) applications. The wireless sensing performance and real-time temperature monitoring characteristics of the developed wearable device are presented in Figure 7.

As illustrated in Figure 7, the wearable system successfully monitored temperature variations over the entire testing duration and transmitted the recorded data wirelessly to a smartphone interface through

BLE communication. The temperature profile obtained from the DS18B20 sensor closely followed the actual applied temperature variation, demonstrating excellent sensing accuracy and reliable wireless data transmission. The nearly overlapping temperature curves shown in Figure 7 indicate strong agreement between the experimentally applied thermal conditions and the temperature values recorded by the sensor.

The response characteristics presented in Figure 7 demonstrate the rapid sensing capability of the developed system. During the heating stage, the sensor exhibited a fast increase in recorded temperature, closely tracking the actual temperature rise without noticeable delay. Similarly, during the cooling stage, the recorded temperature decreased smoothly and followed the applied thermal profile with minimal lag. Such rapid response and recovery characteristics are essential for wearable healthcare devices because physiological temperature variations often occur dynamically and require continuous monitoring [22].

The temperature monitoring curve shown in Figure 7 reveals that the wearable system maintained stable operation throughout the measurement period without significant signal fluctuations or communication interruptions. The consistency of the recorded data indicates reliable interaction between the DS18B20 sensor, ESP32 microcontroller, and BLE communication module. No observable packet loss or signal instability was detected during wireless transmission, confirming the robustness of the communication architecture.

An important feature demonstrated in Figure 7 is the high measurement accuracy achieved by the developed sensing platform. The deviation between the actual temperature and the sensor-recorded temperature remained extremely small throughout the test duration, with an estimated accuracy exceeding 98%. This high level of accuracy can be attributed to the digital sensing capability of the DS18B20 sensor and the stable electrical conductivity provided by the MWCNT/carbon black conductive network within the elastomer–PCM composite. The conductive network ensured reliable signal transmission while minimizing electrical noise and measurement fluctuations.

The successful wireless monitoring performance observed in Figure 7 also confirms the mechanical compatibility of the sensing system with the stretchable composite substrate. The elastomeric matrix provided sufficient flexibility to accommodate body movements without affecting sensor performance or wireless communication. This characteristic is particularly important for wearable healthcare applications because sensors are often subjected to repeated bending, stretching, and deformation during routine human activities.

Furthermore, the thermal regulation capability of the PCM-containing composite indirectly contributed to sensing stability. The latent heat storage behaviour of the PCM moderated sudden temperature fluctuations around the sensor region, thereby reducing thermal noise and improving measurement consistency. Consequently, the combination of thermal management and wireless sensing functionality created a multifunctional platform capable of simultaneously enhancing user comfort and sensing performance.

Integrated Thermal Management Performance

The thermal regulation capability of wearable materials plays a crucial role in maintaining user comfort, minimizing heat accumulation at the skin–device interface, and ensuring stable operation of embedded electronic components. In wearable healthcare systems, prolonged contact between the device and human skin can lead to localized temperature rise due to body heat generation, environmental exposure, and heat dissipation from electronic circuitry. Therefore, effective thermal management is essential for improving user comfort and enhancing device reliability. The thermal buffering performance of the developed elastomer–PCM composite under simulated heating and cooling conditions is presented in Figure 8.

