

REVIEW

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Freeze-casted aerogel-based piezoresistive pressure sensors: materials, structures, and applications

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Abstract

Flexible piezoresistive pressure sensors have emerged as vital components for wearable electronics, soft robotics, and biomedical monitoring. However, simultaneously achieving high sensitivity, a wide detection range, and long-term durability for these sensors remains challenging. Among the various approaches, freeze-casted aerogel-based sensors have garnered significant attention owing to their exceptional properties, such as ultralow density, high porosity, and customizable microstructures. This review summarizes the recent advances in such sensors, with emphasis on material selection, structural design, and practical applications. The integration of one-dimensional, two-dimensional, and hybrid nanomaterials offers synergistic enhancements in electrical conductivity, mechanical robustness, and sensing performance. Advanced structural engineering strategies, including anisotropic pore alignment, gradient architecture, and biomimetic designs, have enabled improved sensitivity, a broader detection range, and enhanced durability. Representative applications in real-time physiological monitoring and human-machine interfaces demonstrate the potential of these sensors in real-world scenarios. This review provides insight into rational design strategies that harness both materials and architecture to improve the performance and applicability of next-generation aerogel-based pressure sensors.

Keywords Freeze-casting, Aerogel, Piezoresistive sensors, Multidimensional nanomaterials, Structural design optimization, Biomedical monitoring, Human-machine interfaces

Introduction

Flexible pressure sensors have garnered significant attention for applications in wearable electronics, soft robots, and human motion monitoring [1–6]. Among the various pressure-sensing mechanisms, piezoresistive pressure sensors are particularly attractive because of their simplicity and reliable electromechanical response [7, 8]. In piezoresistive sensors, an applied pressure or

strain results in a measurable change in electrical resistance. Compared with other methods, the piezoresistive mechanism offers an intuitive sensing mechanism, measurability of static stimuli, good signal stability, rapid responses, and high deformation tolerance [7, 9, 10]. Thus, they are excellent candidates for next-generation wearable and implantable devices that require both sensitivity and resilience. Conventional flexible piezoresistive pressure sensors incorporate conductive nanomaterials, including silver nanowires (AgNWs) [11–13], carbon nanotubes (CNTs) [14–17], graphene [16, 18, 19], and MXenes [20–22] within elastic polymer matrices such as polydimethylsiloxane (PDMS) [11, 12, 16, 23, 24], styrene-ethylene-butylene-styrene [25, 26], and Ecoflex [27,

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28]. However, the dense and less compressible nature of these materials limits their sensitivity. Although various microstructuring strategies (e.g., pyramids, micropillars, and random microstructures) and porous elastomers have been investigated to address these limitations [29–32], further breakthroughs demand innovative materials and structural designs.

Flexible aerogels are unique solid-state materials composed of interconnected three-dimensional (3D) solid networks and numerous air-filled pores. These flexible aerogels typically exhibit high elasticity, thus endowing sensors with sufficient tolerance to large deformations and compressibility while affording an extremely low density, a large active area, and high porosity [33, 34]. These features render aerogels promising for use as scaffolds for high-performance piezoresistive pressure sensors. Various methods exist for fabricating aerogels, such as supercritical drying [35, 36], chemical vapor deposition [37], and hydrothermal methods [38]. However, these methods do not focus on flexible aerogels because of their narrow material range and stochastic pore structure. Meanwhile, freeze casting is a key fabrication technique enabling customized porous structured flexible and electrically conductive aerogels [39, 40]. In this process, a nano-material-based suspension is frozen under controlled conditions such that the solid crystals grown exhibit an ordered pore structure; additionally, the subsequent freeze-drying process (i.e., removal of solid crystals) results in an aerogel with voids. Owing to the availability of freely optimized material selection (or composition) and freeze-casting parameters (e.g., cooling rate and temperature gradient), this approach affords diverse architectures with controlled mechanical strengths and efficient pathways for stress transfer and electrical conduction.

In recent years, freeze-casted aerogel-based pressure sensors have garnered significant attention because of their unique combination of ultralight weight and high sensitivity to subtle pressures [21, 47]. Considering the rapid progress and the increasing number of high-quality studies in this field, a comprehensive review is necessary. This study summarizes recent advances in piezoresistive pressure sensors fabricated via freeze-casting, with emphasis on material selection, structural design, and application aspects, as illustrated in Fig. 1. Particular attention is devoted to design strategies that integrate material and structural advantages to enhance sensing performance and enable diverse applications in wearable electronics, including the real-time detection of physiological signals and human motion at various body locations, as well as human–machine interfaces.

Piezoresistive pressure sensing principles in aerogel

The sensing mechanism of aerogel-based piezoresistive pressure sensors is shown in Fig. 2. The sensor transduces mechanical stimuli into electrical signals via resistance changes, as expressed by the following equation:

$$R = \rho \cdot \frac{L}{A}$$

where ρ denotes resistivity, L the electrical pathway length, and A the cross-sectional area. The two primary contributing mechanisms are as follows: (1) resistivity changes from the dynamic percolation of conductive fillers or quantum tunneling between domains (Fig. 2a) [7]; and (2) geometrical deformations under compression, including length reduction and pore closure increasing conductive contact (Fig. 2b) [6, 48, 49]. Although both mechanisms can contribute to the change in resistance, the dominant factor in aerogel-based sensors is typically the deformation-induced evolution of the porous microstructure, which significantly affects the conductive pathways and overall resistance.

