

Anisotropic PI/rGO aerogels for multifunctional thermal protection and wearable sensing

Jinchao Zhu^{1,§}, Yifan Zhi^{2,§}, Yutao Li¹, Chenghao Lou¹, Jian Zhang¹, Qingqing Zhou¹, Wen Wu¹, Ping Li^{2,3}, Huanxia Zhang¹(✉)

¹ College of Material and Textile Engineering, Jiaxing University, Jiaxing 314001, China

² Shanghai Collaborative Innovation Center of High Performance Fibers and Composite, College of Textiles, Donghua University, Shanghai 201620, China

³ Jiaxing Nanhu University, Jiaxing 314001, China

§ Jinchao Zhu and Yifan Zhi contributed equally to this work.

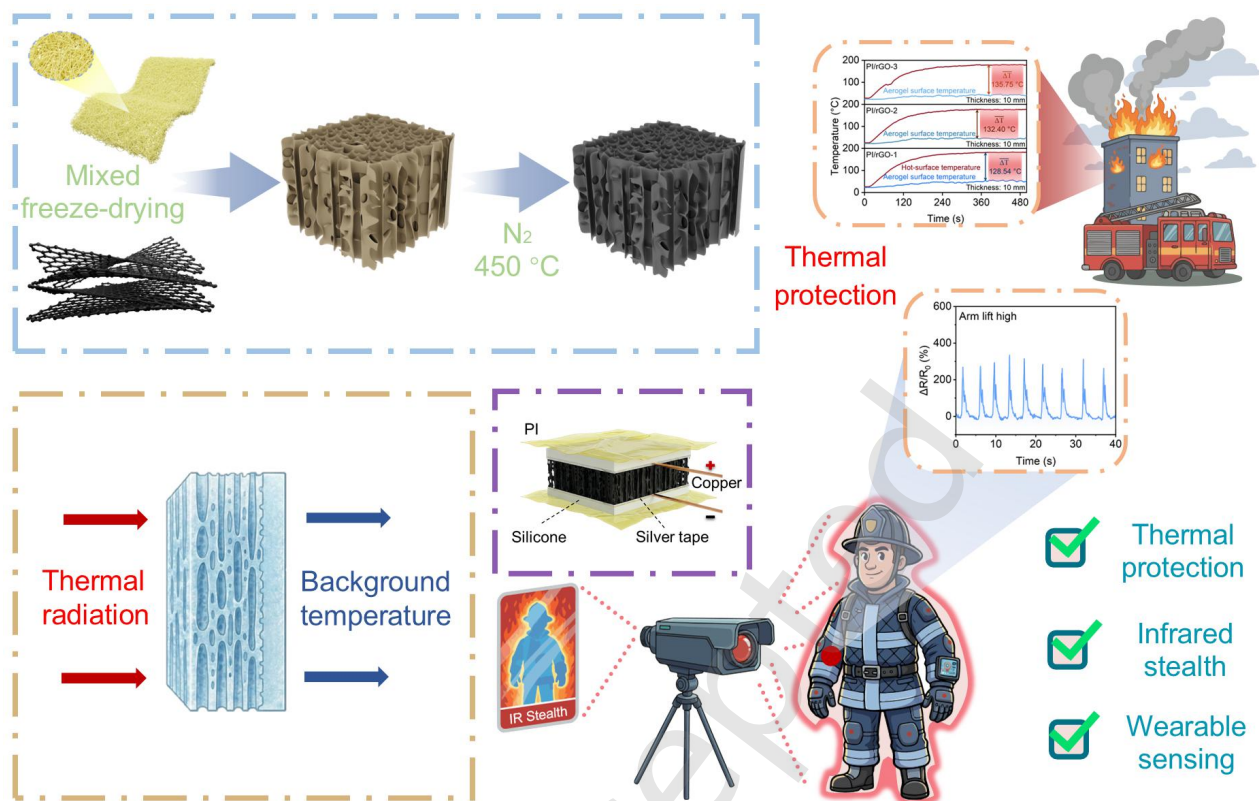
Nano Res., **Just Accepted Manuscript** • <https://doi.org/10.26599/NR.2026.94909056>

<https://www.sciopen.com/journal/1998-0124> on Jul. 24, 2026

© The Authors(s)

Just Accepted

This is a “Just Accepted” manuscript, which has been examined by the peer-review process and has been accepted for publication. A “Just Accepted” manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Tsinghua University Press (TUP) provides “Just Accepted” as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, and the page proofs have been corrected, it will be removed from the “Just Accepted” web site and published officially with volume and article number (e.g., *Nano Research*, **2025**, *18*, 94906990). Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain. In no event shall TUP be held responsible for errors or consequences arising from the use of any information contained in these “Just Accepted” manuscripts. To cite this manuscript please use its Digital Object Identifier (DOI®), which is identical for all formats of publication.



A biomimetic anisotropic PI/rGOA was engineered to synergistically integrate thermal protection, infrared stealth, and wearable sensing. This work provides an effective strategy for designing lightweight multifunctional aerogels for extreme-environment protection and next-generation wearable electronics.

Anisotropic PI/rGO aerogels for multifunctional thermal protection and wearable sensing

Jinchao Zhu^{1,§}, Yifan Zhi^{2,§}, Yutao Li¹, Chenghao Lou¹, Jian Zhang¹, Qingqing Zhou¹, Wen Wu¹, Ping Li^{2,3}, and Huanxia Zhang¹✉

¹ College of Material and Textile Engineering, Jiaying University, Jiaying 314001, China

² Shanghai Collaborative Innovation Center of High Performance Fibers and Composite, College of Textiles, Donghua University, Shanghai 201620, China

³ Jiaying Nanhu University, Jiaying 314001, China

[§] Jinchao Zhu and Yifan Zhi contributed equally to this work

Received: 16 May 2026; **Revised:** 17 July 2026; **Accepted:** 24 July 2026

✉ Address correspondence to zhanghuanxia818@163.com



Cite this article: *Nano Research*, 2026, 19, 94909056 <https://doi.org/10.26599/NR.2026.94909056>

ABSTRACT: High-performance aerogels featuring exceptional thermal insulation and integrated motion-sensing capabilities are pivotal for the advancement of next-generation flexible electronics and protective systems in extreme environments. However, achieving a synergistic balance between multi-functional integration within a single lightweight framework remains a significant challenge due to the structural limitations of conventional isotropic materials. Inspired by the hierarchical porous structures of aquatic plants, we herein report an anisotropic polyimide/reduced graphene oxide aerogel (PI/rGOA) with a biomimetic architecture, fabricated via a synergistic strategy of directional freezing and interfacial regulation. This approach combines directional freezing with hydrogen-bonding-assisted interfacial regulation between polyimide nanofibers (PINF) and graphene oxide (GO), enabling the construction of highly ordered anisotropic channels. The resulting PI/rGOA demonstrates superior thermal regulation, maintaining substantial temperature gradients at both -190 °C and 200 °C, while exhibiting rapid self-extinguishing behavior and structural integrity under a 1300 °C flame. Furthermore, the simultaneous regulation of heat conduction and infrared radiation enables effective stealth performance. The sensor encapsulated with polydimethylsiloxane (PDMS) provides high sensitivity and stability over 500 cycles. Overall, this work provides a versatile paradigm for developing multifunctional, structurally ordered materials, offering a promising solution for aerospace, defense, and wearable electronic devices.

KEYWORDS: anisotropic aerogels, Polyimide nanofibers, rGO, extreme thermal protection, infrared stealth, wearable motion sensing

1 Introduction

Against the backdrop of extreme cold and hot environments and the rapid development of wearable electronic devices, there is an urgent need for an integrated lightweight material that can simultaneously provide human thermal protection and motion sensing, enabling real-time monitoring of human vital activities while maintaining efficient thermal protection [1-5]. Lightweight porous structures are widely found in nature, and through long-term evolution these structures have achieved a balance among low density, high strength, and high transport efficiency. Aquatic plants such as lotus stems and water hyacinth serve as representative examples, in which internally aligned hollow channels along the growth direction ensure structural stability while enabling rapid transport of gases and energy, thereby providing essential support for survival in complex environments. The lightweight, efficient, and multifunctional synergistic characteristics [6-8] embodied by such directionally constructed porous architectures offer important biomimetic inspiration [9-11] for the design of artificial porous materials integrating thermal protection and sensing functionalities.

In recent years, a variety of strategies have been developed to

fabricate aerogels with biomimetic porous architectures, including templating methods [12, 13], sol-gel method [14, 15], 3D printing [16, 17], and directional freezing [18, 19]. However, conventional aerogels predominantly possess isotropic pore structures, resulting in nearly identical thermal resistance in all directions, which makes directional thermal regulation difficult and limits their application in complex thermal environments [20, 21]. In contrast, ice-templated directional freezing techniques [22] enable the construction of highly aligned anisotropic pore channels within aerogels by controlling the growth direction of ice crystals, thereby achieving differentiated thermal transport behaviors along different directions. This approach not only realizes a biomimetic replication of naturally occurring directionally porous, but also provides an effective pathway for constructing functional aerogels that simultaneously offer thermal protection and structural stability.

On the basis that the directional porous architecture endows aerogels with anisotropic thermal protection capability, the selection of the material system further determines their overall performance [23, 24]. Existing aerogels mainly include inorganic aerogels [25, 26], organic aerogels [27, 28], and composite aerogels [29-31] incorporating functional fillers. Inorganic aerogels exhibit ultralow thermal conductivity and

excellent high-temperature resistance, but their high brittleness and poor flexibility make them difficult to adapt to complex deformation environments; Organic aerogels, relying on polymeric backbones, demonstrate improved mechanical toughness and structural stability, however, their electrical inertness and limited capability for thermal radiation regulation restrict multifunctional integration [32-34]. Among polymeric matrices, PI is particularly attractive because of its outstanding thermal stability, intrinsic flame retardancy, superior mechanical properties, and lightweight fibrous framework, making it highly suitable for aerogels operating in extreme environments [1, 2, 18, 24]. The introduction of functional fillers such as carbon nanotubes (CNTs), graphene, or MXene can effectively enhance electrical conductivity and thermal radiation regulation, but is often accompanied by pore structure deterioration, increased density, and degraded flexibility, issues that are particularly pronounced in anisotropic architectures [35-38]. Of these functional fillers, GO is particularly advantageous because its oxygen-containing functional groups facilitate hydrogen-bonding-assisted interfacial interactions with PI, promoting the uniform distribution of GO throughout the PINF framework [39, 40], while the reduced graphene oxide (rGO) network establishes effective conductive pathways and infrared radiation regulation [17, 21]. Therefore, how to construct a flexible conductive composite aerogel with an anisotropic architecture that balances compressive performance, thermal protection, and sensing functionality remains an unresolved and critical scientific challenge.

In this study, an anisotropic porous aerogel composed of PINF and rGO was constructed. Through the synergistic integration of directional freezing and hydrogen-bonding-assisted interfacial regulation between PINF and GO, the spatial confinement provided by the PINF framework, together with the interfacial hydrogen bonding between PINF and GO, promotes the uniform distribution of GO throughout the fibrous framework during directional freezing, leading to the formation of a highly ordered anisotropic porous architecture. In addition, the PINF framework exerts a cooperative confinement effect on ice crystal growth during unidirectional freezing, thereby significantly enhancing the anisotropy of the aerogel pore structure while maintaining the ordered arrangement of the channels. Based on this biomimetic directional architecture, steady-state thermal insulation tests over a wide temperature range from -190 °C to 200 °C, as well as evaluations of flame retardancy and structural stability under a 1300 °C butane flame, were systematically conducted on the PI/rGOA. Meanwhile, infrared thermal imaging was employed to visually characterize the thermal radiation regulation behavior of the PI/rGOA under continuous heating and human-related thermal source conditions, thereby systematically evaluating its infrared stealth performance. Furthermore, a piezoresistive sensor was further constructed through PDMS flexible encapsulation, and its electrical response behavior was systematically tested to evaluate the aerogel's capability to sense human motions of varying amplitudes and its response stability. The study demonstrates that anisotropic PI/rGOA, constructed via an organic-inorganic, achieve integrated in key functions including thermal protection, infrared stealth, and flexible sensing, fully validating their engineering feasibility and application potential in extreme environment protection and wearable smart devices.

2 Experimental Section

2.1 Materials

Polyamic Acid solution (20 wt%, PAA/DMAc) was purchased from Dongguan Ruiyu Plastic Raw Materials Co., Ltd. (Guangzhou, China) and used as received. The preparation procedures for the GO dispersion can be found in our group's previous studies [41-44] and in the Supplementary material.

