Chinese Journal of
POLYMER SCIENCE

REVIEW

https://doi.org/10.1007/s10118-026-3584-y
Chinese J. Polym. Sci. **2026**, *44*, 1645–1666

Functional Ionogels: Design Principles and Applications

Rui Wu[a,†], Jin-Qi Zhang[a,†], Xun Xiao[b,c,d*], and Mei-Xiang Wang[a,e*]

[a] *Key Laboratory of Bio-Inspired Smart Interfacial Science and Technology of Ministry of Education, School of Chemistry, Beihang University, Beijing 100191, China*
[b] *State Key Laboratory of Advanced Waterproof Materials, School of Materials Science and Engineering, Peking University, Beijing 100871, China*
[c] *State Key Laboratory of Advanced Waterproof Materials, Beijing Oriental Yuhong Waterproof Technology Co., Ltd., Peking University, Beijing 100871, China*
[d] *State Key Laboratory of Silicon and Advanced Semiconductor Materials, Zhejiang University, Hangzhou 310058, China*
[e] *Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, North Carolina 27606, United States*

Abstract Ionogels are a class of soft materials composed of ionic liquids and polymer networks. They possess many fascinating intrinsic properties (*e.g.*, ionic conductivity, near-zero vapor pressure, and wide thermal and electrochemical operation windows) that make them promising for applications in ionotronics, sensors, energy storage devices, and flexible electronics. In addition to these intrinsic properties, ionogels can acquire additional functionalities (such as self-healing, shape memory, and adhesion) through structural design and the introduction of functional additives, thereby further expanding their application scope. This review focuses specifically on these additional functionalities of ionogels, elucidating their design strategies and applications and highlighting the current challenges and future opportunities in this rapidly developing field.

Keywords Ionogel; Functionality; Wearable sensors; Energy storage devices; Biomedicine

Citation: Wu, R.; Zhang, J. Q.; Xiao, X.; Wang, M. X. Functional ionogels: design principles and applications. *Chinese J. Polym. Sci.* **2026**, *44*, 1645–1666.

* Corresponding authors, E-mail: xunxiao@pku.edu.cn (X.X.)
E-mail: mwang32@buaa.edu.cn (M.X.W.)
† These authors contributed equally to this work.
Special Topic: Functional Gels
Received December 30, 2025; Accepted January 23, 2026; Published online May 20, 2026

1 INTRODUCTION

Ionogels have developed rapidly over the past three decades owing to growing interest in their enormous application potential.[1–3] Ionogels are composed of polymer networks and ionic liquid (IL) solvents, and possess the characteristics of both solids and liquids.[4–6] In particular, ionic liquids (ILs) are salts that are liquids at low temperatures, typically <100 °C.[3,7] ILs are fascinating because of their unique properties, including ionic conductivity, negligible vapor pressure, non-flammability, wide temperature range, and electrochemical operating range.[8–11] Ionogels inherit these advantages and present them in solid form, making them more convenient for applications in flexible electronics, iontronics, sensors and actuators, and solid-state electrolytes for batteries.[11–16] It is worth emphasizing that these features significantly distinguish ionogels from traditional gels (*e.g.*, hydrogels or organogels), giving them broader application prospects in extreme environments (*e.g.*, high temperature or high vacuum).[5,13,17] For example, ionogels are promising candidates for use as electrolytes in space batteries, whereas traditional gels typically fail owing to solvent evaporation and freezing.

In addition to their intrinsic advantages, ionogels also exhibit exceptional tunability. Specifically, a wide variety of ILs (approximately 10^{18} possible combinations) and diverse polymer matrices allow for precise control over the chemical composition, network structure, and interfacial interactions of the

ionogels.[8,11] This vast design space enables the preparation of ionogels with dynamic bonds (*e.g.*, dipole-dipole interactions and ionic/hydrogen bonds), phase separation, or crystalline regions.[3,18,19] These structural features endow ionogels with additional functionalities (*e.g.*, self-healing, shape memory, adhesion, and stimuli-responsive properties), which not only broaden their application areas but also improve their operational stability and lifetime.[6,20,21] Note that certain functionalities (*e.g.*, magnetism and luminescence) can also be achieved in ionogels by introducing functional additives such as Fe_3O_4 nanoparticles and perovskites.[22–25]