The electromechanical performance of piezoresistive pressure sensors is typically evaluated based on their sensitivity or gauge factor, which are expressed as follows:

$$\text{Sensitivity} = \frac{\Delta I}{I_0 \cdot \Delta P}$$

$$\text{Gauge factor} = \frac{\Delta R}{R_0 \cdot \epsilon}$$

Here, I represents current, P pressure, R resistance, and ϵ compressive strain. Higher values indicate superior performance, thus enabling the detection of minimal stimulus variation. Compared with conventional sensors, aerogel integration significantly enhances these parameters while reducing the detection limits.

Material selection strategies

The performance of aerogel-based piezoresistive pressure sensors is governed significantly by the appropriate selection and integration of constituent materials. These sensors are typically composed of a highly porous aerogel matrix embedded in conductive nanomaterials that form pressure-sensitive electrical networks. Conductive nanofillers modulate electrical resistance in response to mechanical stimuli, whereas the aerogel matrix ensures mechanical support, compressibility, and structural integrity. To achieve optimal performance, a balanced combination of electrical and mechanical properties is essential. Recently, researchers have investigated a wide range of material systems, which can be broadly

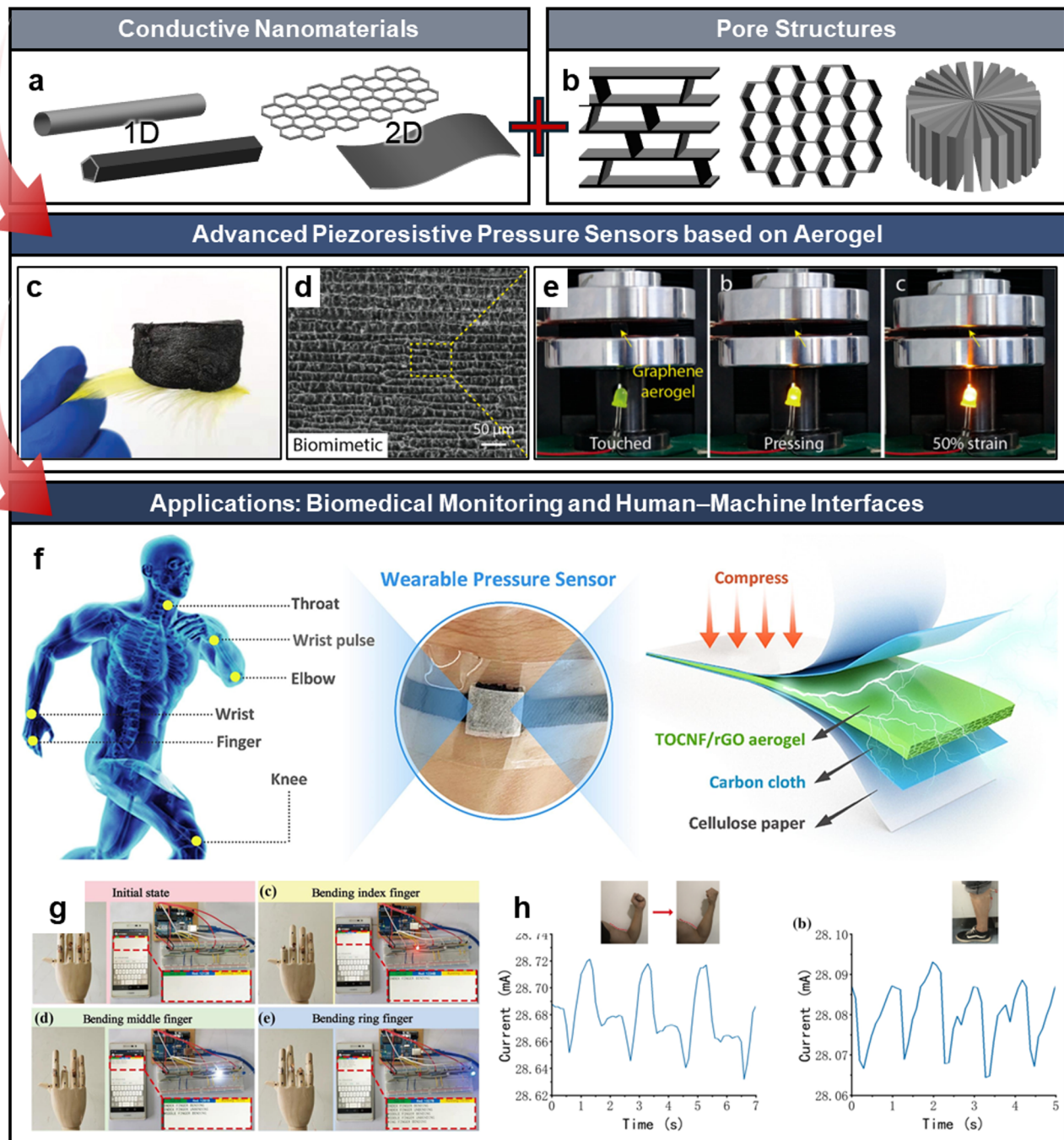


Fig. 1 Overview of freeze-casted aerogel-based piezoresistive pressure sensors. **a** Conceptual illustration of functional materials used as conductive fillers, including 1D and 2D nanostructures. **b** Diverse porous structures fabricated via freeze casting. **c–e** Aerogel-based piezoresistive pressure sensors fabricated by combining various nanomaterials with customized pore architectures [41, 42]. **f–h** Representative application scenarios, including wearable physiological monitoring and human–machine interfaces [43–45]. Reproduced with permission from [46], Copyright 2019 Elsevier. Reproduced with permission from [41], Copyright 2017 American Chemical Society. Reproduced with permission from [42], Copyright 2020 Wiley-VCH. Reproduced with permission from [43], Copyright 2023 Elsevier. Reproduced with permission from [44], Copyright 2021 Elsevier. Reproduced with permission from [45], Copyright 2022 Springer