2.2 Preparation of PINF aqueous dispersion

PINF was prepared through electrospinning PAA followed by thermal imidization. The electrospinning was carried out under ambient conditions with a temperature of 25–28 °C and a relative humidity of 50–60%. A 20-gauge metal needle was used as the spinneret, with a constant spinning voltage of 24.5 kV applied, a solution feeding rate of 0.8 mL/h, and a spinneret-to-collector distance of 23 cm. The resulting PAA nanofiber membranes were vacuum-dried at 60 °C for 6 h, then subjected to thermal imidization in a tubular furnace to obtain PINF. The thermal imidization was carried out by heating in a tubular furnace at a rate of 5 °C/min to 100 °C with a 30 min hold, followed by heating to 160 °C with a 30 min hold, and finally to 280 °C with a 30 min hold. Finally, the obtained PINF was dispersed in deionized water and homogenized by high-speed shear to form a PINF aqueous suspension with a solid content of approximately 1%.

2.3 Preparation of PPI/rGO aerogels

Aerogels were prepared by co-mixing PINF aqueous dispersion and GO dispersion at predetermined ratios. Specifically, the concentration of the PINF aqueous dispersion was ~1 wt%, and that of the GO dispersion was ~1.5 wt%. The PINF aqueous dispersion and GO dispersion were mixed at specific ratios and poured into a freezing mold with a copper bottom and polytetrafluoroethylene sidewalls, followed by freezing under liquid nitrogen. Due to the imposed temperature gradient, rapid cooling at the bottom of the container induced ice crystal formation, guiding ice crystal growth from bottom to top, during which GO sheets and PINF were expelled to the ice crystal boundaries, forming dense vertically aligned pore channels [8, 45-47].

After freeze-drying for 48 h, PI/GO aerogels (PI/GOA) were obtained. According to the different ratios of PI and GO, the aerogels with PI:GO ratios of 7:3, 5:5, and 3:7 were designated as PI/GO-1, PI/GO-2, and PI/GO-3, respectively. Thermal reduction was conducted in a tubular furnace under a nitrogen atmosphere at a heating rate of 5 °C/min, with isothermal holding at 200 °C and 450 °C for 30 min at each temperature, yielding PI/rGOA. The aerogels obtained after thermal reduction were correspondingly designated as PI/rGO-1, PI/rGO-2, and PI/rGO-3. After immersion in a PDMS solution suspension followed by drying for 8 h, the resulting PI/rGOA were named PPI/rGO-1, PPI/rGO-2, and PPI/rGO-3, respectively.

2.4 Fabrication of PPI/rGO PRS

The PPI/rGO pressure-resistive sensor (PPI/rGO PRS) was fabricated in a sandwich configuration. The PI/rGO-3 was immersed in a PDMS solution to endow the aerogel with excellent elastic recovery, serving as the sensing layer. Conductive silver tape was attached to the upper and lower surfaces as electrodes, and a PI film was used as the outermost encapsulation layer, yielding the PPI/rGO PRS.

2.5 Characterization

The morphology of the materials was characterized using scanning electron microscopy (SEM, Gemini360, ZEISS). Fourier Transform Infrared Spectroscopy (FTIR, VERTEX-70, Bruker) was used to determine the chemical structure of PAA, PI, and composite aerogels in the wavelength range of 400–4000 cm^{-1} . X-ray photoelectron spectroscopy (XPS, XSAM800, Kratos) was conducted to analyze surface composition, using an Al $K\alpha$ X-ray source (1486.6 eV photons) with a power of 180 W (12 kV, 15 mA) under a vacuum of 2×10^{-7} Pa. The thermal weight loss properties were analyzed using a Thermogravimetric Analyzer (TGA, Q50, TA), and the TGA curves were recorded within the temperature range of 30 to 800 $^{\circ}\text{C}$, with a heating rate of 10 $^{\circ}\text{C}/\text{min}$ under N_2 atmosphere. while the electrical signals of the sensors were recorded using a source meter (2450, Keithley). ImageJ software was utilized for manual marking on SEM images to determine the diameter of the nanofibers.

3 Results and discussion

3.1 Preparation and microstructural analysis of PPI/rGOA

Inspired by the tubular gas-chamber structures aligned along the growth direction of lotus stems, this study constructed a bottom-up oriented nanofibrous aerogel, and the fabrication pathway and biomimetic structure of the PPI/rGOA are shown in Figure 1a, b. For clarity, the Z-axis is defined as the freezing direction, while the XY plane is perpendicular to the freezing direction. Initially, PAA nanofiber membranes were synthesized via electrospinning (Figure S1), manifesting a uniform diameter distribution centered at $\sim 0.47 \mu\text{m}$ with negligible Beaded fibers (Figure S2). Subsequently, the PAA nanofiber membranes underwent stepwise thermal imidization in a tubular furnace (Figure S3). This dehydration and cyclization process successfully converted the PAA nanofiber membranes into PINF membranes (Figure 1c), accompanied by a distinctive color transition from off-white to golden yellow (Figure S4). The resulting PINF membranes were dispersed in deionized water and fragmented via high-shear homogenization to yield $\sim 1 \text{ wt}\%$ PINF aqueous dispersion. Subsequently, GO dispersion with a concentration of $\sim 1.5 \text{ wt}\%$ was introduced into the PINF aqueous dispersion, and after thorough stirring, the mixture was poured into a freezing mold and subjected to freeze-drying and high-temperature thermal reduction (Figure S5) to obtain PI/rGOA. Finally, PI/rGOA was crosslinked with PDMS to obtain PPI/rGOA.

The oriented pore-channel structure was realized through the vertical growth of ice crystals [8, 45–47]. The copper bottom of the mold, possessing high thermal conductivity, together with

the surrounding polytetrafluoroethylene walls with low thermal conductivity, establishes a temperature-gradient environment, allowing the cold flux to be rapidly transferred to the bottom of the solution. Cold flux then propagates upward from the bottom, inducing the stepwise bottom-up growth of ice crystals. During freezing, the PINF framework provides spatial confinement during directional ice growth, while hydrogen-bonding-assisted interfacial interactions between GO and PINF promote the uniform distribution of GO throughout the framework. Together, these effects lead to the formation of a vertically interconnected pore-channel architecture. After sublimation of the ice crystals, PINF forms the skeleton, while GO adheres to the fiber surfaces.

PI/rGOA with different composition ratios all exhibit pronounced directionally porous structural features on the longitudinal cross-sections (XZ plane), as shown in Figure 1d–f. In contrast, the corresponding SEM images of the XY plane (Figure S6) show that no continuous aligned pore channels comparable to those observed in the XZ plane are present, further confirming the anisotropic porous architecture generated by directional freezing. With the gradual increase in rGO content, the internal pore morphology and orientation characteristics of the aerogels undergo noticeable changes. Compared with PI/rGO-1, PI/rGO-2 and PI/rGO-3 display clearer longitudinal pore channels and more regularly arranged rGO sheets, among which PI/rGO-3 exhibits the most prominent directional architecture (Figure 1f and Figure S6c). Locally magnified images further reveal the internal microstructural construction of the PI/rGOA. It can be observed that the rGO sheets are stacked along the X direction to form a lamellar architecture with an interlayer spacing of 20–30 μm , and are interwoven with PINF to form a stable three-dimensional porous skeleton structure, exhibiting typical anisotropic porous characteristics [48, 49].

Figure 1d'–f' present the longitudinal cross-sectional (XZ plane) morphologies of the PPI/rGOA after PDMS infiltration. It is evident that the incorporation of PDMS leads to partial filling of the pores, resulting in a reduction in overall pore size and an increase in pore wall thickness. Nevertheless, the oriented features of the longitudinal interconnected channels remain well-preserved. This indicates that the PDMS encapsulation process enhances structural stability and flexibility without destroying the intrinsic anisotropic porous architecture of the aerogels [50]. Therefore, the PPI/rGOA successfully construct anisotropic porous structures with pronounced orientation through directional freezing, providing an important structural foundation for their subsequent mechanical response behaviors and electrical sensing performance.

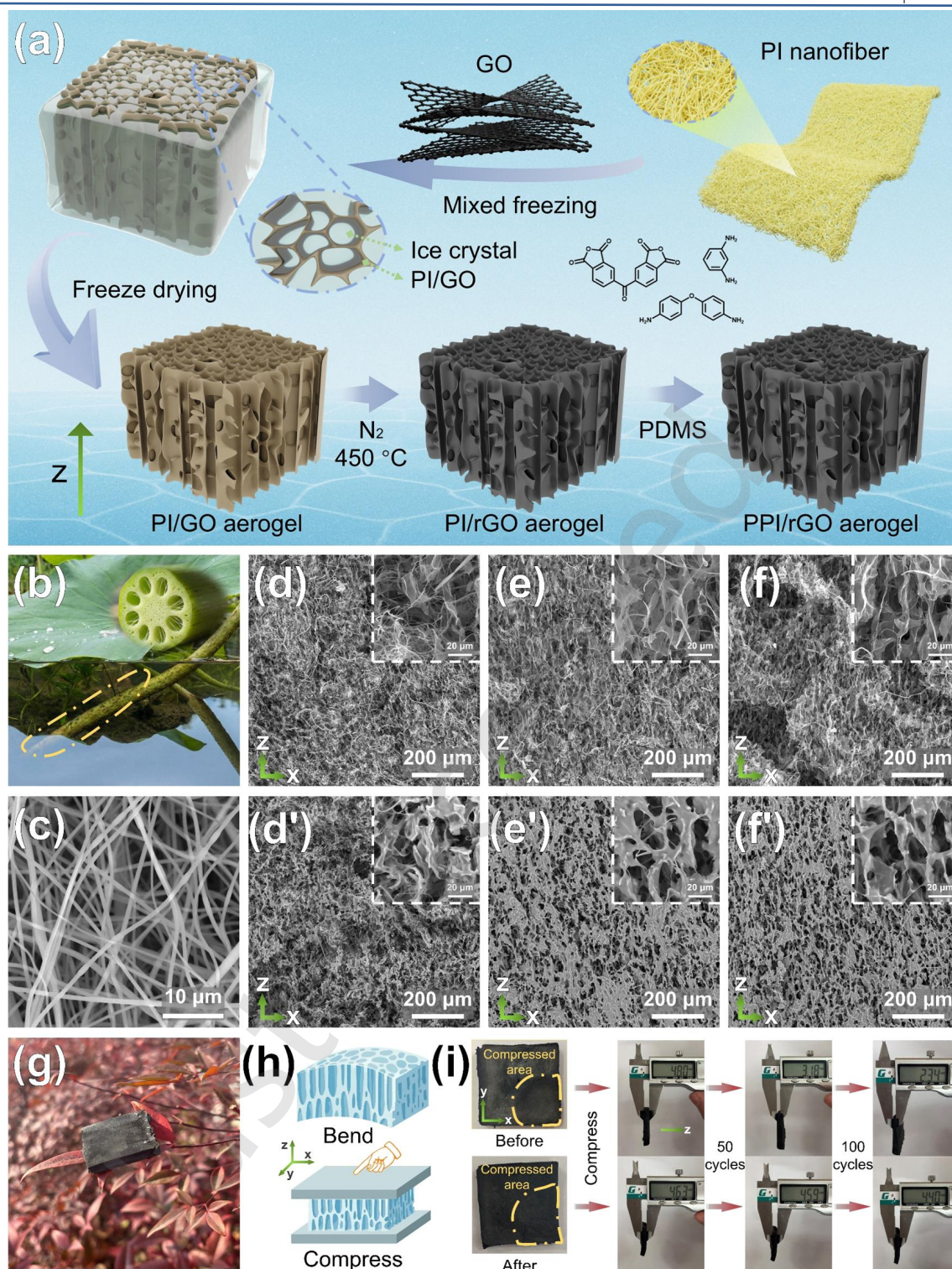


Figure 1 Preparation and SEM images of the PPI/rGOA. (a) Schematic illustration of the fabrication process of the PPI/rGOA, where the Z-axis represents the freezing direction and the XY plane is perpendicular to the freezing direction. (b) Photograph of a lotus stems. (c) SEM image of PINF membrane. (d, e, f) SEM images (XZ plane) of PI/rGO-1, PI/rGO-2, and PI/rGO-3, respectively. (d', e', f') SEM images (XZ plane) of PPI/rGO-1, PPI/rGO-2, and PPI/rGO-3, respectively. (g) Photograph of the PPI/rGOA. (h) Schematic diagram illustrating the compression and bending behavior of the aerogel, where the compressive load is applied along the Z-axis. (i) PPI/rGO-3 Compression tests before and after PDMS treatment, with the compressive load applied along the Z-axis.