Despite the promising prospects of multifunctional ionogels, their design and preparation still face several challenges. In particular, their synthesis is often complex and time-consuming (*e.g.*, solvent-exchange strategy), primarily because the thermodynamic behavior (*e.g.*, interactions, miscibility, and coordination) between ILs and monomers, polymers, or additives is not yet fully understood, particularly considering the diversity of ILs.[3,26,27] The lack of fundamental understanding hinders the rational selection of components, thereby limiting the predictive control of the structural, mechanical, and functional properties of ionogels. Fortunately, some effective strategies (*e.g.*, *in situ* phase separation and solvent crosslinking) have been developed that utilize structure-property relationships to achieve the desired functionalities in ionogels.[6,20] These advancements have significantly facilitated the development of ionogels.

This review provides a comprehensive overview of the latest advancements in the design and application of multifunctional ionogels. Specifically, it focuses on the functionalities arising from carefully designed structures or the introduction of functional additives rather than those solely stemming from the intrinsic physicochemical properties of ILs. We begin by outlining the design principles that govern the structure and performance of functional ionogels, followed by a detailed discussion of the representative systems that exemplify these strategies. Subsequently, we summarize the applications of functional ionogels and highlight how tailored structures and chemical properties expand their applications across different fields. Finally, we identified the current challenges facing multifunctional ionogels and explored future development opportunities, hoping to inspire researchers in this field.

2 DESIGN-ENABLED FUNCTIONALITIES

In addition to the intrinsic properties inherited from ILs, ionogels can also be designed to possess specific functionalities by modifying their structures or introducing functional additives. In this section, we systematically highlight the design-enabled functional features of the ionogels, such as self-healing, shape-memory, stimuli-responsiveness, magnetism, and luminescence.

2.1 Self-healing

The self-healing property enables ionogels to automatically repair damage, thereby effectively maintaining their structural integrity and functional performance.[28] Consequently, self-healing significantly extends the lifespan of ionogels, which is beneficial for their applications. This capability is closely related to the type of crosslinking in the ionogels (*e.g.*, covalent crosslinking and noncovalent crosslinking). In other words, self-healing functionality can be effectively introduced into ionogels by rationally selecting monomers, polymers, and ILs to construct structures with reversible crosslinks, which can reversibly dissociate and reform to enable self-healing.[29–39] Fig. 1(a) shows the most typical reversible bonds and interactions used for self-healing capability. Specifically, compared to dynamic covalent bonds (*e.g.*, disulfide bonds and Diels-Alder-type bonds), ionogels crosslinked by noncovalent crosslinking (*e.g.*, hydrogen bonds and coordination interactions) typically exhibit better self-healing properties (Table 1).[40–42] This may be attributed to the high reversibility of noncovalent bonds and their lower strength compared to that of dynamic covalent bonds.[21,29–35] It is worth noting that self-healing behavior can also be achieved by integrating different dynamic bonds into gel matrix.

A typical example of a dynamic covalent bond is the disulfide bond, which has been used to create a self-healing ionogel (Fig. 1b).[37] The working principle is that disulfide bonds break to form sulfur radicals, which then recombine and undergo exchange reactions, thus reforming the disulfide bonds. When the damaged surfaces come into contact, sulfur-free radicals undergo exchange reactions with the adjacent disulfide bonds to form new bonds, thereby restoring the integrity of the network structure. This ionogel exhibited efficient self-healing properties, achieving almost complete recovery after healing for 6 h at 80 °C (healing efficiency= about 90%), whereas the scratch disappeared gradually within 6 h at 100 °C (Fig. 1b). Similarly, a self-healing ionogel was achieved by introducing dynamic oxime-urethane bonds.[43] The ionogel exhibited a healing efficiency of 70% after being storage at 70 °C for 24 h, and this efficiency further increased at higher temperatures. Self-healing ionogels based on dynamic covalent bonds typically require external stimuli (*e.g.*, heating) to promote bond reformation or exchange reactions during the healing process.[38,39]