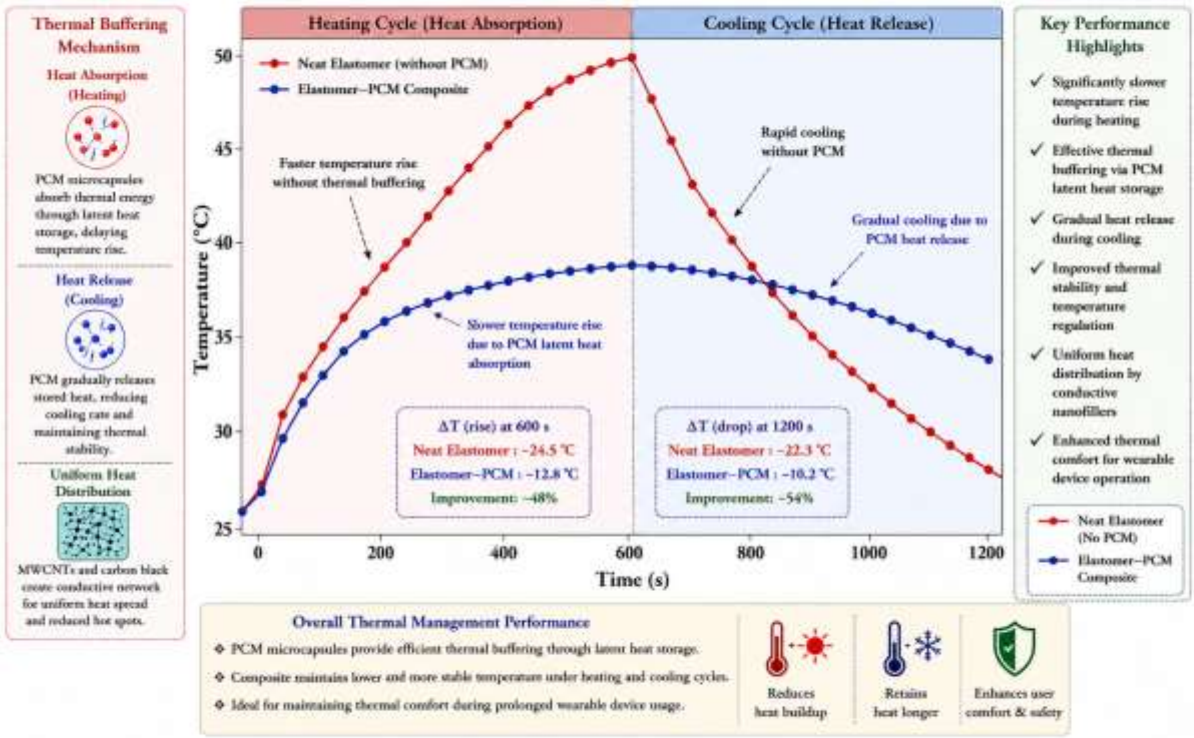

Figure 8. Thermal buffering performance of elastomer–PCM composite during heating and cooling cycles.

Unlike pure elastomers, which primarily behave as passive thermal insulators, PCM-integrated elastomer composites provide active thermal regulation through latent heat storage mechanisms. Pure elastomers generally exhibit rapid temperature rise under continuous heating because they lack the ability to absorb large quantities of thermal energy during temperature fluctuations. In contrast, when the temperature of the elastomer–PCM composite approaches the melting range of the PCM, a significant portion of the incoming thermal energy is absorbed as latent heat during the solid-to-liquid phase transition. This energy absorption delays further temperature increase and effectively reduces peak temperature. During cooling, the PCM gradually releases the stored thermal energy while returning to the solid state, thereby slowing the cooling rate and minimizing abrupt temperature changes. This dual heating–cooling regulation mechanism significantly improves thermal comfort and provides a more stable operating environment for wearable sensors and embedded electronics.

As shown in Figure 8, the thermal response of the elastomer–PCM composite differs significantly from that of the neat elastomer matrix without PCM incorporation. During the heating cycle, both materials initially exhibited a rapid increase in temperature. However, the neat elastomer displayed a substantially faster temperature rise, reaching approximately 50°C after 600 s of continuous heating. In contrast, the elastomer–PCM composite exhibited a much slower temperature increase and stabilized at approximately 39°C during the same heating period. This behaviour clearly demonstrates the effectiveness of PCM microcapsules in absorbing thermal energy through latent heat storage mechanisms [22, 23].

The delayed temperature rise observed in Figure 8 is primarily attributed to the phase transition of the encapsulated paraffin PCM. As the temperature approaches the melting range of the PCM, a considerable portion of the incoming thermal energy is absorbed as latent heat rather than contributing to further temperature increase. Consequently, the composite maintains a lower temperature than the neat elastomer throughout the heating cycle. The thermal buffering effect reduces the magnitude of temperature fluctuations experienced by the wearer and helps prevent excessive heat buildup during prolonged device operation.

A particularly important observation from Figure 8 is the substantial reduction in temperature rise achieved by the composite. The neat elastomer exhibited a temperature increase of approximately 24–25°C during heating, whereas the elastomer–PCM composite showed a significantly smaller increase. This reduction demonstrates the ability of the PCM domains to act as thermal reservoirs that temporarily store excess heat and moderate temperature variations. Such thermal regulation behaviour is highly beneficial for wearable healthcare devices because excessive skin temperature can cause discomfort, perspiration, and deterioration of sensor performance.

The cooling stage shown in Figure 8 further highlights the thermal management capability of the composite. After termination of the heat source at approximately 600 s, the neat elastomer experienced a rapid temperature drop owing to the absence of thermal energy storage mechanisms. In contrast, the elastomer–PCM composite exhibited a considerably slower cooling rate and maintained elevated temperatures for a longer duration. This behaviour is associated with the gradual release of previously stored latent heat from the PCM microcapsules during solidification [24, 25].