Based on the analysis of the longitudinally anisotropic porous skeleton of PPI/rGOA, to further evaluate the lightweight nature and favorable rebound performance of this structure at the macroscopic scale, Figure 1g-i present the photographs of PPI/rGOA placed on a leaf, the mechanical schematic illustration, and the compression test results, with the compressive load applied along the Z-axis. It can be observed that the PDMS-encapsulated PPI/rGOA does not deform the leaf

even when placed on it. The rebound performance of PPI/rGOA was further qualitatively evaluated through compression tests (Figure 1i). The results show that PI/rGOA (initial thickness of 4.80 mm) exhibited a thickness of 2.34 mm after 100 compression cycles, corresponding to a deformation of 2.46 mm, whereas PPI/rGOA (initial thickness of 4.63 mm) retained a thickness of 4.4 mm after 100 compression cycles, with only 0.23 mm deformation. Therefore, PPI/rGOA maintains excellent

shape recovery during 100 compression–release cycles, indicating that the flexible crosslinked network formed by PDMS among the fibrous skeleton effectively buffers external stresses and suppresses pore-wall collapse. Such a structure, synergistically constructed from an oriented porous skeleton and an elastic polymer, provides an important guarantee for the repeated deformation service of PPI/rGOA in applications such as wearable sensing and flexible devices.

3.2 Chemical characterization and thermal property analysis of the aerogels

Detailed chemical structure analysis and fiber diameter characterization were performed on the PAA nanofiber membranes and the thermally treated PINF membranes. The FTIR spectra (Figure 2a) show that the absorption peak at 1654 cm^{-1} for the PAA nanofiber membrane is assigned to the C=O stretching vibration of the amide group. After thermal treatment, the PINF membrane exhibits distinct characteristic peaks at 1776 cm^{-1} (asymmetric C=O stretching vibration), 1720 cm^{-1} (symmetric C=O stretching vibration), 1500 cm^{-1} (C=C stretching vibration), 1377 cm^{-1} (C–N stretching vibration), and 725 cm^{-1} (imide ring deformation vibration), indicating the successful dehydration and cyclization of PAA into PI [18, 24, 51], with an average PINF diameter of $0.66\text{ }\mu\text{m}$ (Figure 2c). To further elucidate the structural evolution of the PI/rGOA, FTIR analyses were performed before and after thermal treatment (Figure 2b). Following thermal reduction, the infrared band at $\sim 1600\text{ cm}^{-1}$, associated with aromatic C=C vibrations, becomes more pronounced, signifying the partial restoration of the sp^2 conjugated carbon network [52].

To further substantiate this structural evolution, XPS was utilized to investigate the elemental composition and chemical states of the PI/rGOA (Figure 2d–f). Upon thermal reduction, a substantial enrichment in carbon content is observed within the aerogel framework, accompanied by a pronounced depletion of oxygen species. This evolution demonstrates that oxygenated functional groups are efficiently eliminated during the thermal reduction process, thereby re-establishing a more extensive sp^2 conjugated carbon network. Specifically, in the high-resolution C 1s spectra, the intensity of the peak at 284.8 eV (C–C) is enhanced, whereas the component peaks associated with oxygen-containing functional groups (such as C–O and C=O) are weakened. These changes further corroborate the FTIR results, demonstrating that thermal treatment not only restores the sp^2 conjugated carbon network of graphene but also effectively removes oxygen functional groups, thereby enhancing the electrical conductivity and thermal stability of graphene. In addition, XPS analysis reveals the persistent presence of peaks at 286.9 eV (C=O) and 285.8 eV (C–N), as well as a peak at 289.9 eV attributed to the aromatic ring, indicating that the imide structure and aromatic main chain of PI are largely preserved [53]. This confirms that the imide structure of PI remains stable during thermal treatment without significant thermal decomposition, which is consistent with the FTIR results.

To further verify the overall structural stability of the aerogels and their service potential in high-temperature environments,

TG and DTG were employed to systematically evaluate the thermal stability and thermal decomposition behavior of the PI/rGOA. As shown in Figure 2g and Figure S7, all samples exhibit low mass loss below $500\text{ }^\circ\text{C}$, indicating good thermal stability within this temperature range. For aerogels with higher rGO contents, a relatively faster mass loss occurs below $500\text{ }^\circ\text{C}$. This phenomenon is primarily ascribed to the thermal decomposition of residual oxygenated functional groups and the elimination of physisorbed species from the graphene [54]. The main thermal decomposition process of the aerogels occurs between $550\text{ }^\circ\text{C}$ and $650\text{ }^\circ\text{C}$, and in the temperature range of $600\text{--}800\text{ }^\circ\text{C}$, the residual mass of PI/rGOA is significantly higher than that of pure PI, with the residual mass increasing as the rGO content increases. This phenomenon demonstrates that rGO significantly bolsters the thermal stability of the aerogels by establishing a resilient carbon skeleton and acting as a physical barrier that retards the diffusion and volatilization of volatile decomposition fragments. The corresponding DTG profiles further substantiate the reinforced thermal resistance, as evidenced by the noticeable shift of the temperature at maximum decomposition rate (T_{max}) toward higher regions upon the incorporation of rGO. Specifically, pristine PI initiates thermal decomposition at approximately $500\text{ }^\circ\text{C}$, with the T_{max} occurring at around $593\text{ }^\circ\text{C}$. In contrast, for the PI/rGOA, the onset decomposition temperature is elevated to $537\text{ }^\circ\text{C}$, and the T_{max} is further shifted to $602\text{ }^\circ\text{C}$. The delayed thermal degradation indicates the barrier effect between PI chains and rGO, as well as strong interfacial interactions, which hinder heat transfer and suppress chain scission [54, 55].

To evaluate the thermal protection performance of the material under extreme environments, a temperature-testing platform (Figure S8) was used to characterize the thermal insulation performance of the PI/rGOA under high-temperature ($200\text{ }^\circ\text{C}$) and low-temperature ($-190\text{ }^\circ\text{C}$) conditions (Figure 2h, i). At low temperatures, the PI/rGOA exhibit superior thermal insulation capacity, maintaining stable average temperature differences of $184.71\text{ }^\circ\text{C}$, $186.60\text{ }^\circ\text{C}$, and $188.56\text{ }^\circ\text{C}$ for PI/rGO-1, PI/rGO-2, and PI/rGO-3, respectively. Under high-temperature conditions at $200\text{ }^\circ\text{C}$, these aerogels likewise demonstrate exceptional thermal insulating performance; the average temperature differences between the aerogel top surfaces and the heating stage surface reach $128.54\text{ }^\circ\text{C}$, $132.40\text{ }^\circ\text{C}$, and $135.75\text{ }^\circ\text{C}$ for the respective samples. To further visualize the thermal insulation performance, an infrared thermal imager was employed for real-time monitoring of the temperature distribution across the aerogel cross-sections, as depicted in Figure 2j. Consistent with the numerical, PI/rGO-3 demonstrates superior thermal insulation capabilities over PI/rGO-1 and PI/rGO-2 under both low- and high-temperature extremes. This phenomenon is primarily ascribed to its higher rGO content; the increased rGO loading facilitates the development of a more continuous and integrated pore architecture during the ice-templating process. Such a structure effectively traps air and heat within the voids, thereby significantly hindering heat conduction and diffusion along the vertical orientation of the pore channels.

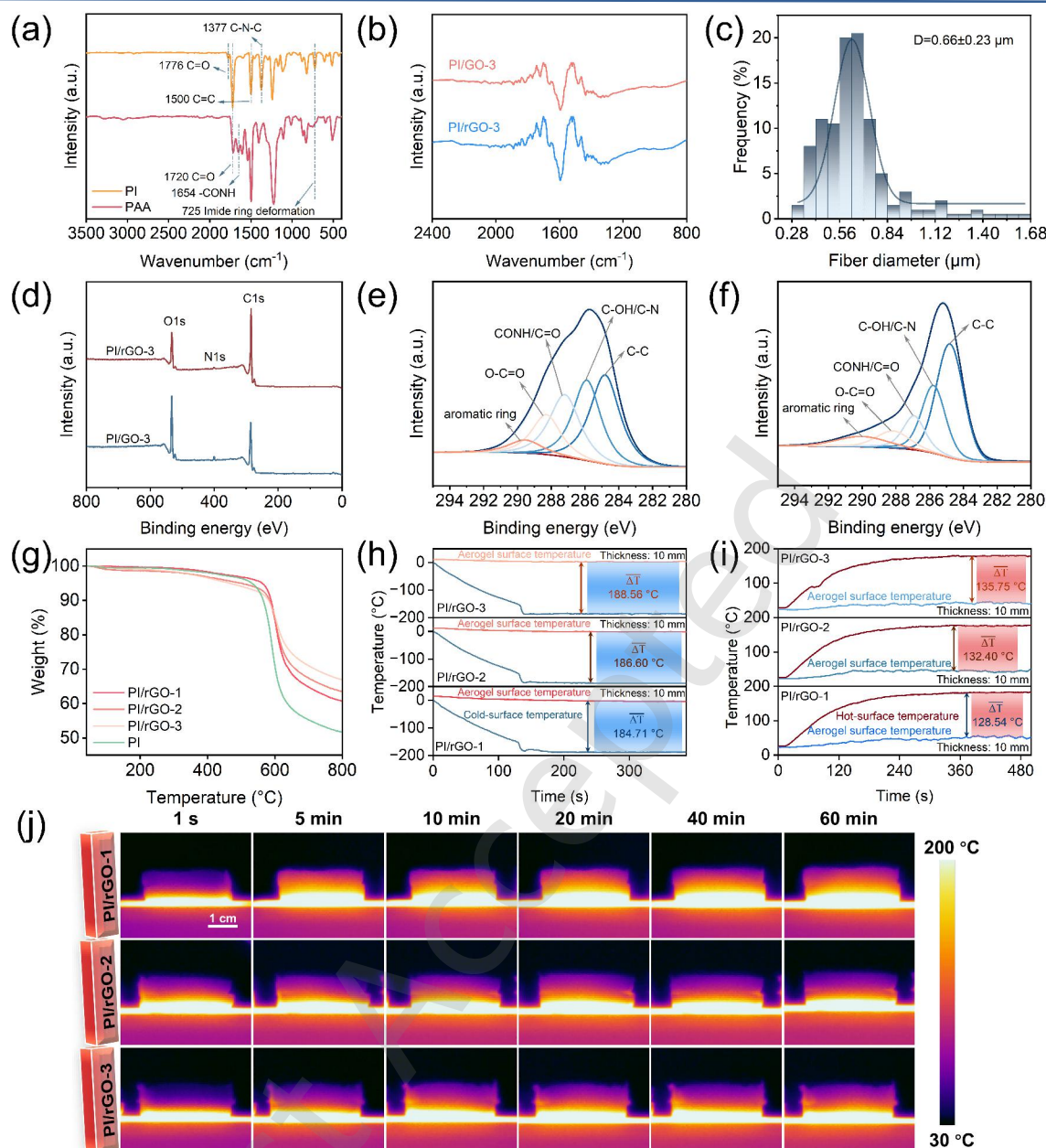


Figure 2 (a) FTIR spectra of PAA nanofiber membranes and PINF membranes. (b) FTIR spectra of PI/GO-3 before and after thermal treatment. (c) Diameter distribution of PINF. (d–f) XPS spectra of PI/GO-3 before and after thermal treatment. (g) TG curves of PI/rGOA. (h, i) Thermal insulation performance of PI/rGOA. (j) Side-view infrared thermal images of PI/rGOA after being held on a constant-temperature hot plate for 1 h.

Building upon the validated exceptional thermal insulation of the aerogels, a butane blowtorch combustion test was further carried out to systematically evaluate the high-temperature flame-retardant behavior and the corresponding microstructural evolution of PI/rGOA with varying rGO loadings (Figure 3). During the combustion tests, the PI/rGO-1, PI/rGO-2 and PI/rGO-3 samples underwent rapid surface heating and instantaneous carbonization upon direct impingement by a $\sim 1300\text{ }^{\circ}\text{C}$ butane flame. Notably, no sustained flaming, melting, or dripping was observed throughout the process; all samples exhibited rapid self-extinguishment immediately upon the removal of the fire source (Figure 3a–c). These observations collectively demonstrate the excellent intrinsic flame retardancy of the composite materials.

Upon 10 s of flame impingement, the front surfaces of the aerogels exhibited inward bending, with the most significant

shrinkage observed in PI/rGO-3, which possesses the highest rGO loading (Figure 3d–f). Further SEM observations (Front) reveal that the primary rGO pore channels in PI/rGO-3 are retained, whereas significant sintering of the PINF occurs. This results in a more pronounced contraction of the fibrous framework, which serves as the primary driver for the observed inward bending. In contrast, in samples with lower rGO loadings, the discontinuous pore network fails to establish a coherent carbonaceous barrier. The resultant heat diffusion facilitates the structural collapse of the rGO pore architecture, leading to an increased interfacial exposure between the flame and the PINF. Consequently, the flame-retardant behavior in these instances is primarily contingent upon the inherent thermal stability of the PINF itself. These findings demonstrate that the incorporation of rGO exerts a profound regulatory effect on the structural response of the material during flame impingement.