Another strategy for achieving self-healing is to establish noncovalent bonds (such as hydrogen/ionic bonds and dipole-dipole interactions) within the ionogel matrix. Among these, hydrogen bonds are among the most widely used noncovalent bonds. This stems from the abundance and ease of access of hydrogen bonds, as many common functional groups (*e.g.*, amide, carboxyl, hydroxyl, and amine) can readily act as hydrogen bond donors or acceptors.[44] For example, an ionogel is fabricated by forming abundant hydrogen bonds between the acylsemicarbazide (ASCZ) groups hanging on the polymer chains (Fig. 1c).[40] The high density of hydrogen bonds and good mobility of the polymer chains endow the ionogel with excellent self-healing properties. As shown in Fig. 1(d), the crack on the ionogel disappeared and the healed ionogel could hold a weight of 2 kg after storage at room temperature (RT) for 36 h. Notably, this structure also provided the ionogel good mechanical properties (*e.g.*, tensile strength of about 5.6 MPa, elongation of about 3200% strain).

Additionally, hydrogen bonds within the gel matrix can be designed into multilevel structures to enhance the self-healing capability. Inspired by the hierarchical structure of spider silk, ionogels with weak and strong hydrogen bonds have

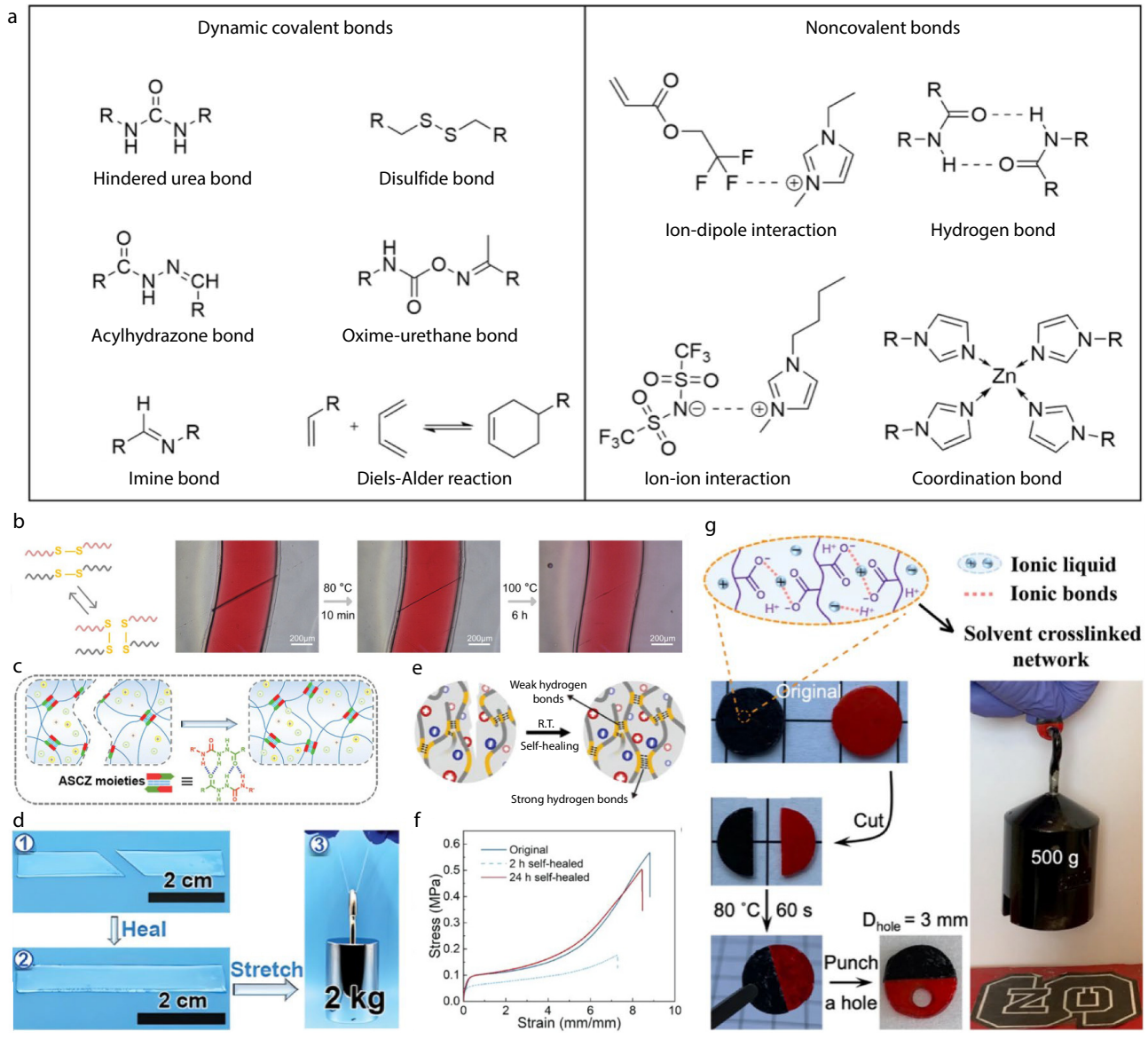


Fig. 1 Self-healing ionogels. (a) Chemical structures of typical dynamic covalent bonds and noncovalent bonds used for self-healing; (b) Schematics illustrating the dynamic exchange of disulfide bonds (left) and self-healing images under different conditions (right) (Reproduced with permission from Ref. [37]; Copyright (2024), Wiley); (c) Self-healing mechanism is achieved by hydrogen bonds (Reproduced with permission from Ref. [40]; Copyright (2023), Wiley); (d) Images of the self-healing process and the healed ionogel can hold a weight of 2 kg (Reproduced with permission from Ref. [40]; Copyright (2023), Wiley); (e) Self-healing ionogel is realized through multilevel (*i.e.*, strong and weak) hydrogen bonds (Reproduced with permission from Ref. [41]; Copyright (2024), Wiley); (f) Tensile stress-strain curves of ionogels at different healing times (Reproduced with permission from Ref. [41]; Copyright (2024), Wiley); (g) Solvent-crosslinking based on ion-dipole interactions enables self-healing functionality (Reproduced with permission from Ref. [20]; Copyright (2024), Springer Nature).