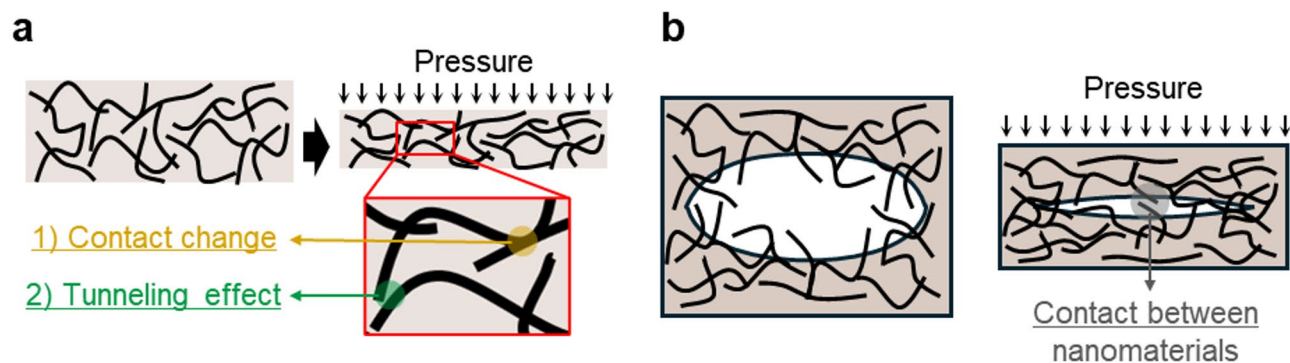


Fig. 2 Sensing mechanism of aerogel-based piezoresistive pressure sensors. **a** Pressure-induced variation in resistivity due to tunneling and percolation effects between conductive nanomaterials. **b** Geometric modulation of conductive pathways through pore deformation under compressive strain. Both mechanisms contribute to overall resistance change, primarily driven by deformation of the aerogel microstructure

categorized into one-dimensional (1D), two-dimensional (2D), and hybrid nanomaterial systems.

The 1D nanomaterials, such as CNTs and metal nanowires, have been widely adopted due to their high aspect ratios, excellent electrical properties, and mechanical flexibility [45, 50–54]. These materials can readily form percolated networks at low loading concentrations, while preserving the low density and high porosity of aerogels, and simultaneously enabling reliable electrical pathways. Additionally, their entangled structure endows them with elasticity and structural recoverability, thus rendering them highly suitable for pressure sensors subjected to repeated deformations. For example, an aerogel composed of AgNWs and carboxymethylcellulose achieved an ultralow density ($\sim 6 \text{ mg/cm}^3$) and high porosity ($\sim 99.2\%$) while maintaining a low resistivity ($\sim 0.9 \text{ }\Omega\cdot\text{cm}$) (Fig. 3a) [48]. The incorporation of AgNWs not only ensured robust electrical conductivity but also enhanced the elastic modulus (740 kPa) and resilience of the scaffold. The resulting sensor demonstrated excellent electro-mechanical performance, with a sensitivity of 2.64 kPa^{-1} and stable operation over 100 cycles at 70% compressive strain. In a more recent study, a CNT-based aerogel was developed using tannic acid as both a dispersing agent and crosslinker, which resulted in a single-walled CNT/tannic acid core-shell architecture through hydrothermal and freeze-drying processes [52]. This approach enabled the fabrication of lightweight, highly conductive, and mechanically robust aerogels without requiring high CNT concentrations. The optimized single-walled CNT/tannic acid aerogel exhibited a hierarchical porous network with good compressive strength ($\sim 112.6 \text{ kPa}$), high electrical conductivity ($\sim 98 \text{ S}\cdot\text{m}^{-1}$), and outstanding sensing performance. Specifically, it demonstrated a high linear sensitivity of 432 kPa^{-1} over a wide pressure range (0.14–28 kPa), along with a fast response time of $\sim 300 \text{ ms}$ and excellent durability over 250 cycles. These results highlight the potential of tannic acid-assisted

CNT aerogels as high-performance, sustainable sensing materials for next-generation wearable electronics.