Additionally, SEM observations (Back) reveal that the surfaces shielded from direct flame impingement retain an essentially intact porous architecture without discernible damage, highlighting the significantly enhanced resistance of the material against flame penetration. Therefore, no through-thickness damage is observed in any of the samples, and the flame-affected regions are localized while the macroscopic structure remains intact.

Elemental mapping results reveal a significant depletion of oxygen (O) content alongside a moderate relative increase in nitrogen (N) following combustion (Figure 3g), indicating further carbonization of GO under flame exposure, while the PINF are exposed and the N-containing structures in the molecular backbone are not completely decomposed, which is consistent with their excellent thermal stability. From a

microscopic mechanism perspective, the rGO introduced on the surface of the PINF framework effectively promotes the formation of a dense carbonaceous protective layer during combustion, which is consistent with a typical condensed-phase flame-retardant mechanism [54-57]. The coherent carbonaceous layer potentially mitigates further heat diffusion during the combustion process, thereby substantially bolstering the overall flame retardancy of the material. Collectively, the flame retardancy of the PI/rGOA stems from the synergistic interplay between the intrinsic flame resistance of PINF and the rGO-induced formation of a carbonaceous barrier. Among the samples, PI/rGO-3, characterized by its higher rGO loading, develops a more coherent carbon layer architecture, which manifests as superior thermal protection and exceptional fire-retardant performance.

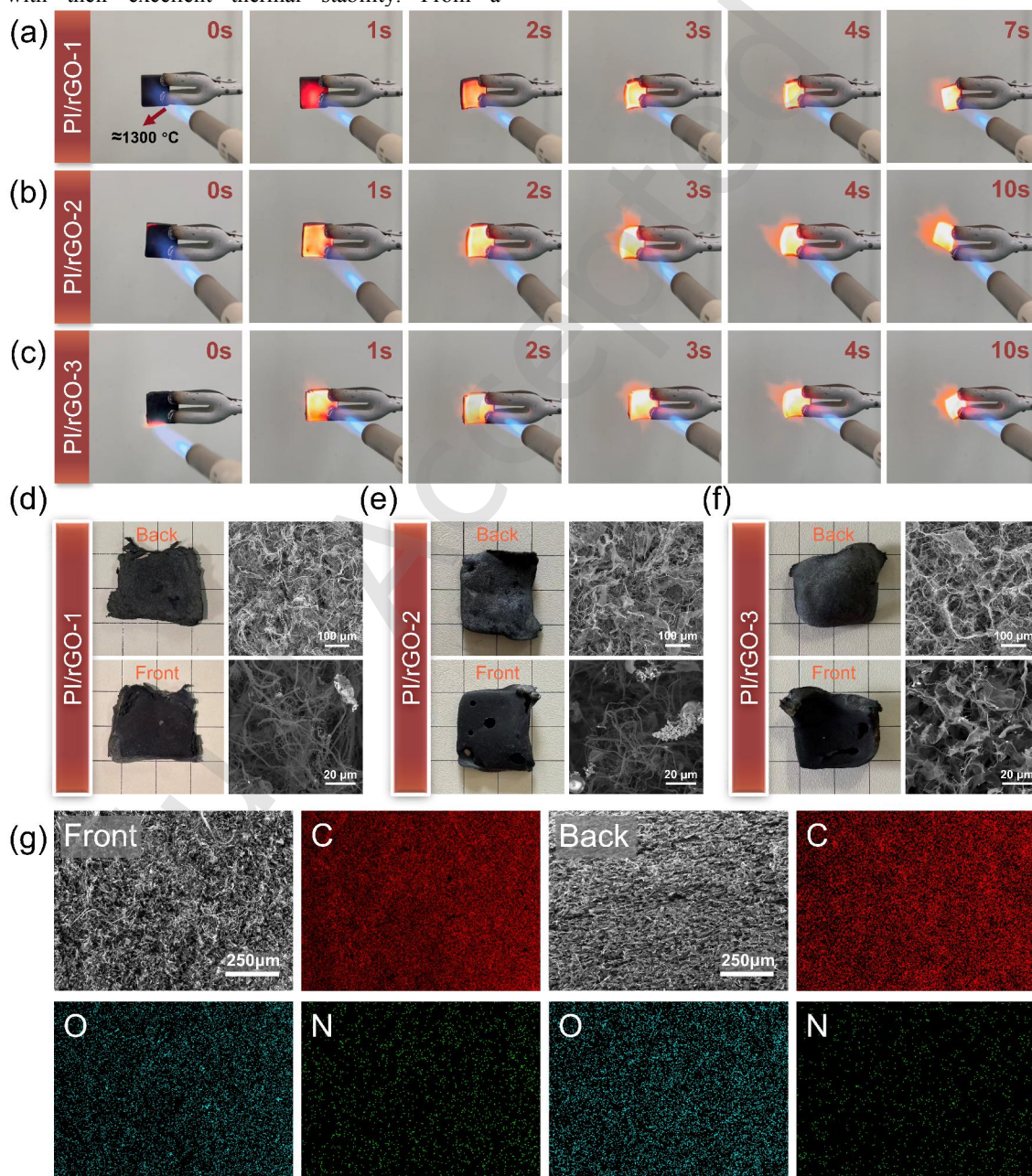


Figure 3 Flame-retardant behavior and microscopic morphology of PI/rGOA. (a–c) Photographs of PI/rGO-1, PI/rGO-2, and PI/rGO-3 with a thickness of 5 mm exposed to a butane flame at ~1300°C. (d–f) SEM images of the front and back surfaces of PI/rGO-1, PI/rGO-2, and PI/rGO-3 after flame exposure. (g) EDS elemental mapping images of the front and back surfaces of PI/rGO-3.

3.3 Infrared stealth performance of aerogels with anisotropic pore architectures

In view of the structural integrity and heat transfer suppression capability exhibited by PI/rGOA under flame exposure, infrared (IR) thermal imaging technology was further employed to systematically evaluate their infrared stealth performance and related application potential from the perspective of infrared radiation regulation. Under continuous heating conditions, the external surface temperatures of the PI/rGOA were maintained at a consistently low level throughout a prolonged 60 min duration, with no discernible escalation (Figure 4a). This observation demonstrates that the material can effectively impede heat propagation from the thermal source to the outer surface. A comparative analysis across samples with varying rGO loadings reveals that the surface temperature distribution becomes increasingly homogeneous as the rGO content rises, with localized hot-spot phenomena being markedly suppressed.

The infrared stealth capabilities of the PI/rGO-3 were subsequently visually validated through human-related practical trials (Figure 4b). The baseline apparent temperature of the human hand was measured at approximately 28.8 °C. When the PI/rGO-3 sample was interposed between the human hand and the infrared thermal imager, its external surface registered an initial apparent temperature of only 17.8 °C. This value underwent a subtle elevation to 18.9 °C and 20.5 °C after 30 s and 60 s of continuous monitoring, respectively. Under sustained thermal loading from the human heat source, the external surface temperature of the PI/rGO-3 remains significantly lower than that of the human body and closely approximates the ambient background level. This thermal characteristic effectively masks the covered regions, rendering them virtually indistinguishable in the infrared thermal profile. These results demonstrate that the PI/rGOA can potentially shield human-originated thermal radiation, thereby realizing a robust and stable infrared stealth effect under practical heat-source

conditions. To further underscore the superiority of PI/rGOA in infrared stealth, commercial expanded polyethylene (EPE) foam with an identical thickness (5 mm) was utilized as a benchmark for comparative testing against the vertically aligned PI/rGO-3 (Figure 4c and Figure S9). In contrast to PI/rGO-3 (average temperature 53.8 °C), the 5 mm-thick EPE foam underwent a rapid escalation in external surface temperature under identical conditions, reaching an average of 67.5 °C. Furthermore, the foam exhibited a markedly non-uniform spatial thermal profile, suggesting that its insulation mechanism is predominantly governed by the passive thermal blocking intrinsic to its low-density cellular structure. Consequently, it possesses a constrained capacity for mitigating radiative heat transfer.

Ultimately, correlating the infrared stealth performance with the intrinsic architectural attributes of the aerogels (Figure 4d) reveals that the infrared stealth capabilities of the PI/rGOA stem from the synergistic modulation of both heat conduction and thermal radiation [58, 59]. The vertically aligned channel architecture, tailored via directional freezing, substantially extends the heat transfer pathways across the solid framework. Concurrently, the air immobilized within these micro-channels effectively suppresses both solid-phase and gaseous heat transport, thereby significantly mitigating the temperature elevation of the external surface. Concurrently, the rGO facilitates a cascade of multiple scattering, reflection, and partial absorption of thermal radiation within the mid-to-far infrared spectra. This synergistic mechanism further attenuates the intensity of infrared radiation emitted from the internal heat source to the surrounding environment [58-60]. Driven by the synergistic integration of suppressed thermal conduction and modulated infrared radiation, the PI/rGOA achieve robust infrared stealth capabilities—even at a constrained thickness of a mere 5 mm—under heating and human-related scenarios, thereby demonstrating a comprehensive superiority that far surpasses that of conventional polymer foam materials (EPE).

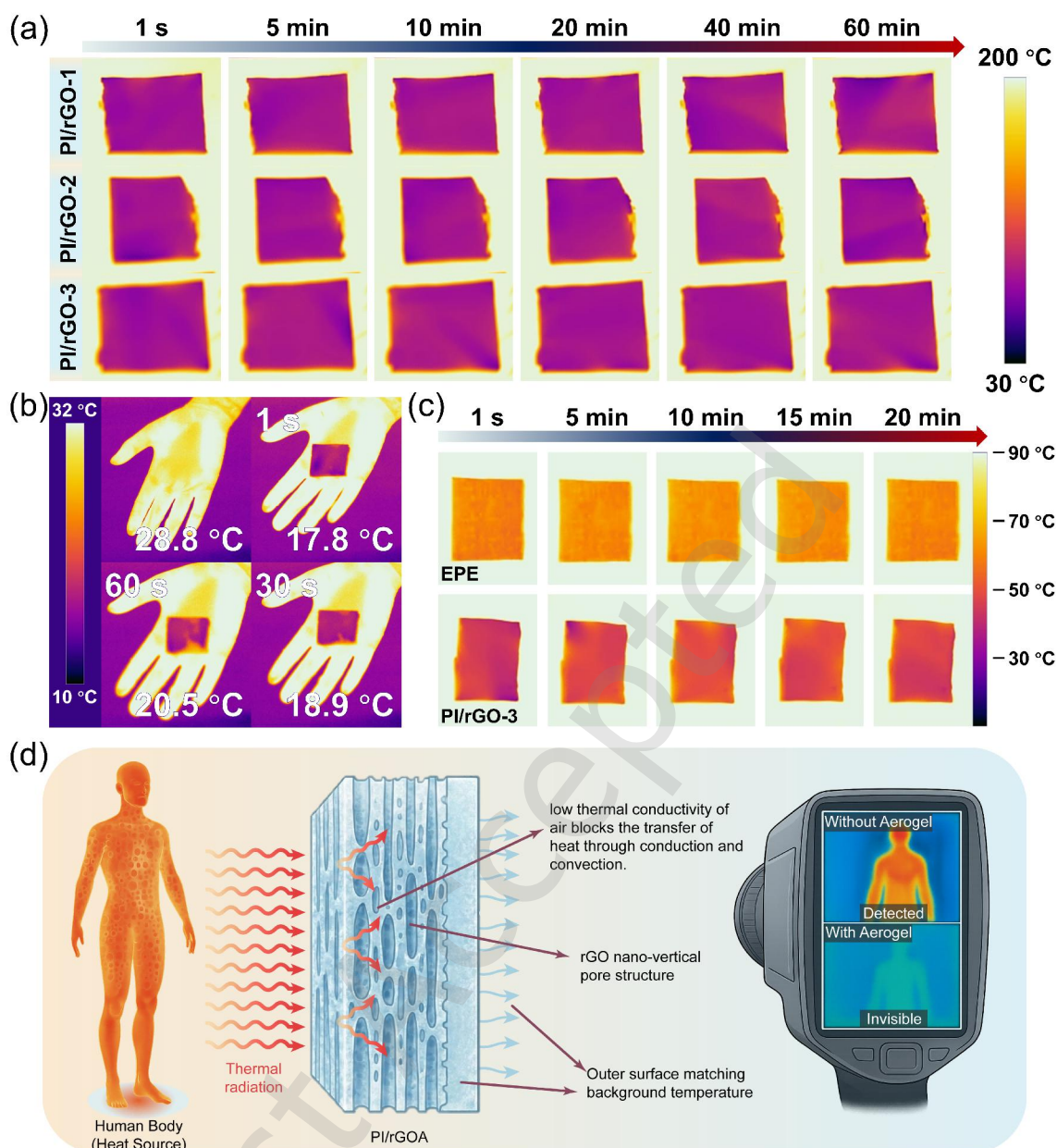


Figure 4 Infrared stealth performance of PI/rGOA. (a) Infrared thermal images of PI/rGOA on a constant-temperature hot plate. (b) Infrared thermal images of PI/rGO-3 placed on a human hand. (c) Comparative infrared thermal images of PI/rGO-3 and commercial EPE material on a constant-temperature hot plate. (d) Schematic illustration of the infrared stealth mechanism.