been developed (Fig. 1e).[41] The synergistic effect of the weak and strong hydrogen bonds endows this ionogel with good stretchability (*e.g.*, about 900% strain) and self-healing performance (*e.g.*, tensile strength recovered by 90% after 24 h) (Fig. 1f). In addition to hydrogen bonds, electrostatic or coordination interactions (*e.g.*, imidazole-zinc (Zn) ion coordination) can also enable self-healing.[32,35] A typical example is that, by enhancing the polarity of the polymer chains, abundant electrostatic interactions (*e.g.*, ion-dipole or dipole-dipole interactions) can form *in situ* within the gel matrix (Fig. 1g).[20] This resulted in ultra-trough ionogels with excellent self-healing properties. The ionogel can heal in 60 s at 80 °C and can withstand a weight of 500 g (Fig. 1g).[20]

Importantly, by integrating different dynamic bonding mechanisms, synergistic dynamic networks can be constructed to achieve multifunctionality.[42,45,46] For example, ionogels with multiple functionalities (*e.g.*, self-healing, recyclability, and adhesion) can be achieved by combining hydrogen bonds and ion-dipole interactions.[45] Similarly, through the synergistic effect of dynamic lithium (Li)-ether oxygen coordination and hydrogen bonds, ionogels can be developed that not only possess excellent mechanical properties but also ex-

Table 1 Self-healing efficiency and mechanical strength of ionogels with different self-healing mechanisms.

Crosslinking method	Self-healing mechanism	Self-healing condition	Self-healing efficiency (%)	Mechanical strength (MPa)[d]	Ref.
Dynamic covalent bonds	Disulfide bonds	80 °C; 6 h	about 90 [a]	about 1.6	[37]
	Disulfide bonds	80 °C; 6 h (UV; 10 min)	about 96 (>99) [a]	about 0.28	[38]
	Acylhydrazone bonds	60 °C; 12 h	>95 [a]	about 0.048	[39]
	Oxime-urethane bonds	70 °C; 24 h	70 [a]	about 2.5	[43]
Noncovalent bonds	Hydrogen bonds	RT; 6 h	99.2 [a]	about 0.025	[29]
	Hydrogen bonds	RT; 36 h	>99 [a]	5.59	[40]
	Hydrogen bonds	RT; 24 h	>90 [a]	0.51	[41]
	Electrostatic interactions	RT; 1 h	about 82 [b]	about 1.4	[32]
	Coordination bonds	RT; 12 h	about 83 [b]	about 1.2	[34]
	Coordination bonds	RT; 1.5 h	98 [b]	0.58	[35]
	Hydrogen bonds, Electrostatic interactions	20 °C; 24 h (30 °C; 12 h)	>99 [c]	about 0.52	[42]

[a, b, c] Self-healing efficiency was calculated based on the fracture strength, fracture strain, and toughness. [d] Mechanical strength of self-healing samples.

hibit remarkable self-healing capabilities (cracks disappear within 3 h at RT).[46] This strategy allows us to better balance the trade-off between the mechanical properties and self-healing performance. Therefore, the synergistic effect of multiple reversible interactions has become one of the most promising and effective strategies for designing high-performance self-healing ionogels.