The 2D nanomaterials, particularly graphene and MXenes, exhibit extremely high surface-to-volume ratios and excellent functionalization capabilities, thus facilitating the formation of conductive pathways and chemical interaction sites [43, 55–57]. Owing to the exceptional properties of graphene—such as high conductivity ($\sim 10^6 \text{ S/cm}$), high Young's modulus ($\sim 1 \text{ TPa}$), and large specific surface area ($\sim 2500 \text{ m}^2/\text{g}$)—graphene aerogels are excellent candidates for aerogel-based pressure sensors [58]. For instance, a TEMPO-oxidized cellulose nanofibers-reduced graphene oxide (rGO) aerogel exhibited high compressibility and fatigue resistance with stable performance under 2000 cycles at 60% (Fig. 3b) [43]. The sensor showed a sensitivity of 1.12 kPa^{-1} with a wide detection range and fast response ($< 100 \text{ ms}$). MXenes, which is another class of 2D nanomaterials, possess inherently hydrophilic surfaces and a high density of functional groups, thus rendering them highly compatible with aqueous freeze-casting processes and suitable for chemical bonding with polymeric matrices [59]. An MXene/aramid nanofiber aerogel was reported to exhibit a chemically bonded 3D porous architecture with excellent mechanical durability, an outstanding sensitivity of 128 kPa^{-1} , and stable operation over 1000 cycles [56]. Despite these advantages, restacking 2D nanomaterials remains challenging, thereby reducing accessible surface areas and non-optimal electrical properties. Hence, the precise preparation of suspensions for freeze-casting is essential to maintain their performance benefits.

Hybrid nanofiller systems have been developed to combine the advantages of 1D and 2D nanomaterials while mitigating their respective limitations. In such systems, 1D nanomaterials serve as interlayer spacers or conductive bridges between 2D sheets, thus preventing restacking and promoting the formation of multidirectional conductive networks [42, 44, 60–62]. A notable example is a hybrid aerogel composed of CNTs and graphene

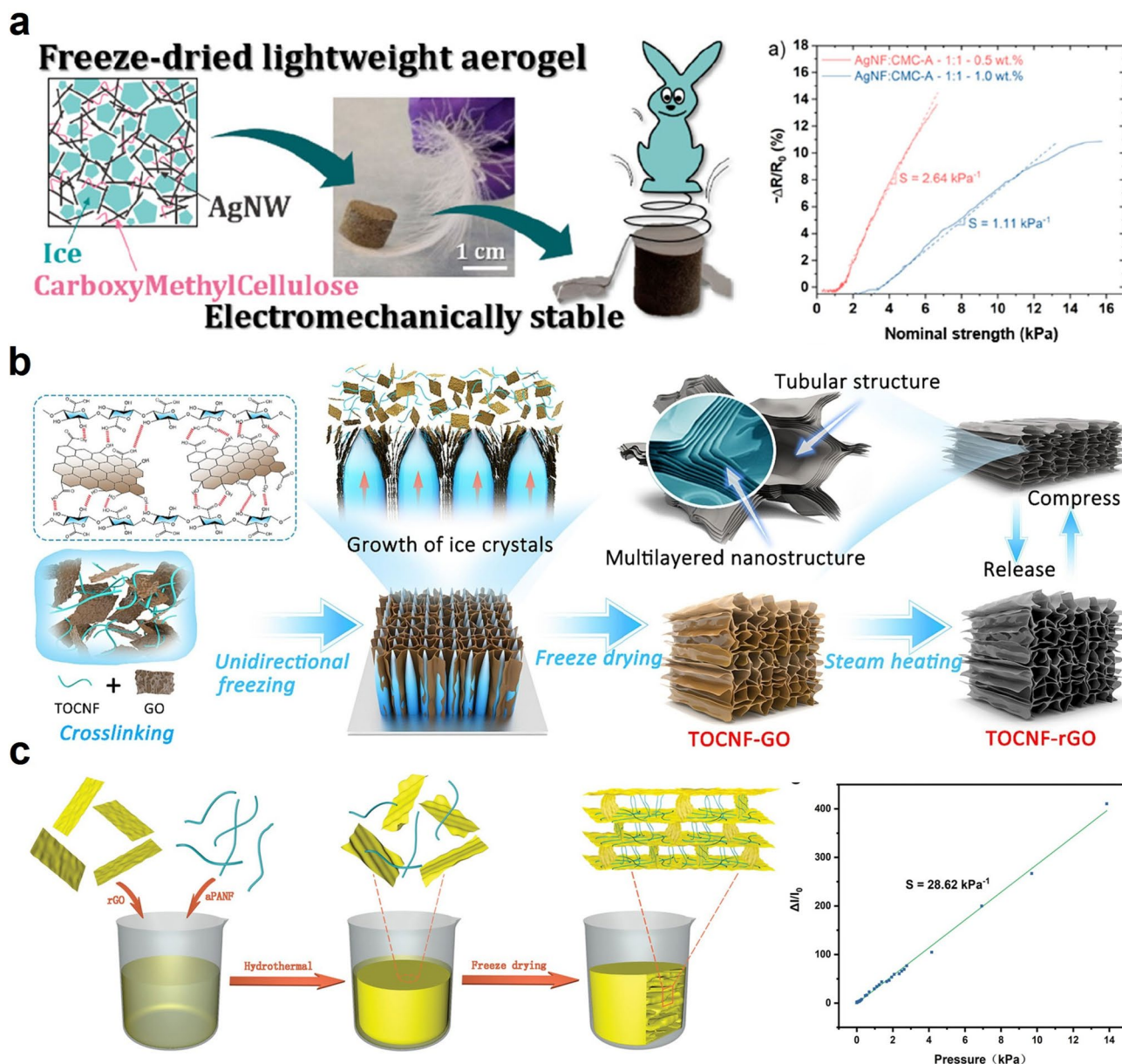


Fig. 3 Nanomaterial configurations of aerogel-based piezoresistive sensors, which highlight effects of 1D, 2D, and hybrid nanomaterials on sensor performance. **a** Performance of AgNW/carboxymethylcellulose hybrid aerogel [50]. **b** TEMPO-oxidized cellulose nanofibers/reduced graphene oxide (rGO) aerogel combining 2D conductivity and mechanical resilience [43]. **c** Hierarchical CNT/graphene oxide hybrid aerogel enabling multidimensional conductive network [42]. Reproduced with permission from [50], Copyright 2022 American Chemical Society. Reproduced with permission from [43], Copyright 2023 Elsevier. Reproduced with permission from [42], Copyright 2020 Wiley-VCH