3.4 Construction of wearable flexible sensors and monitoring of human motion

Following the demonstration of the excellent thermal management and infrared stealth performance of the PI/rGOA, its potential for applications in flexible electronics and wearable sensing was further explored. As shown in Figure 5a, the PPI/rGO PRS was attached to different regions of the human body to evaluate its motion-monitoring capability. The sensor exhibited excellent pressure-sensing performance and operational stability. When mounted on the inner side of a finger, touching or pressing induced compression of the aerogel, giving rise to a low-resistance response with a $\Delta R/R_0$ value of approximately -37.5% (Figure 5b). Moreover, the electrical response remained highly reproducible throughout 500 consecutive loading-unloading cycles (Figure 5c), indicating the

excellent structural integrity and stable electromechanical performance of the device.

Beyond pressure sensing, the PPI/rGO PRS is also well suited for wearable human motion monitoring. Owing to the prestress introduced during the encapsulation process, the sensor exhibits distinct resistance responses to different motion amplitudes when attached to the forearm. During low-amplitude forearm lifting, the partial release of the prestress permits limited elastic recovery of the aerogel skeleton, producing a relative resistance change ($\Delta R/R_0$) of approximately 100–200% (Figure 5d). In comparison, high-amplitude forearm lifting almost completely releases the prestress, allowing more pronounced structural recovery of the aerogel and consequently a substantially larger $\Delta R/R_0$ variation of approximately 200–350% (Figure 5e). The sensor also exhibits excellent capability for monitoring joint

motions. When attached to the antecubital region (inner elbow), the compressive deformation generated during elbow flexion reduces the relative resistance to approximately -30% (Figure 5f). Similarly, when mounted on the knee joint, bending induces a $\Delta R/R_0$ variation of approximately -10% (Figure 5g). These results demonstrate the capability of the PPI/rGO PRS to capture complex human motions with high sensitivity and repeatability.

The fabrication process and working mechanism of the PPI/rGO PRS are illustrated in Figure 5h, i. The PPI/rGO-3 was sequentially assembled with copper wires, conductive silver tape, and silicone, followed by encapsulation within a PI film to

ensure mechanical robustness and stable electrical pathways. Owing to the intrinsic compressibility of the PDMS-cured aerogel, external mechanical deformation induces reversible changes in the internal conductive pathways (Figure S10). Upon compression, the densification of the aerogel framework augments the population of rGO contact sites and diminishes the tunneling distance between adjacent conductive domains, thereby precipitating a significant reduction in electrical resistance [61, 62]. Conversely, the unloading of external stress triggers elastic recovery of the structure, resulting in a concomitant increase in resistance (Figure 5i).

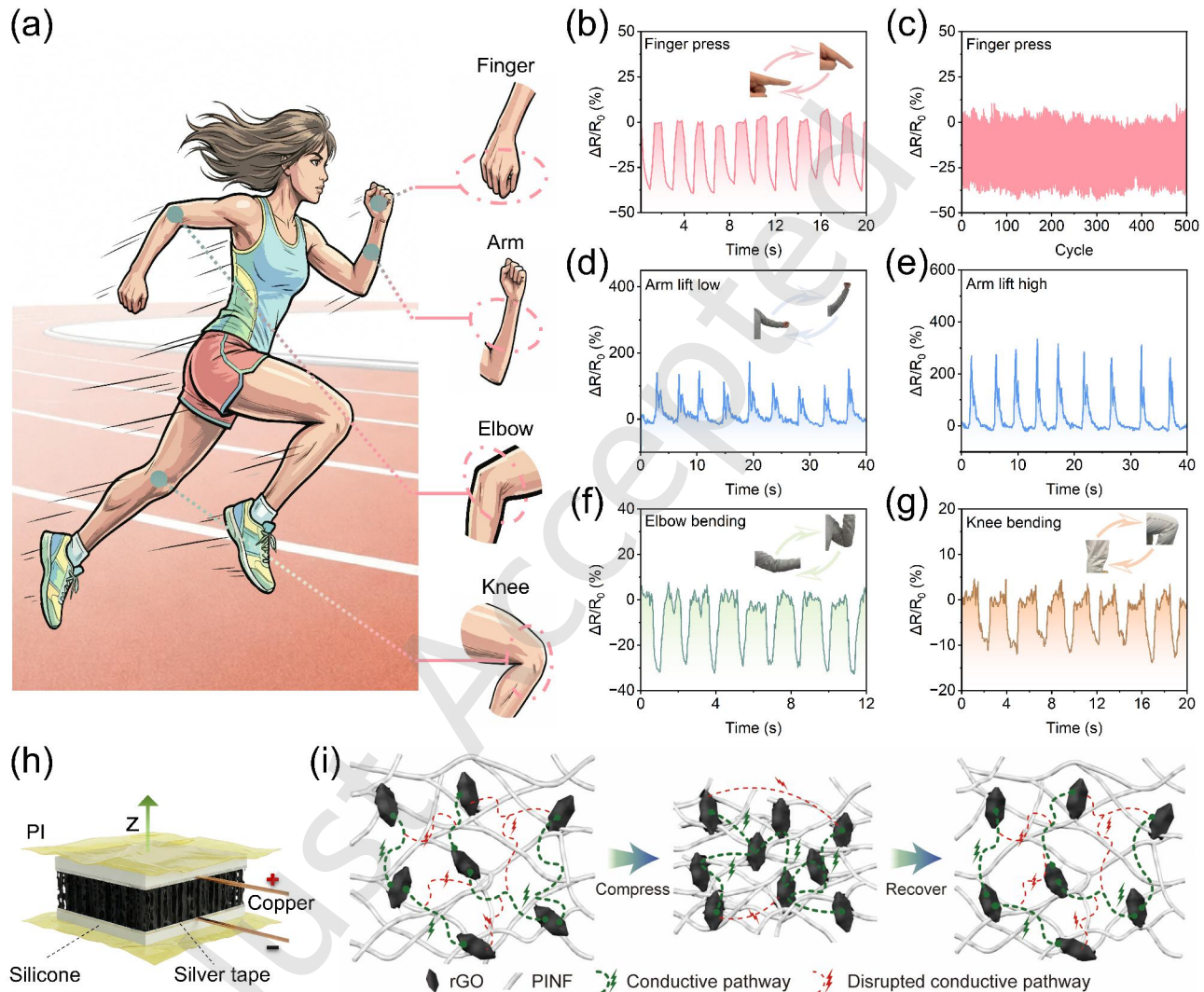


Figure 5 Flexible aerogel-based electrical sensor and its wearable motion-sensing performance. (a) Schematic illustration of the application of the PPI/rGO PRS for human motion monitoring. (b) $\Delta R/R_0$ under finger pressing. (c) Cycling stability test over 500 repeated loading–unloading cycles under finger pressing. (d) $\Delta R/R_0$ during low-amplitude forearm lifting. (e) $\Delta R/R_0$ during high-amplitude arm lifting. (f) $\Delta R/R_0$ during inner-elbow bending. (g) $\Delta R/R_0$ during knee bending. (h) Schematic illustration of the encapsulation of the PPI/rGO PRS. (i) Schematic illustration of the evolution of conductive pathways in the PPI/rGO PRS during compression and recovery.

4. Conclusions

In summary, we have successfully engineered an anisotropic PI/rGOA with vertically aligned pore channels by integrating directional freezing with hydrogen-bonding-assisted interfacial regulation between PINF and GO. This biomimetic architecture enables the optimized PI/rGO-3 to exhibit exceptional thermal insulation along the transverse direction, maintaining substantial temperature gradients of 188.56 °C at -190 °C and 135.75 °C at 200 °C. Beyond thermal management, the material demonstrates robust flame retardancy; a sample (5 mm) withstands a 1300 °C

butane flame with only superficial carbonization, preserving its structural integrity through rapid self-extinction. In addition, the aerogel demonstrates excellent infrared stealth performance through the combined regulation of heat conduction and infrared radiation, effectively minimizing thermal signatures under both continuous heating and human-related thermal source conditions. When integrated into PPI/rGO PRS sensor, the system maintains high cyclic stability over 500 cycles, delivering sensitive resistance changes across varying motion amplitudes. Collectively, these findings highlight that the anisotropic

PI/rGOA offers a lightweight, structurally stable, and multifunctional platform, providing an engineering-feasible solution for advanced thermal protection and next-generation wearable electronics.

Electronic Supplementary Material: Supplementary material (please provide the brief detail of the ESM) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909056>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.”

Acknowledgements

This research was financially supported by the Natural Science Foundation of Zhejiang province, China (LMS26E030013); National Natural Science Foundation of China (22303032); the Joint Fund of Zhejiang Provincial Natural Science Foundation of China (LJXSQY26E030001); Jiaxing Youth Science and Technology Talent Special Program (2023AY40027); Qinshen Youth Backbone Training Program of Jiaxing University (CD70623038).

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

J. C. Z.: Writing – original draft, Validation, Methodology. Y. F. Z.: Methodology, Software. Y. T. L.: Data curation. C. H. L.: Data curation. J. Z.: Software. Q. Q. Z.: Software. W. W.: Investigation. P. L.: Project administration. H. X. Z.: Writing – review & editing, Funding acquisition. All the authors have approved the final manuscript.

Use of AI statement

None.

References

- [1] Li, C. M.; Xu, R.; Han, D.; Li, P. H.; Liu, W.; Guang, M. J.; Chao, X. J.; Wang, P. Gradient nanofiber aerogels for extreme cryogenic and thermal environments. *Nat. Commun.* **2026**, 17, 721.
- [2] Wang, W. P.; Xu, C. G.; Li, X. J.; Zhang, Z. P.; Li, W. T.; Zhang, Z. M.; Feng, Y. E.; Wang, D. A. Flexible and multifunctional polyimide aerogel-based triboelectric nanogenerator for motion monitoring applications. *Nano Energy* **2025**, 139, 110932.
- [3] Wu, B.; Qi, Q. J.; Liu, L.; Liu, Y. J.; Wang, J. Wearable Aerogels for Personal Thermal Management and Smart Devices. *ACS Nano* **2024**, 18, 9798–9822.
- [4] Lin, J. W.; Chen, Z. W.; Zhuang, Q. B.; Chen, S. Y.; Zhu, C. C.; Wei, Y. M.; Wang, S. F.; Wu, D. Z. Temperature-Immune, Wide-Range Flexible Robust Pressure Sensors for Harsh Environments. *ACS Appl. Mater. Interfaces* **2023**, 15, 49642–49652.
- [5] Xu, T.; Tan, S.; Li, S.; Zhao, Y.; Chen, T.; Yang, Z.; Ji, G. Adaptive Photothermal Superhydrophobic Modular Unit for Anti-/De-Icing Electromagnetic Window. *Adv. Funct. Mater.* **2026**, 36, e17713.
- [6] Mao, A. R.; Chen, J. W.; Bu, X. C.; Tian, L. L.; Gao, W. W.; Saiz, E.; Bai, H. Bamboo-Inspired Structurally Efficient Materials with a Large Continuous Gradient. *Small* **2023**, 19, 2301144.
- [7] Mao, Y.; Tang, C.; Sun, H.; Sheng, Y.; Yang, C.; Liu, J.; Wang, Y.; Zhang,