2.2 Shape Memory

Shape memory properties typically refer to a material's ability to be fixed in a temporary shape and then recover its permanent shape under external stimuli.[47] Currently, most ionogels are thermally induced unidirectional dual-shape memory materials.[48–50] That is, shape recovery is primarily triggered by thermal stimulation and is essentially irreversible, involving a two-state transition between the metastable temporary shape and the original permanent shape.[51] There are three main strategies for achieving ionogels with shape-memory properties: (i) double-network (DN) structure, (ii) reversible crystallization-melting structure (*e.g.*, crystalline domains), and (iii) phase separation.[6,52–57] Note that shape memory properties in ionogels can also be triggered by humidity through introducing hygroscopic amphoteric monomers.[58] We elucidate these strategies using typical examples in the following discussion.

A typical structure for achieving shape memory in ionogels is a DN structure consisting of a dynamic network and permanent network.[52] The dynamic network fixes the temporary shape through physical crosslinking, whereas the permanent network is covalently crosslinked (although in some cases, physical interactions may also play a role) and generally provides the driving force for recovering the original shape.[52,53] For example, a DN ionogel can be programmed under heating and cooling to form temporary structures by breaking and reforming hydrogen bonds in the dynamic network, whereas the permanent network drives the polymer chains to recover to their original state upon reheating, thus restoring the original shape (Fig. 2a).[53]

Shape memory can also be achieved through a mechanism mediated by glass transition.[54–56] In a typical example, a tough and covalently crosslinked ionogel composed of a solvent-rich phase and polymer-rich phase was fabricated by a simple one-step polymerization.[6] The polymer-rich phase exhibits a glass transition temperature (T_g) of 48.2 °C, while the solvent-rich phase has a T_g of –42.6 °C. When the temperature is elevated (*e.g.*, above the T_g of the polymer-rich phase, 80 °C), the polymer-rich phase softens to reconstruct the polymer network and maintain its structure after cooling. Upon reheating, the covalently crosslinked network drives the polymer chains back to their original state (Fig. 2b). Glassy ionogels with excellent shape-memory properties were realized through a similar mechanism.[20] Besides mechanisms based on glass transition, shape memory can also be realized through reversible crystallization-melting transition. For instance, poly(ionic liquid) ionogels incorporating rigid crystalline domains have been reported to exhibit a good shape-memory behavior.[57] Similarly, a semicrystalline polymer (poly-ε-caprolactone (PCL)) has been used to impart shape memory to ionogels by melting and reforming PCL crystallization.[48]

More importantly, ionogels can be designed to possess dual programmability and multiple shape-memory functions. For instance, hygroscopic amphoteric monomers have been used to prepare ionogels containing hydrogen bonds and electrostatic interactions, which can be triggered by two different mechanisms (*i.e.*, temperature and humidity).[58] In addition to temperature-induced shape programming, these reversible interactions can also be reversibly broken and reformed through water absorption and dehydration, thereby achieving shape memory functionality. As shown in Fig. 2(c), after heating, the ionogel could be programmed into a "9" shape and then reconfigured into a second temporary "U" shape. This "U" shape can also be achieved by dehydrating the swollen ionogel, which can be further shaped into an "S" shape by heating. Note that the "S" shape can revert back to the "U" shape upon reheating.