oxide nanosheets. In this system, CNTs serve as conductive bridges between adjacent graphene oxide layers, forming a hierarchically interconnected structure with enhanced electrical conductivity and mechanical robustness (Fig. 3c) [42]. The resulting pressure sensor demonstrated a wide linear sensing range (up to 75% strain), high sensitivity (5.3 kPa^{-1}), and excellent durability over 10,000 compression cycles. Another design integrates CNTs, graphene, waterborne polyurethane, and cellulose nanocrystals into a composite aerogel. The synergistic

combination of 1D and 2D conductive fillers afforded a 3D conductive framework with enhanced compressive strength (76.16 kPa) and mechanical stability under repeated deformation (>800 cycles) while achieving a sensitivity of 0.25 kPa^{-1} [61]. To systematically assess the comparative performance of freeze-casted aerogel-based piezoresistive pressure sensors utilizing various 1D, 2D, and hybrid nanomaterials, we summarize critical performance metrics, such as density, sensitivity, sensing range, and durability, in Table 1.

Table 1 Performance of representative freeze-casted aerogel-based piezoresistive pressure sensors using different nanomaterials

Nanomaterial type	Sensing materials	Density (mg/cm ³)	Sensitivity (kPa ⁻¹)	Sensing range (kPa)	Cyclic stability	Ref.
1D nanomaterial	AgNW/carboxymethylcellulose	~ 6	2.64	< 7	>100	[50]
	Carbonized cellulose nanofiber	10.7	6.63	0.002–7	>920	[63]
	AgNW/cellulose nanofiber	13.58	3.86	0.5–1.5	>1,200	[64]
			0.43	1.5–5		
			0.23	5–8		
	CNT/cellulose nanofiber	-	66.4	0–15	>10,000	[51]
			14.8	15–50		
	Mg ²⁺ /CNT/tannic acid	-	13,662	0.014–1.05	>250	[52]
	CNT/tannic acid	-	432	0.014–28	>250	[52]
	CNF/rGO	10.2	1.12	0–3	>1500	[43]
2D nanomaterial	MXene/aramid nanofiber	25	2.13	3–7	>1000	[56]
			1.19	7–10		
			1.32	1–3		
	GO/cellulose nanofiber/acrylonitrile butadiene styrene	1.82	17.65	0–0.36	>500	[65]
			3.4	1.5–3.2		
	GO/hydroxypropyl methyl cellulose	8.16	15.8	0–18	>1000	[66]
	GO/PEDOT: PSS	-	6.1	0.1–50	>525	[67]
	rGO/polyvinyl alcohol	-	7.48	0–1	>1000	[68]
			1.32	1–3		
	Graphene/polyacrylonitrile nanofiber	-	28.62	< 14	>2600	[42]
Hybrid nanomaterial	CNT/rGO/cellulose nanofiber	2.64	5.61	0–0.21	>2000	[60]
	CNT/graphene/polyurethane/cellulose nanocrystal	135	0.25	< 4.2	>800	[61]
	CNT/MXene/cellulose nanofiber	7.48	817.3	0–0.2	>2000	[69]
			234.9	0.2–1.5		
	MXene/CNT/chitosan	-	3.84	0–12.4	>1000	[44]
			0.18	32.8–80.9		
	CNT/rGO/polyvinyl alcohol/polyacrylonitrile nanofiber	20.54	33	0–2	>1000	[54]

Structural design optimization

Similar to the materials utilized, the structural design of an aerogel sensor is crucial for achieving superior performance. By customizing both micro- and macroscale architectures, key sensing parameters such as sensitivity, dynamic range, and durability can be finely tuned—beyond what is achievable with ordinary structures. In freeze-casted aerogel-based sensors, the solidification process enables precise control over the pore alignment, size distribution, and connectivity, thus enabling the fabrication of well-defined architectures that directly translate into enhanced electromechanical performance.

Freeze-casting enables precise control over the internal architecture of aerogels by modulating freezing parameters such as the cooling rate, temperature gradient, and solvent composition [44, 60, 70–72]. By tuning these parameters, various anisotropic pore structures can be customized to enhance the electromechanical performance of pressure sensors. Among the strategies,

bidirectional freeze-casting enables the formation of long-range, interconnected lamellar structures via the application of vertical and lateral temperature gradients. For example, performing ethanol-assisted bidirectional freezing was employed to fabricate a lamellar graphene aerogel with weakened strut strength and highly aligned layers, which exhibited exceptional piezoresistive performance, with a sensitivity of -3.69 kPa^{-1} and a detection limit of 0.15 Pa (Fig. 4a) [70].