- K.; Fu, S. Dynamically tunable and broadband electromagnetic wave absorption cellulose nanofiber-based aerogel metamaterial via one-dimensional interface engineering. *J. Colloid Interface Sci.* **2026**, 710, 139998.
- [8] Liu, H. G.; Shao, Y. W.; Wang, Z.; Jiang, L. T.; Mou, B.; Tian, N.; You, C. Y.; Li, Y. Mechanically robust and multifunctional Ti3C2Tx MXene composite aerogel for broadband EMI shielding. *Carbon* **2024**, 221, 118948.
- [9] Zhang, H.; He, Q. X.; Zhang, F.; Duan, Y. S.; Qin, M. M.; Feng, W. Biomimetic Intelligent Thermal Management Materials: From Nature-Inspired Design to Machine-Learning-Driven Discovery. *Adv. Mater.* **2025**, 37, 2503140.
- [10] Wei, F.; Zhao, Q.; Pei, D.; Li, C. Physically cross-linking phase change aerogels with moldability and structural thermostability for thermal management. *J. Colloid Interface Sci.* **2025**, 700, 138447.
- [11] Chen, Z. H.; Zhuo, H.; Hu, Y. J.; Lai, H. H.; Liu, L. X.; Zhong, L. X.; Peng, X. W. Wood-Derived Lightweight and Elastic Carbon Aerogel for Pressure Sensing and Energy Storage. *Adv. Funct. Mater.* **2020**, 30, 1910292.
- [12] Xu, X.; Zhang, Q. Q.; Hao, M. L.; Hu, Y.; Lin, Z. Y.; Peng, L. L.; Wang, T.; Ren, X. X.; Wang, C.; Zhao, Z. P.; Wan, C. Z.; Fei, H. L.; Wang, L.; Zhu, J.; Sun, H. T.; Chen, W. L.; Du, T.; Deng, B. W.; Cheng, G. J.; Shakir, I.; Dames, C.; Fisher, T. S.; Zhang, X.; Li, H.; Huang, Y.; Duan, X. F. Double-negative-index ceramic aerogels for thermal superinsulation. *Science* **2019**, 363, 723–727.
- [13] Song, Y. X.; Li, B.; Yang, S. W.; Ding, G. Q.; Zhang, C. R.; Xie, X. M. Ultralight boron nitride aerogels via template-assisted chemical vapor deposition. *Sci. Rep.* **2015**, 5, 10337.
- [14] Dhavale, R. P.; Parale, V. G.; Choi, H.; Kim, T.; Ransing, A. A.; Phadtare, V. D.; Lee, K. Y.; Park, H. H. Sol-gel synthesized homogeneous nanofibers to multidimensional in-situ and ex-situ silica nanofiber aerogels in thermal management applications. *Chem. Eng. J.* **2025**, 503, 158485.
- [15] Chen, L. X.; Li, L. S.; Zhang, X. T. Solvent-regulable interfacial groups enable on-demand superhydrophobic/superhydrophilic silica aerogels. *Nat. Commun.* **2025**, 16, 2228.
- [16] Cheng, Q. Q.; Sheng, Z. Z.; Ding, Y. F.; Li, Y. Z.; Zhang, X. T. 3D printed colloidal aerogels: Principle, process, performance, and perspective. *Prog. Mater. Sci.* **2025**, 152, 101456.
- [17] Zhu, C.; Han, T. Y. J.; Duoss, E. B.; Golobic, A. M.; Kuntz, J. D.; Spadaccini, C. M.; Worsley, M. A. Highly compressible 3D periodic graphene aerogel microlattices. *Nat. Commun.* **2015**, 6, 6962.
- [18] Qiao, S. Y.; Chen, H. M.; Zhao, Y. H.; Wang, Z.; Yan, J. L. Bioinspired Polyimide/Carbon Nanotube Aerogels With Core-Radiating and Omasum-Like Morphology toward Excellent Electromagnetic Shielding and Superior Elasticity. *Adv. Mater.* **2025**, 37, e13423.
- [19] Li, C.; Wang, X. D.; Zhang, C.; Zhang, Z. H.; Zhou, B. W.; Shen, J. Elastic, flexible, and tough hierarchical polyimide aerogels with dynamic reversible physical entanglement structure. *Chem. Eng. J.* **2025**, 509, 161429.
- [20] Fu, J.; Lian, W.; Deng, Y.; Fang, Z.; Cheng, Q. Isotropic thermal insulating cuttlebone-inspired MXene aerogel. *Natl. Sci. Rev.* **2025**, 12, nwaf342.
- [21] Qian, W.; Zhang, H. Z.; Li, L.; Chen, P. F.; Li, X.; Li, P.; Wang, Z.; He, D. P. Superelastic isotropic carbon aerogel with spherical cavity structure. *Nano Res.* **2025**, 18, 94907690.
- [22] Zeng, X.; Ye, L.; Yu, S.; Sun, R.; Xu, J.; Wong, C.-P. Facile Preparation of Superelastic and Ultralow Dielectric Boron Nitride Nanosheet Aerogels via Freeze-Casting Process. *Chem. Mater.* **2015**, 27, 5849–5855.
- [23] Wang, Y. Y.; Pang, N.; Yin, X. Q.; Yu, M. J.; Wang, C. G.; Zhou, C. J. Designed Composite Aerogels With Solid-Solid Phase Transition and Nanoscale Pores for Infrared Stealth. *Small* **2025**, 21, 2411460.
- [24] Liu, C.; Wang, M. K.; Zhao, X.; Yang, C. P.; Wei, R.; Zeng, W. T.; Ding, F.; Zhang, S. Z.; Lei, Y. J. High-Temperature Resistant Polyimide Aerogels With Extreme Condition Tolerance Constructed by In Situ Skeleton Encapsulation Growth. *Adv. Funct. Mater.* **2025**, 35, 2500881.

- [25] Cheng, X. T.; Chang, X. Y.; Wu, F.; Liao, Y. L.; Pan, K.; Fong, H.; Yu, J. Y.; Liu, Y. T.; Ding, B. Advanced nanofabrication for elastic inorganic aerogels. *Nano Res.* **2024**, *17*, 8842-8862.
- [26] Yu, H. X.; Li, M. L.; Deng, Y. P.; Fu, S. B.; Guo, J. R.; Zhao, H.; Zhang, J. N.; Dang, S. X.; Zhang, P. Y.; Zhou, J.; Liu, D. Z.; Wang, D. L.; Zhang, C. W.; Hao, M. L.; Xu, X. Chemically bonded multi-nanolayer inorganic aerogel with a record-low thermal conductivity in a vacuum. *Natl. Sci. Rev.* **2023**, *10*, nwad129.
- [27] Sonu, S. S.; Rai, N.; Chauhan, I. Multifunctional Aerogels: A comprehensive review on types, synthesis and applications of aerogels. *J. Sol-Gel Sci. Technol.* **2023**, *105*, 324-336.
- [28] Xu, Y.; Yan, C. T.; Du, C. L.; Xu, K.; Li, Y. X.; Xu, M. J.; Bourbigot, S.; Fontaine, G.; Li, B.; Liu, L. B. High-strength, thermal-insulating, fire-safe bio-based organic lightweight aerogel based on 3D network construction of natural tubular fibers. *Composites, Part B* **2023**, *261*, 110809.
- [29] Guan, X.; Jiang, M.; Shen, Z.; Tan, S.; Ji, G.; Xu, Z. J. High-Entropy Interface Engineering in Multifunctional Green Fiber Aerogels for Coupled Electromagnetic and Waste-Heat Management. *Adv. Funct. Mater.* **2026**, *36*, e27596.
- [30] Xu, T.; Wang, Y.; Liu, K.; Zhao, Q.; Liang, Q.; Zhang, M.; Si, C. Ultralight MXene/carbon nanotube composite aerogel for high-performance flexible supercapacitor. *Adv. Compos. Hybrid Mater.* **2023**, *6*, 108.
- [31] Wang, L. B.; Liu, H.; Lv, X. L.; Cui, G. Z.; Gu, G. X. Facile synthesis 3D porous MXene Ti₃C₂Tx@RGO composite aerogel with excellent dielectric loss and electromagnetic wave absorption. *J. Alloys Compd.* **2020**, *828*, 154251.
- [32] Hou, X.; Chen, J.; Chen, Z.; Yu, D.; Zhu, S.; Liu, T.; Chen, L. Flexible Aerogel Materials: A Review on Revolutionary Flexibility Strategies and the Multifunctional Applications. *ACS Nano* **2024**, *18*, 11525-11559.
- [33] Maleki, H.; Duraes, L.; Portugal, A. An overview on silica aerogels synthesis and different mechanical reinforcing strategies. *J. Non-Cryst. Solids* **2014**, *385*, 55-74.
- [34] Yang, J.; Li, Y.; Zheng, Y. Y.; Xu, Y. M.; Zheng, Z. K.; Chen, X. D.; Liu, W. Versatile Aerogels for Sensors. *Small* **2019**, *15*, 1902826.
- [35] Dilamian, M.; Joghataei, M.; Ashrafi, Z.; Bohr, C.; Mathur, S.; Maleki, H. From 1D electrospun nanofibers to advanced multifunctional fibrous 3D aerogels. *Appl. Mater. Today* **2021**, *22*, 100964.
- [36] Wu, J.; Liu, D.; Sun, Y.; Wei, B.; Dai, K.; Sun, Y.; Zhang, F.; Li, C.; Xue, J.; Zhu, Z.; Gao, X.; Zheng, Q. Ultralight anisotropic Ti₃C₂Tx MXene/Carbon nanotube hybrid aerogel for highly efficient solar steam generation. *Carbon* **2024**, *223*, 118976.
- [37] Xu, T.; Song, Q.; Liu, K.; Liu, H.; Pan, J.; Liu, W.; Dai, L.; Zhang, M.; Wang, Y.; Si, C.; Du, H.; Zhang, K. Nanocellulose-Assisted Construction of Multifunctional MXene-Based Aerogels with Engineering Biomimetic Texture for Pressure Sensor and Compressible Electrode. *Nano-Micro Lett.* **2023**, *15*, 98.
- [38] Shamshirgar, A. S.; Qin, L.; Rojas-Hernández, R. E.; Halim, J.; Fernandez, J. F.; Hussainova, I.; Rosen, J. Bidirectional Mo₄/3CTx MXene/Graphene Aerogels for Tailored Microwave Absorption. *ACS Appl. Nano Mater.* **2025**, *8*, 1978-1990.
- [39] Junghwan, K.; Sungyong, K.; Jeong, H. S.; Gyun, K. S.; Nam-Ho, Y.; Gi, C. H.; Chul, K. H.; Bon-Cheol, K. Longitudinal alignment effect of graphene oxide nanoribbon on properties of polyimide-based carbon fibers. *Carbon* **2022**, *198*, 219-229.
- [40] Dong, J.; Yin, C.; Zhao, X.; Li, Y.; Zhang, Q. High strength polyimide fibers with functionalized graphene. *Polymer* **2013**, *54*, 6415-6424.
- [41] Ai, J.; Cheng, S. R.; Wu, M. H.; Zhu, G. C.; Xu, J.; Zhang, H. X. Preparation of Graphene Thermally Responsive Double-Layer Composite Fibers via Dry Spinning for Wearable Intelligent Sensors. *ACS Appl. Polym. Mater.* **2024**, *6*, 4300-4309.
- [42] Zhi, Y. F.; Zhang, H. H.; Zhang, L. G.; Li, Q. Q.; Kuang, X. T.; Wu, W.; Zhou, Q. Q.; Li, P.; Li, W.; Zhang, H. X. Pressure Sensors Based on Densely Structured Graphene Fibers for Motion Monitoring. *Adv. Fiber Mater.* **2025**, *7*, 541-553.
- [43] Zhi, Y. F.; He, J. L.; Xu, J. H.; Wei, Y. J.; Xu, J.; Zhang, H. X. Graphene/PET-based temperature-sensitive conductor with enhanced responsiveness via magnetic induction for resistance-temperature sensors. *Colloids Surf., A* **2023**, *673*, 131875.
- [44] Zhi, Y. F.; Zhang, H. H.; Cheng, N.; Li, P.; Peng, S.; He, M. Y.; Zhou, Q. Q.; Wu, W.; Li, W.; Zhang, H. X. High-performance pressure sensors based on graphene fibers with bilateral dense structures for human motion monitoring. *J. Mater. Sci. Technol.* **2026**, *259*, 209-219.
- [45] Cui, Y. H.; Yang, K.; Zhang, F. R.; Lyu, Y. T.; Zhang, Q. Y.; Zhang, B. L. Ultra-light MXene/CNTs/PI aerogel with neat arrangement for electromagnetic wave absorption and photothermal conversion. *Composites, Part A* **2022**, *158*, 106986.
- [46] Zong, Y. Y.; Fan, Y. W.; Chen, Z.; Ouyang, X. F.; Liu, Y. P.; Zhou, S. Y.; Mei, J. W.; Niu, K. M. Control of microstructure to prepare compressible graphene aerogel via ice template. *Carbon* **2024**, *227*, 119269.
- [47] Bai, H.; Walsh, F.; Gludovatz, B.; Delattre, B.; Huang, C. L.; Chen, Y.; Tomsia, A. P.; Ritchie, R. O. Bioinspired Hydroxyapatite/Poly(methyl methacrylate) Composite with a Nacre-Mimetic Architecture by a Bidirectional Freezing Method. *Adv. Mater.* **2016**, *28*, 50-56.
- [48] Garemark, J.; Yang, X.; Sheng, X.; Cheung, O.; Sun, L. C.; Berglund, L. A.; Li, Y. Y. Top-Down Approach Making Anisotropic Cellulose Aerogels as Universal Substrates for Multifunctionalization. *ACS Nano* **2020**, *14*, 7111-7120.
- [49] Yin, F. M.; Lin, H.; Wang, W. Z.; Zhao, L. J.; Paul, R.; Li, J. H.; Liu, W.; Kong, D. Y.; Jiang, Y. Q.; Hu, C. A. Multifunctional Anisotropic Aerogels for Intelligent Electromagnetic Wave Absorption. *Adv. Funct. Mater.* **2025**, *35*, 2418257.
- [50] Qiao, A. H.; Huang, R. L.; Penkova, A.; Qi, W.; He, Z. M.; Su, R. X. Superhydrophobic, elastic and anisotropic cellulose nanofiber aerogels for highly effective oil/water separation. *Sep. Purif. Technol.* **2022**, *295*, 121266.
- [51] Tian, J.; Yang, Y.; Xue, T. T.; Chao, G. J.; Fan, W.; Liu, T. X. Highly flexible and compressible polyimide/silica aerogels with integrated double network for thermal insulation and fire-retardancy. *J. Mater. Sci. Technol.* **2022**, *105*, 194-202.
- [52] Yan, R. H.; Huang, Z.; Chen, Y.; Zhang, L.; Sheng, X. X. Phase change composite based on lignin carbon aerogel/nickel foam dual-network for multisource energy harvesting and superb EMI shielding. *Int. J. Biol. Macromol.* **2024**, *277*, 134233.
- [53] Yue, J. W.; Qin, M. M.; Yu, H. T.; He, Q. X.; Feng, W. Superelastic Graphene-Based Composite Aerogel for Thermal and Electromagnetic Protection in Extreme Temperature Environments. *Adv. Funct. Mater.* **2025**, *35*, 2508319.
- [54] Li, Y. M.; Li, Y. R.; Hu, W. J.; Wang, D. Y. Designing of an rGO-based heterostructure for highly efficient microwave absorption performance and flame retardancy. *Ceram. Int.* **2023**, *49*, 32600-32610.
- [55] Wang, Z. H.; Liu, B. W.; Zeng, F. R.; Lin, X. C.; Zhang, J. Y.; Wang, X. L.; Wang, Y. Z.; Zhao, H. B. Fully recyclable multifunctional adhesive with high durability, transparency, flame retardancy, and harsh- environment resistance. *Sci. Adv.* **2022**, *8*, eadd8527.
- [56] Zhao, Y. Z.; Chu, Y.; Xu, Y. J.; Zhu, P.; Wang, Y. Z. Highly flame-retardant vinyl ester resins with well-balanced comprehensive performance. *Chem. Eng. J.* **2023**, *464*, 142659.
- [57] Temane, L. T.; Ray, S. S.; Orasugh, J. T. Review on Processing, Flame-Retardant Properties, and Applications of Polyethylene Composites with Graphene-Based Nanomaterials. *Macromol. Mater. Eng.* **2024**, *309*, 2400104.
- [58] Sun, H.; Zhang, M. Y.; Ji, D. X.; Ma, C.; Yuan, B. L.; Feng, R. H.; Tan, J. J.; Yang, B. Resin-free aramid honeycombs with extraordinary microwave absorption, thermal insulation, flame retardant and mechanical performance. *J. Mater. Sci. Technol.* **2025**, *233*, 132-143.