Another typical example of shape memory is the combination of attapulgite (ATP) nanorods with a chemically crosslinked network to obtain anisotropic ionogels.[59] The strain induced microphase separation and orientation of the ATP nanorods in the ionogel, thereby altering the T_g of the deformed region and enabling dual-programmable (*i.e.*, at two different temperatures) shape-memory functionality (Fig. 2d). The ionogel can be programmed into "temporary shape#1" by heating it to a temperature (*e.g.*, 60 °C) above its initial T_{g1} (Fig. 2e). Stretching the ionogel changed the T_g of its

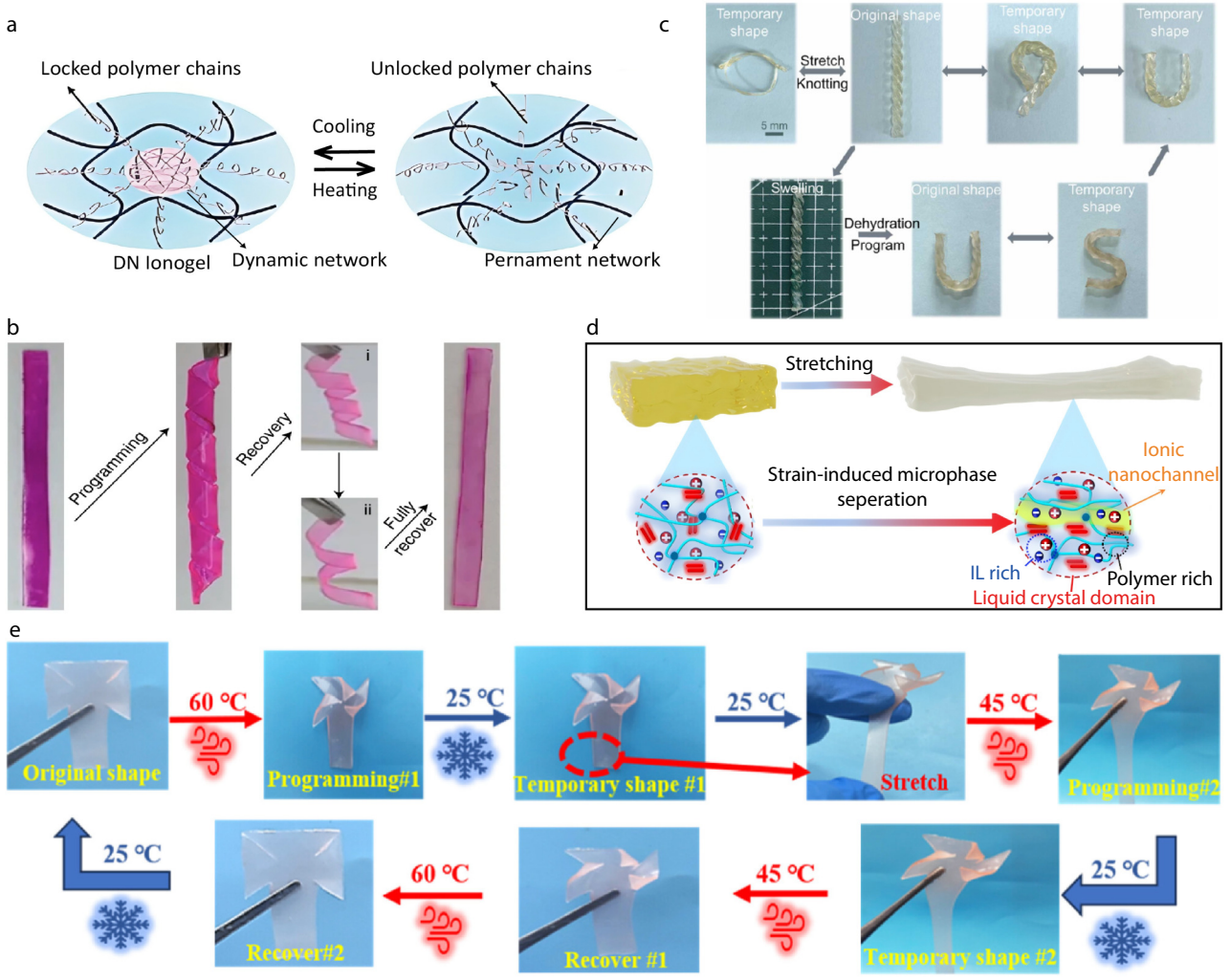


Fig. 2 Shape memory ionogels. (a) Schematics illustrating the shape memory mechanism of DN ionogels (Reproduced with permission from Ref. [53]; Copyright (2024), Wiley); (b) Shape memory behavior of phase-separated ionogels induced by heating (Reproduced with permission from Ref. [6]; Copyright (2022), Springer Nature); (c) Dual-programmable shape memory ionogels triggered by temperature and humidity (Reproduced with permission from Ref. [58]; Copyright (2024), Elsevier); (d) Strain-induced microphase separation in ionogels (Reproduced with permission from Ref. [59]; Copyright (2024), American Chemical Society); (e) Multiple programmable shape memory ionogels governed by different temperatures (Reproduced with permission from Ref. [59]; Copyright (2024), American Chemical Society).