Hierarchical and gradient pore architectures have been introduced to further improve the performance of aerogel-based pressure sensors [67, 73]. One notable strategy involves stacking aerogel layers with varying pore densities to form multiscale architecture. This approach enables sequential deformation across layers under pressure, which increases sensitivity and broadens the detection range. For instance, a graphene aerogel fabricated via freeze-assisted transfer printing exhibited a sensitivity up to 29.6 kPa^{-1} across 0.1–50 kPa along with robust cycling durability (Fig. 4b) [67]. Its gradient structure facilitated smooth stress transfer and maintained a linear resistance–pressure correlation, even under large

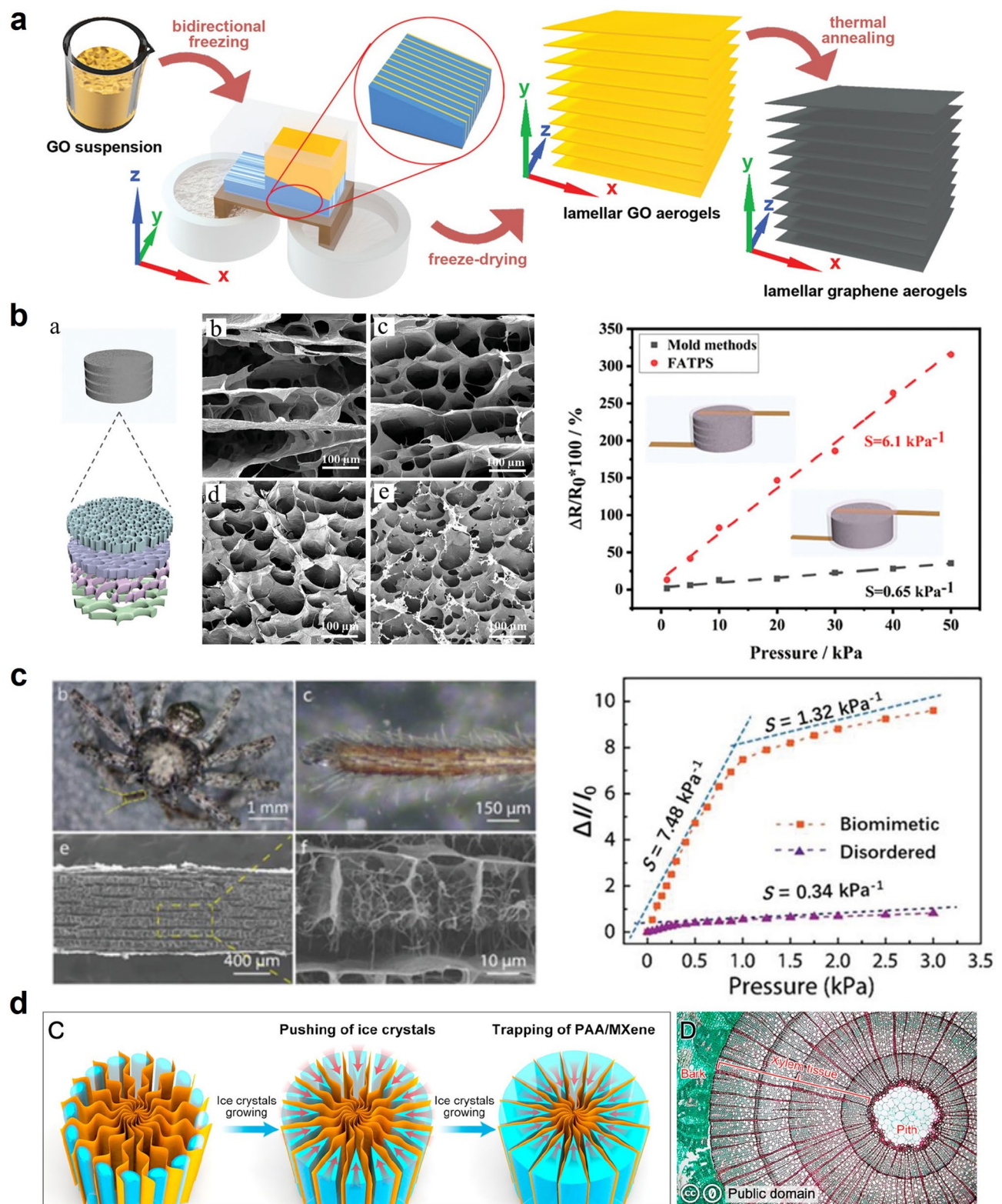


Fig. 4 Structural engineering strategies for enhanced pressure sensing. **a** Bidirectionally freeze-casted graphene aerogel exhibiting lamellar alignment [70]. **b** Stacked aerogel layers featuring multiscale pores with broad detection range [67]. **c** Spider-inspired fluff-like aerogel mimicking vibration-sensitive biological systems [68]. **d** Radially freeze-casted aerogel comprising xylem-inspired microchannels [71]. Reproduced with permission from [70], Copyright 2021 Wiley-VCH. Reproduced with permission from [67], Copyright 2024 Wiley-VCH. Reproduced with permission from [68], Copyright 2021 Wiley-VCH. Reproduced with permission from [71], Copyright 2022 American Chemical Society

deformations. Similarly, a polypyrrole/PDMS conductive aerogel with a gradient pore structure exhibited improved compressibility and resilience, thus enabling the detection of both subtle and high-pressure stimuli with enhanced reliability and stability [73]. These gradient architectures offer adaptable mechanical compliance and gradual resistance modulation.