- [59] Gu, W. H.; Luo, Z. T.; Wang, J.; Tan, X.; Tao, Z.; Zhou, P. P.; Zhang, H. Y.; Lan, D.; Xia, A. L. Multifunctional lightweight rGO/polyimide hybrid aerogels for highly efficient infrared-radar-acoustic compatibility via heterogeneous interface engineering strategies. *J. Mater. Sci. Technol.* **2026**, 243, 102-114.
- [60] Liu, J.; Tan, S.; Yang, X.; Zhu, J.; Yan, X.; Chen, T.; Ji, G. A Multi-Scale Cross-Band Defense System Integrating Decoupled Visible, Dynamic Infrared Camouflage and Electromagnetic Shielding. *Nano-Micro Lett.* **2026**, 18, 115.
- [61] Ma, Y. N.; Yue, Y.; Zhang, H.; Cheng, F.; Zhao, W. Q.; Rao, J. Y.; Luo, S. J.; Wang, J.; Jiang, X. L.; Liu, Z. T.; Liu, N. S.; Gao, Y. H. 3D Synergistical MXene/Reduced Graphene Oxide Aerogel for a Piezoresistive Sensor. *ACS Nano* **2018**, 12, 3209-3216.
- [62] Li, L.; Cheng, Y. F.; Cao, H. H.; Liang, Z. S.; Liu, Z. Y.; Yan, S. W.; Li, L. Y.; Jia, S. F.; Wang, J. B.; Gao, Y. H. MXene/rGO/PS spheres multiple physical networks as high-performance pressure sensor. *Nano Energy* **2022**, 95, 106986.

© The Author(s) 2026. *Nano Research* published by Tsinghua University Press. The articles published in this open access journal are distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Anisotropic PI/rGO aerogels for multifunctional thermal protection and wearable sensing

Jinchao Zhu^{1,§}, Yifan Zhi^{2,§}, Yutao Li¹, Chenghao Lou¹, Jian Zhang¹, Qingqing Zhou¹, Wen Wu¹, Ping Li^{2,3}, and Huanxia Zhang¹✉

¹ College of Material and Textile Engineering, Jiaying University, Jiaying 314001, China

² Shanghai Collaborative Innovation Center of High Performance Fibers and Composite, College of Textiles, Donghua University, Shanghai 201620, China

³ Jiaying Nanhu University, Jiaying 314001, China

[§] Jinchao Zhu and Yifan Zhi contributed equally to this work

✉ Address correspondence to zhanghuanxia818@163.com

Supporting information to <https://doi.org/10.26599/NR.2026.94909056>

1. Required chemicals and raw materials preparation

1.1 Chemicals

Potassium permanganate (KMnO_4 , analytical reagent grade, AR) was purchased from Huzhou Shuanglin Chemical Technology Co., Ltd. (Zhejiang, China). Hydrogen peroxide (H_2O_2 , analytical reagent grade, AR, 30.0 wt%) was purchased from Shanghai Lingfeng Chemical Reagent Co., Ltd. (Shanghai, China). Sodium nitrate (NaNO_3 , analytical reagent grade, AR) was purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Concentrated sulfuric acid (H_2SO_4 , analytical reagent grade, AR, $\geq 98.0\%$) was purchased from Zhejiang Zhongxing Chemical Reagent Co., Ltd. (Zhejiang, China). Graphite powder (325 mesh) was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

1.2 Preparation of graphene oxide (GO)

A total of 0.6 g NaNO_3 and 22.5 mL H_2SO_4 were reacted in an ice–water bath at 0 °C for 2.5 h, followed by the addition of 1.1 g graphite powder (325 mesh). After 50 min, 3.6 g of KMnO_4 was slowly added over 1.5 h, and the reaction was continued for an additional 1 h. The temperature was then raised to 45 °C and maintained for 1 h, followed by the addition of 65 mL deionized water. Subsequently, the temperature was increased to 70 °C and maintained for 30 min, and 150 mL deionized water was added. Thereafter, 12 mL of H_2O_2 (30%) was added, and the mixture was allowed to react for 15 min. Finally, the precipitate was washed with hydrochloric acid (3%), followed by repeated washing with deionized water.

1.3 Preparation of polydimethylsiloxane (PDMS) solution

PDMS and the curing agent were mixed at a mass ratio of 10:1, diluted with n-hexane at a mass ratio of 1:6, and stirred at room temperature for 1 h to obtain the PDMS solution.

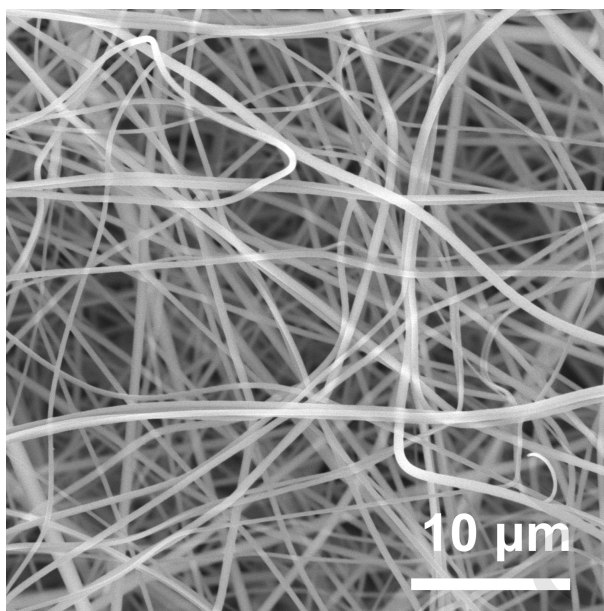


Figure S1 PAA nanofibrous membrane

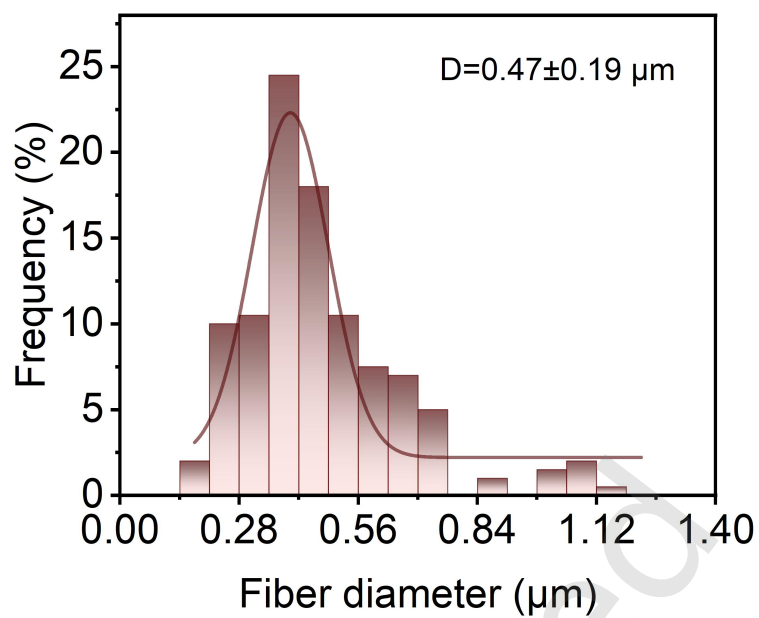


Figure S2 Diameter distribution of PAA nanofibers

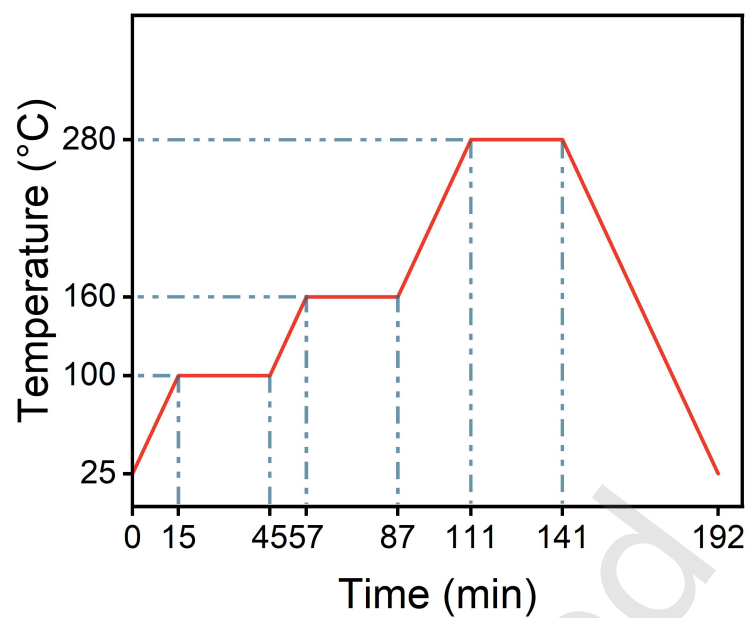


Figure S3 Thermal imidization treatment of PAA



Figure S4 PAA nanofibrous membrane (left) and PINF membrane (right)