loaded region from T_{g1} to T_{g2}, enabling "temporary shape #2" to be programmed by heating it to a temperature above T_{g2} (*e.g.*, 45 °C). These programmed shapes can be gradually recovered to their original shapes by reheating them at the corresponding temperatures.

2.3 Stimuli-responsive Properties

The stimuli-responsive behavior of the ionogels allows them to dynamically respond to changes in the external environment, including temperature, light, deformation, and magnetic fields. Stimulus-responsive ionogels can be prepared using the following strategies. First, polymers with inherent responsiveness to the ionogels were introduced. For example, as shown in Fig. 3(a), thermosensitive polymers can be used to prepare ionogels with thermoresponsive behaviors.[40] Second, the conductive properties of the ILs within the ionogel provide a basis for the response mechanism.[60–71] Third, incorpating exogenous functional molecules (*e.g.*, photochromic molecules, magnetic nanocrystals) as responsive units can endow ionogels with stimuli-responsive properties (such as photoresponse, magnetic response).[72–81] Finally, the design and introduction of functional groups that can specifically recognize chemical substances in the ionogel can achieve selective responses to target chemical stimuli (*e.g.*, CO_2).[82] This property greatly expands the application scope of ionogels, particularly in sensitive and intelligent devices.

2.3.1 Thermal response

Thermoresponsive behavior is one of the most widely studied properties of ionogels, primarily because the temperature is an easily controllable and convenient external stimulus. The thermoresponsive mechanisms of ionogels can be divided into two categories: polymer- and IL-driven.[40,45,60–63] Polymer-driven thermoresponsiveness is mainly related to the critical solution temperature of polymers in ionogels. For example, poly(urethane-urea) (PU) exhibits lowest critical solution temperature (LCST)