Biomimetic structural designs provide inspiration for engineering high-performance aerogel-based pressure sensors [41, 43, 68, 71, 74–76]. For example, a graphene aerogel film mimicking the fluffy legs of spiders was fabricated using bidirectional freezing to form lamellar layers with interlayer dendrites (Fig. 4c) [68]. This structure facilitates efficient deformation and signal conduction, leading to remarkable performance metrics including a sensitivity of 7.48 kPa^{-1} (0–1 kPa), an ultralow detection limit of 5 Pa, and an ultrafast response time of 31 ms. The sensor reliably detected subtle vibrations such as human pulses and lightweight objects, thus underscoring the benefit of replicating nature's finely tuned microstructures. Similarly, xylem-inspired radial freeze-casted aerogels exhibited concentric lamellar channels radiating from the center, which mimicked the compressible yet resilient architecture of plant stems (Fig. 4d) [71]. The resulting polyimide/MXene aerogel exhibited excellent directional conductivity and mechanical robustness, high sensitivity (4.3 kPa^{-1}), a broad detection range (60–76.5 kPa), and durable cycling stability. Such radial biomimetic structures not only enhance structural integrity and longitudinal compressibility but also enable robust signal transduction under complex loading conditions.

Applications: biomedical monitoring and human-machine interfaces

The exceptional mechanical compliance, ultralow density, and high piezoresistive sensitivity of aerogel-based pressure sensors make them highly versatile for applications in biomedical monitoring and human-machine interfaces. Their lightweight nature and conformity allow intimate integration with soft biological tissues or curved robotic surfaces, supporting real-time acquisition of subtle pressure variations with minimal interference.

In biomedical monitoring, these sensors offer promising capabilities for continuous, noninvasive physiological tracking [43, 52, 63–69]. For example, an aerogel composed of tannic acid-functionalized CNTs exhibited hierarchical porosity and tunable conductivity via Mg^{2+} modulation, thus enabling the detection of weak physiological signals, such as wrist pulses, jugular venous pressure, respiration, wallowing, and pronunciation (Fig. 5a) [52]. The sensor maintained its stable performance under cyclic deformation and

achieved a low detection limit of 2.8 mPa, thus rendering it suitable for wearable diagnostic platforms and real-time patient monitoring. Another notable design is a wood-inspired anisotropic aerogel composed of TEMPO-oxidized cellulose nanofibers and rGO (Fig. 5b) [43]. The sensor, inspired by the tubular and multilayered structure of natural wood, was successfully applied to detect various human biological and motion signals. It enabled reliable monitoring of joint movements such as finger, wrist, elbow, and knee bending, and was also capable of capturing subtle physiological signals, including arterial pulse and speech pronunciation, demonstrating its suitability for wearable biomedical monitoring applications.

For human-machine interfaces, aerogel-based sensors offer high-resolution tactile feedback with robust signal reliability. A biomimetic pressure sensor composed of MXenes and a bacterial cellulose aerogel with a negative Poisson's ratio was fabricated via bidirectional freezing, which resulted in a honeycomb-like microarchitecture (Fig. 5c) [76]. The sensor exhibited anisotropic mechanical response and excellent durability under multidirectional loading. Integrating it into a smart glove enabled the spatial mapping of finger motions and grip forces, thus allowing the effective interpretation of object-manipulation patterns. The primary focus was on real-time mechanical feedback from hand movements, while advanced virtual perception capabilities were conceptually discussed.

These applications demonstrate how material-structure integration in aerogel-based sensors enables multifunctional performance. Future studies may explore multimodal sensing platforms capable of discriminating multiple physical and biochemical stimuli—such as pressure, strain, temperature, humidity, and biomarkers—within a single aerogel framework. Feasible technological pathways can be derived from recent advances in heterogeneous architectures and decoupled signal designs. For example, multi-material integration strategies combining aerogel skeletons with thermoresponsive polymers, ionically conductive hydrogels, MXene- or CNT-based thermoelectric layers, and photo- or magnetoactive nanocomposites have demonstrated effective decoupling of mechanical, thermal, and optical inputs [77–81]. Algorithmic decoupling methods, including machine-learning-assisted signal separation and physics-informed modeling, further enhance discrimination accuracy under complex, cross-coupled stimuli [82, 83]. These developments highlight aerogels as scalable platforms for multimodal intelligent skins, adaptive wearable diagnostics, and robotic interfaces where diverse sensory channels must be selectively integrated and interpreted.