Just Accepted

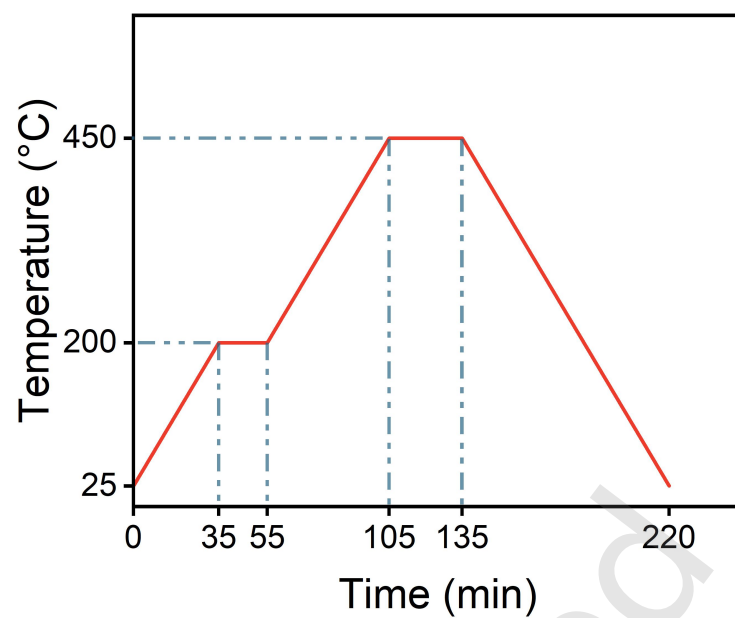


Figure S5 Reduction of PI/GOA

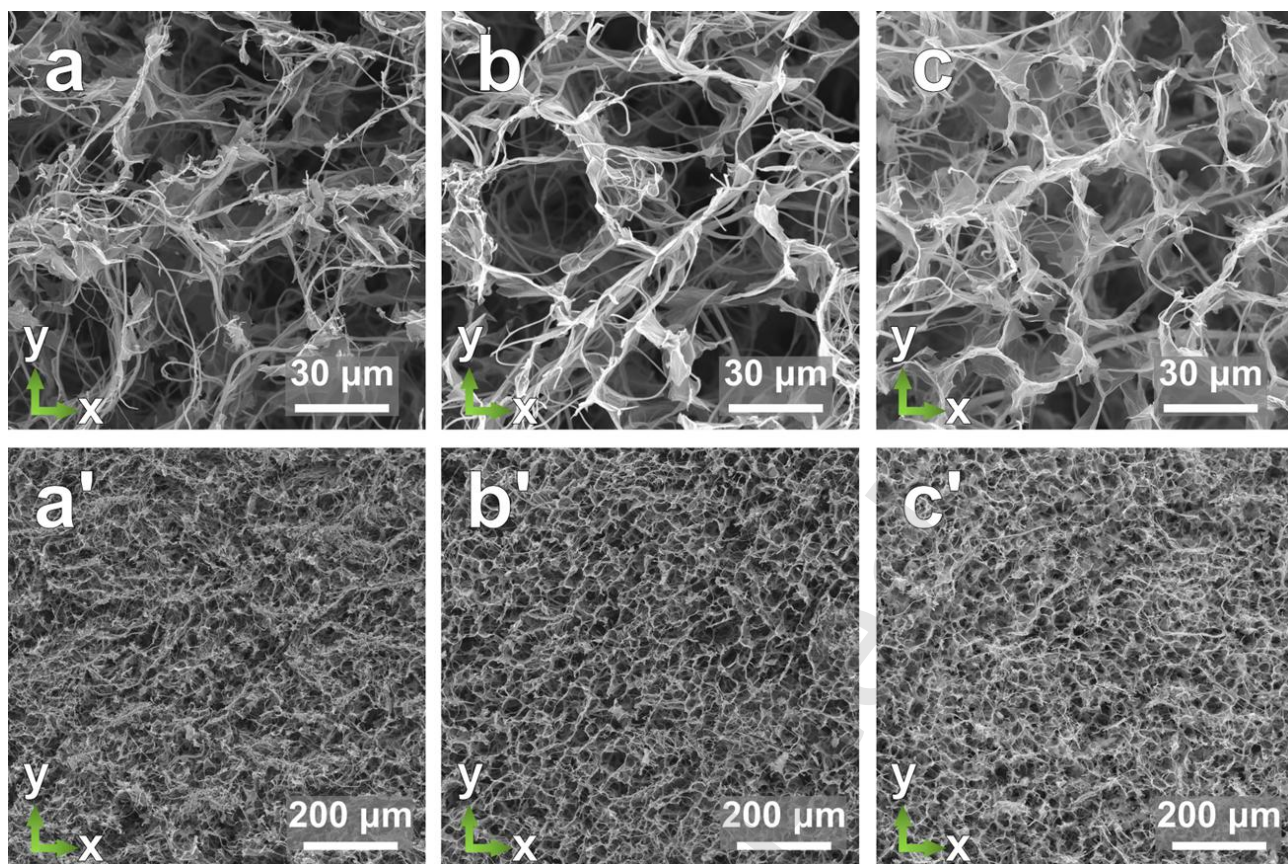


Figure S6 (a, b, c) SEM images (XY plane) of PI/rGO-1, PI/rGO-2, and PI/rGO-3 at $\times 2000$ magnification, respectively. (a', b', c') SEM images (XY plane) of PI/rGO-1, PI/rGO-2, and PI/rGO-3 at $\times 300$ magnification, respectively.

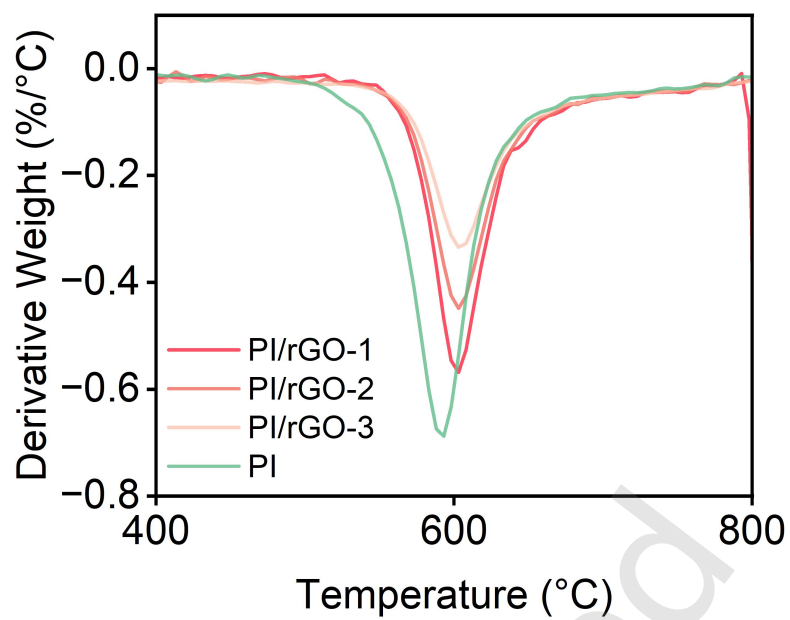


Figure S7 DTG curves of PI/rGOA

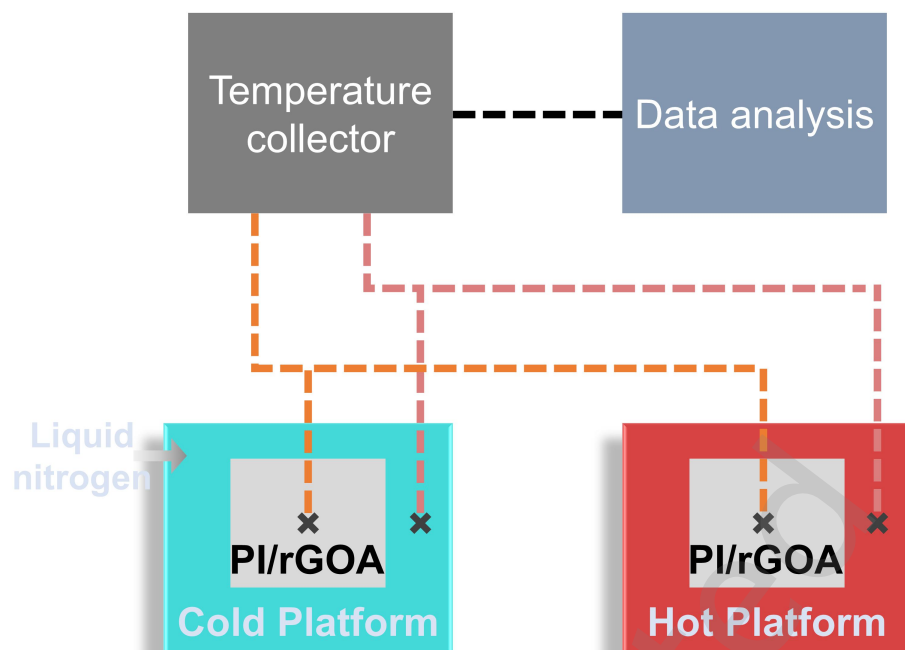


Figure S8 Temperature testing platform

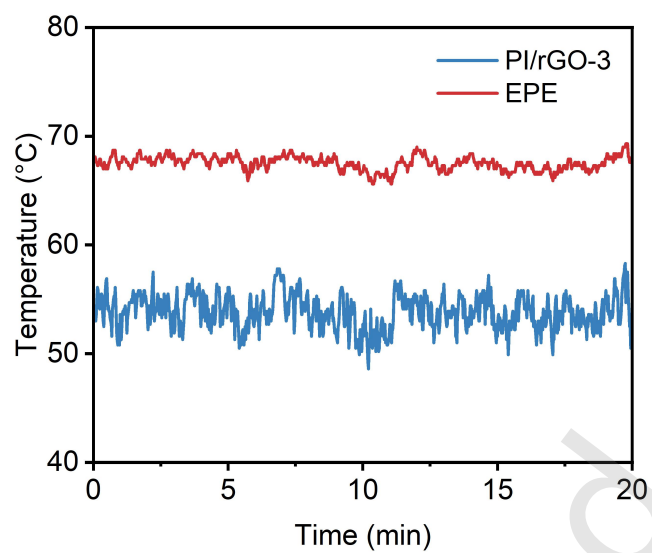


Figure S9 Surface temperatures of PI/rGO-3 and EPE

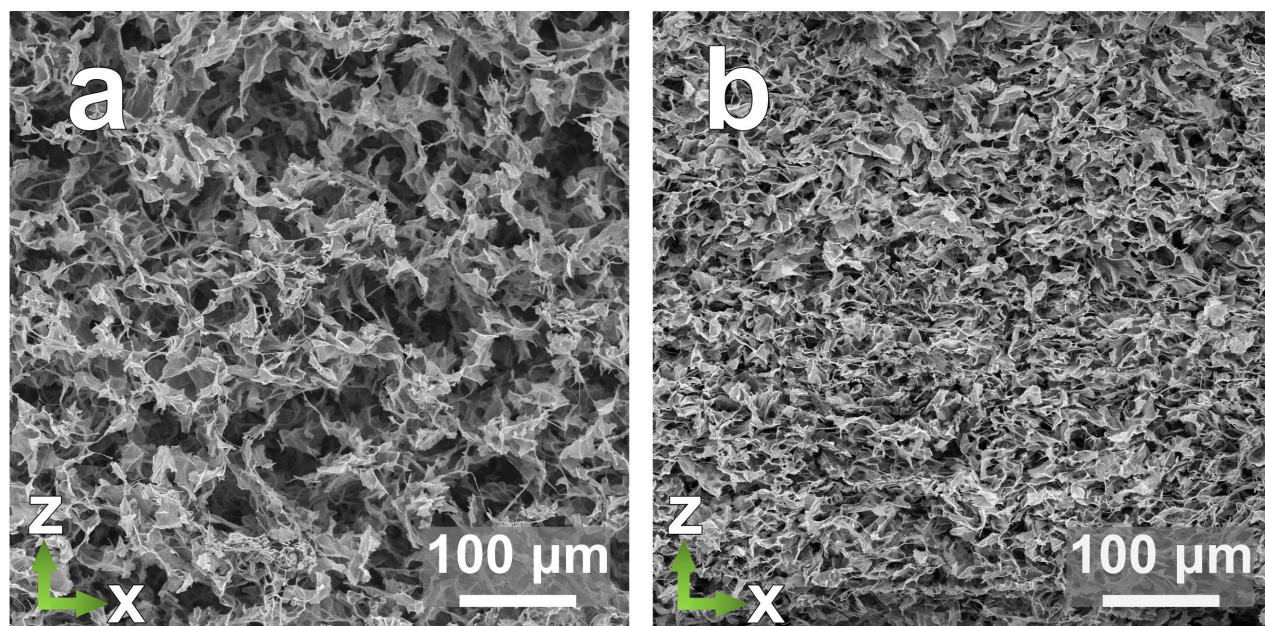


Figure S10 SEM images (XZ plane) of the PPI/rGO PRS after 500 compression cycles. (a) Uncompressed state. (b) Compressed state.