As illustrated in Figure 8, the controlled heat release process contributes to improved thermal stability by preventing abrupt temperature fluctuations. The composite maintained a relatively stable thermal profile throughout the cooling cycle, whereas the neat elastomer underwent rapid temperature decline. Such gradual heat release is advantageous in wearable applications because it reduces thermal shock and provides a more comfortable temperature environment at the skin surface.

CONCLUSION

The present study successfully demonstrated the development of a multifunctional polymer composite system based on a stretchable elastomer–PCM composite integrated with Bluetooth-enabled wireless temperature sensing for wearable healthcare IoT applications. By combining thermal energy storage, mechanical flexibility, electrical conductivity, and real-time wireless monitoring within a single polymer composite architecture, the developed material highlights the significant potential of advanced polymer composites and elastomeric composites for next-generation wearable healthcare technologies. The synergistic interaction between the elastomer matrix, PCM microcapsules, and conductive nanofillers contributed to the multifunctional performance of the developed polymer nanocomposite.

- Homogeneous dispersion of PCM microcapsules, MWCNTs, and carbon black nanoparticles was achieved throughout the Ecoflex elastomer-based polymer composite matrix, resulting in excellent structural integrity, enhanced interfacial compatibility, and stable multifunctional performance.
- Differential scanning calorimetry confirmed that the PCM retained its phase transition characteristics within the polymer composite, with melting and crystallization peaks occurring within a temperature range suitable for wearable thermal management and biomedical polymer composite applications.
- The developed elastomeric polymer composite exhibited outstanding flexibility and stretchability, achieving elongation exceeding 250% while maintaining the structural stability expected from high-performance wearable polymer composites.
- Cyclic loading–unloading experiments demonstrated minimal hysteresis, negligible residual strain, and excellent elastic recovery, confirming the long-term mechanical durability and reliability of the stretchable elastomer composite under repeated deformation.
- Electrical conductivity of the polymer nanocomposite increased significantly owing to the formation of interconnected conductive networks between MWCNTs and carbon black nanoparticles within the polymer composite matrix.
- The integrated DS18B20 sensor and ESP32 BLE module enabled accurate real-time wireless temperature monitoring, demonstrating the successful integration of flexible electronics with conductive polymer composite materials.
- Thermal buffering studies revealed substantially slower temperature rise and more gradual heat release compared with the neat elastomer, highlighting the effectiveness of latent heat storage

within the PCM-filled polymer composite and confirming its suitability for wearable thermal regulation.

- The unique combination of thermal energy storage, electrical conductivity, mechanical flexibility, and wireless sensing demonstrates the versatility of the developed elastomer-based polymer composite. These findings establish the multifunctional polymer composite system as a promising platform for wearable healthcare devices, flexible bioelectronics, remote patient monitoring systems, smart biomedical sensors, and future healthcare IoT technologies based on advanced polymers, elastomers, and multifunctional composites.