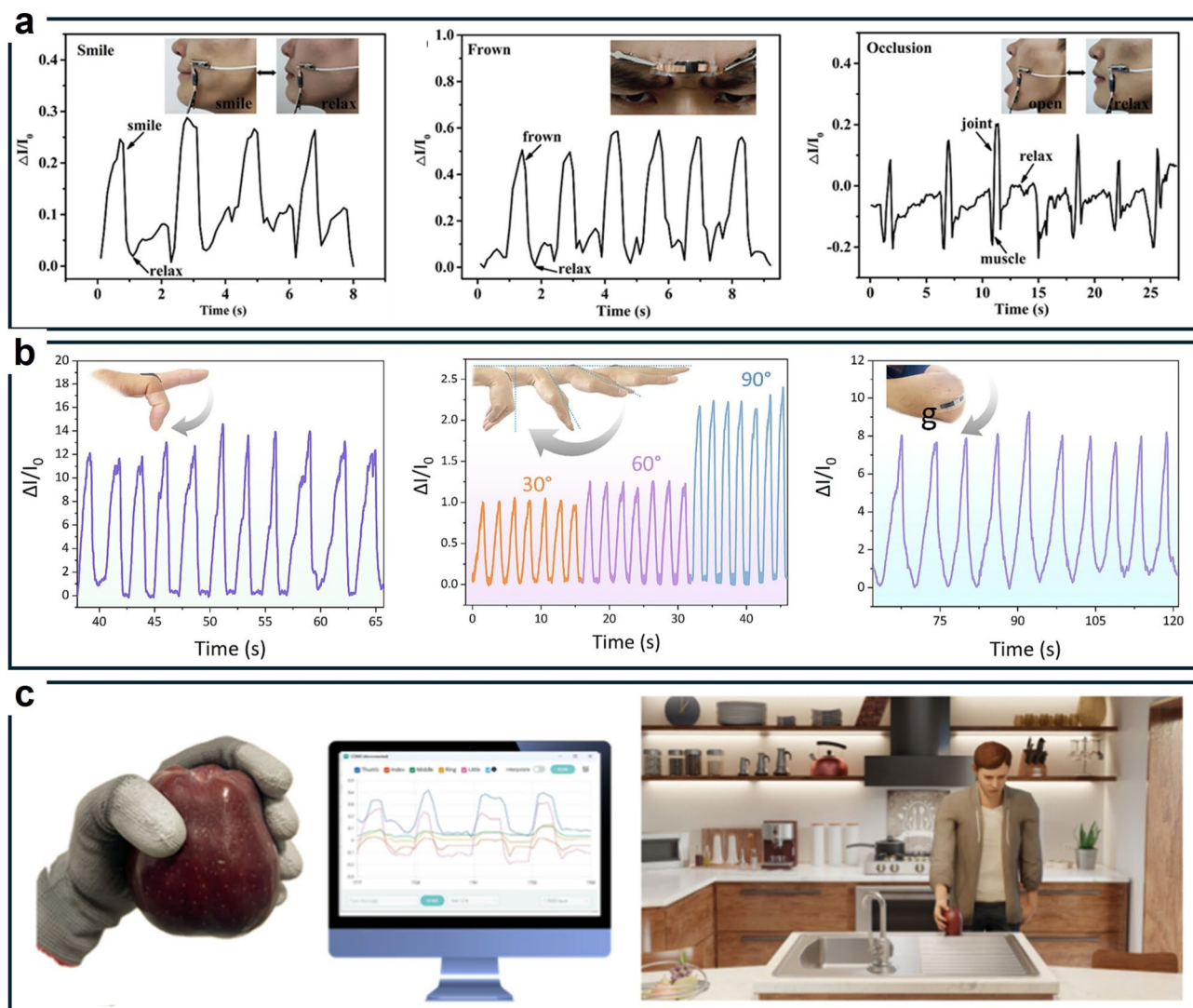


Fig. 5 Aerogel-based piezoresistive pressure sensors for biomedical monitoring and human-machine interfaces. **a** Detection of physiological signals using a Mg^{2+} -modulated CNT-tannic acid aerogel with hierarchical structure and ultralow detection limit [52]. **b** Detection of human motion and physiological signals using a wood-inspired TEMPO-oxidized cellulose nanofiber/rGO aerogel pressure sensor, demonstrating applicability in wearable biomedical monitoring [43]. **c** Smart glove-integrated MXene/bacterial cellulose aerogel sensor with honeycomb-like architecture and negative Poisson's ratio, which enables multidirectional force mapping and robust tactile signal transduction [76]. Reproduced with permission from [52], Copyright 2023 American Chemical Society. Reproduced with permission from [43], Copyright 2023 Elsevier. Reproduced with permission from [76], Copyright 2024 American Chemical Society

Conclusion and outlook

Freeze-casted aerogel-based piezoresistive pressure sensors are promising for realizing highly sensitive, lightweight, and mechanically compliant pressure-sensing platforms. By judiciously selecting conductive nanomaterials—ranging from 1D CNTs and AgNWs to 2D graphene and MXenes—and employing architected porous networks via freeze-casting, researchers have significantly enhanced the sensitivity, compressibility, and durability of such sensors. Moreover, gradient and biomimetic structural designs further elevate the functional performance of such sensors, thus enabling customized

electromechanical responses under diverse operating conditions.

Despite these advances, several challenges remain. The long-term reliability of aerogels under cyclic deformation, environmental variations, and real-world mechanical stresses must be further evaluated. Additionally, scalable fabrication processes that maintain fine control over material dispersion and pore alignment are essential for commercial viability. Looking forward, integrating aerogels into multimodal sensing systems that simultaneously detect pressure, strain, temperature, humidity, and biochemical signals represents a logical evolution. Such systems could exploit multi-material heterogeneous

integration—for example, combining thermoelectric, ionic, or photoactive components within aerogel matrices—and algorithm-driven signal decoupling to achieve accurate multi-signal discrimination and adaptive functionality in complex environments.

Abbreviations

AgNW	Silver nanowire
CNT	Carbon nanotube
PDMS	Polydimethylsiloxane
Mg ²⁺	Magnesium ion
rGO	Reduced graphene oxide

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Author contributions

All authors contributed to writing and editing the manuscript and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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