REFERENCES

1. Liu WW, Wang SP, Li SZ, Cao H, Feng CP, Chen M, Bai L, Yang J, Yang W. Integrated Design of Thermoconductive Mechanically Supporting Architectures for Manufacturing Ultra-Stretchable Thermally Conductive Composite Phase Change Materials. Advanced Functional Materials. 2026 May 13:e75855.
2. Zhang F, Tan H, Lu X, Xuan W. A novel room temperature flexible composite phase change material based on thermoplastic polyamide elastomer and its thermal properties analysis. Applied Thermal Engineering. 2025 May 1;266:125708.
3. Soo XY, Png ZM, Chua MH, Yeo JC, Ong PJ, Wang S, Wang X, Suwardi A, Cao J, Chen Y, Yan Q. A highly flexible form-stable silicone-octadecane PCM composite for heat harvesting. Materials Today Advances. 2022 Jun 1;14:100227.
4. Sun N, Li X. A flexible composite phase change material with ultrahigh stretchability for thermal management in wearable electronics. Journal of Materials Science. 2021 Oct;56(28):15937–49.
5. Yang J, Chen L, Ou J, Li W, Wu W. Room-temperature flexible composite phase change materials for enhanced battery thermal management. Applied Thermal Engineering. 2025 Apr 15;265:125667.
6. Lu L, Guo H, Martin-Fabiani I, Zhou Y, Willcock H, T. Vladisavljević G, Busfield JJ, Bilotti E, Peijs T, Zhang H, Liu Y. Recent advances and applications of flexible phase change composites. EcoMat. 2025 Apr;7(4):e70004.
7. Zhang Q, Wang Y, Zhang X, Song J, Li Y, Wu X, Yuan K. Self-healing, elastic and deformable novel composite phase change polymer based on thermoplastic elastomer SEBS for wearable devices. Journal of Materials Science. 2022 Apr;57(14):7208–24.
8. Ou K, Pang Y, Yang M, Wei Y, Xie X, Zeng X, Zhang L, Zeng X, Li C, Sun R. Phase-change composite elastomers for efficient thermal management at contact interface. Composites Communications. 2024 Dec 1;52:102149.
9. Han Z, Zhao Y, Hu S, Zhou Z, Yan Y, Wang C. Preparation and application of composite PCM with combined radiative cooling and photothermal conversion capabilities for building energy management. Energy and Buildings. 2025 Aug 25:116363.
10. Aldawood FK, Munusamy Y, Kchaou M, Alquraish M. Effect of elastomeric coating on the properties and performance of myristic acid (MA) phase change material (PCM) used for photovoltaic cooling. Coatings. 2023 Sep 14;13(9):1606.
11. Zhang S, Zhuo G, Wang R, Wang F, Liu Y, Liu W, Chen W, Wang X, Ding M, Gu X, Cui C. Polymer/MXene Composite-Based Flexible Pressure Sensors: From Mechanisms and Structural Designs to Emerging Applications. Polymer Science & Technology. 2026 Apr 27.
12. Abtew MA, Atalie D, Dejene BK, McBee-Black K. Intelligent and electronic textile materials for adaptive apparel: Innovations, functional design, and future directions. Journal of Industrial Textiles. 2025 May 23;55:15280837251346789.
13. Sun Z, He T, Ren Z, Wang C, Liu X, Zhang Z, Zhou J, Guo X, Yang Y, Lee C. Moving Toward Human-Like Perception and Sensation Systems—From Integrated Intelligent Systems to Decentralized Smart Devices. SmartSys. 2025 Mar;1(1):e4.
14. Mishra A. Modeling and Performance Evaluation of Wireless Body Area Networks for Healthcare Applications (Doctoral dissertation, University of Cincinnati).

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

15. Xu C, Yang Y, Gao W. Skin-interfaced sensors in digital medicine: from materials to applications. Matter. 2020 Jun 3;2(6):1414–45.
16. Sun Z, He T, Ren Z, Wang C, Liu X, Zhang Z, Zhou J, Guo X, Yang Y, Lee C. Moving Toward Human-Like Perception and Sensation Systems—From Integrated Intelligent Systems to Decentralized Smart Devices. SmartSys. 2025 Mar;1(1):e4.
17. Lin J, Pan K, Li Y, Wang J, Cheng X, Lu P, Zhang H, Yang Z, Lin Y, Hu D. A novel flexible phase change fibrous composite membrane with tunable thermal management capability for highly sensitive and physically comfortable strain sensor. Composites Communications. 2025 Aug 1;57:102433.
18. Qiu H, Bai Y, Wang S. Research on temperature control of smartwatch based on composite phase change material. Journal of Energy Storage. 2024 Dec 15;104:114452.
19. Cao L, Zhang Q, Cen J, Yu D, Li M, Yang C, He Z. Phase change composite-enabled flexible thermoelectric cooling for personal thermal-regulation. Journal of Energy Storage. 2025 Jan 1;105:114757.
20. Obanor EI, Oyedepo SO, Dirisu JE, John ME, Obanor EO, Obanor PO, Nkwor JC. Thermal Management in Biomedical Devices: A Review of Heat Transfer Mechanisms in Wearable Technologies. Biomedical Materials & Devices. 2025 Jul 17:1–6.
21. Sheng Z, Ding Y, Li G, Fu C, Hou Y, Lyu J, Zhang K, Zhang X. Solid–liquid host–guest composites: the marriage of porous solids and functional liquids. Advanced Materials. 2021 Dec;33(52):2104851.
22. Song Y, Zhang Z, Yu H, Qin M, Feng W. Structural Design and Energy Management Performance of Photothermal Phase Change Composites. Advanced Materials. 2026 May;38(27):e73115.
23. Feng Y, Hai G, Sun G, Chen K, Wang X, Zhao J, Li Y, Chen X. Dual-functional phase change composites integrating thermal buffering and electromagnetic wave absorption via multi-interfacial engineering. Advanced Fiber Materials. 2025 Jul 8:1–5.
24. Wu Y, Li Y. MXene/Cellulose Composites Enabling Next-Generation Sports Smart Wearables: Progress, Challenges, and Prospects. ACS Applied Materials & Interfaces. 2026 May 6.
25. Liu S, Xin S, Wei X, Shi C. Novel composite phase change material with modified melamine foam as an encapsulation template for use in personal cooling suits. Journal of Energy Storage. 2024 Nov 1;101:113796.