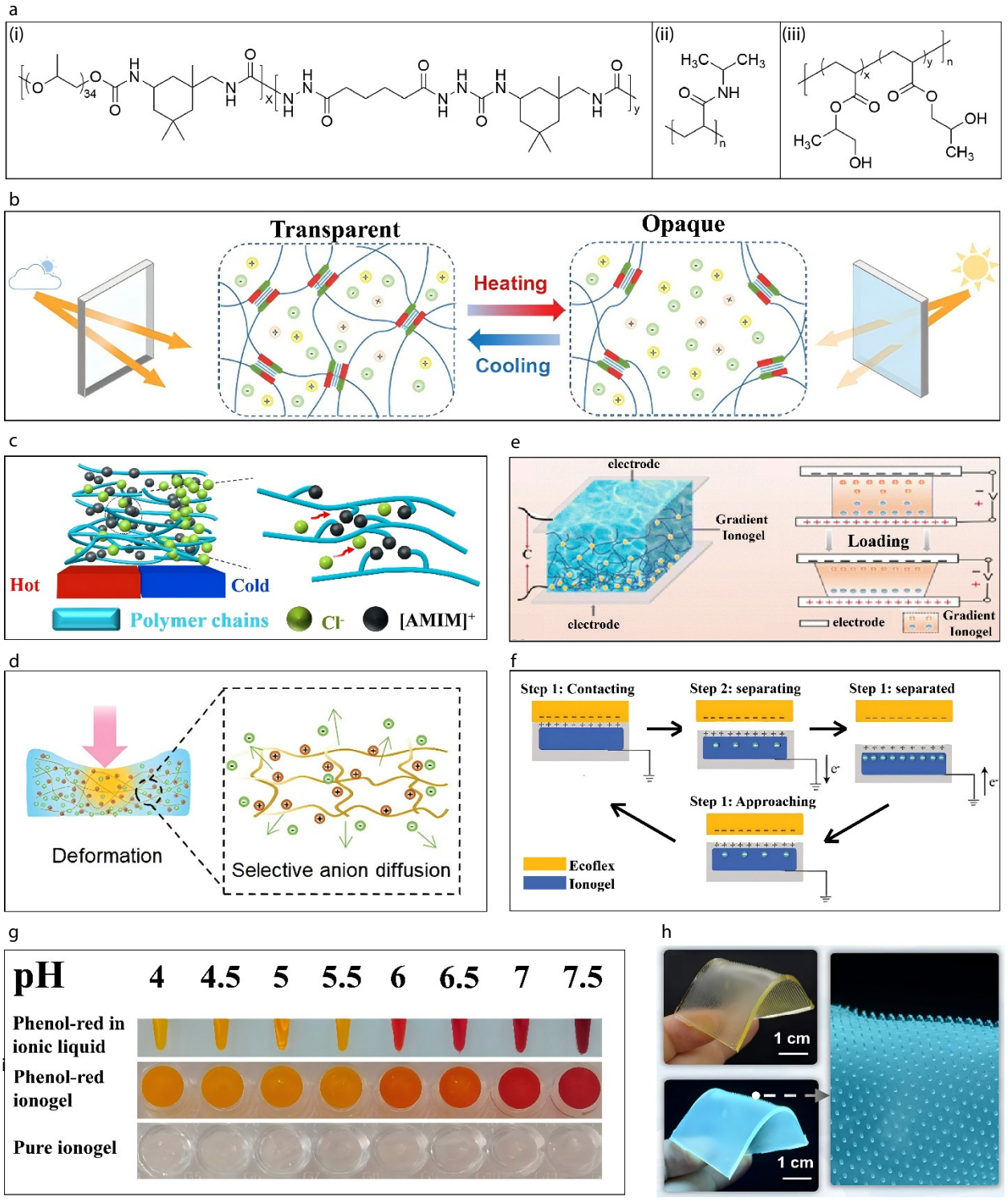


Fig. 3 Stimuli responsive ionogels. (a) Chemical structures of thermosensitive polymers: (i) poly(urethaneurea), (ii) poly(*N*-isopropyl acrylamide), (iii) poly(2-hydroxypropyl acrylate); (b) LCST behavior endows ionogels with thermoresponsiveness (Reproduced with permission from Ref. [40]; Copyright (2023), Wiley); (c) Thermoelectric response ionogels based on differences in ion mobility (Reproduced with permission from Ref. [63]; Copyright (2025), Wiley); (d) Piezoionic ionogels is achieved by mechanical stimuli (Reproduced with permission from Ref. [62]; Copyright (2024), Wiley); (e) Ionogels exhibit capacitive response by automatically forming EDL at the interface with electrodes (Reproduced with permission from Ref. [66]; Copyright (2024), The Royal Society of Chemistry); (f) Ionogels have triboelectric effect due to their charged nature (Reproduced with permission from Ref. [67]; Copyright (2025), Wiley); (g) Phenol red is introduced into ionogels to enable pH response (Reproduced with permission from Ref. [86]; Copyright (2022), American Chemical Society); (h) Images of pH-triggered fluorescent ionogel under 365 nm UV light (pH=7.4) (Reproduced with permission from Ref. [89]; Copyright (2026) Wiley).

behavior in a mixture of two ILs.[40] At temperatures below the LCST, PU and ILs are completely miscible, yet phase separation occurs when the temperature exceeds the LCST, thus achieving thermoresponsiveness (Fig. 3b). Notably, the LCST could be easily adjusted by varying the composition ratio of the two ILs. Conversely, thermoresponsive behavior can also be triggered by the upper critical solution temperature (UCST) of the polymers in the ionogels.[64] The polymers are insoluble in the ionogel at temperatures below the UCST, whereas at temperatures above the UCST, the polymers become highly solvated.

The freely moving cations and anions in the ILs endow the ionogels with inherent ionic conductivity. The temperature dependence of this conductivity is another important mechanism that contributes to the thermoresponsiveness of ionogels. Specifically, as the temperature increased, the dissociation and migration rates of ions in the ILs increased, thereby improving the ionic conductivity.[45] Note that elevating the temperature may loosen physically crosslinked networks, which will benefit conductivity by reducing the resistance to ion migration. Beyond simple conductivity changes, ionogels can impart thermoelectric properties by leveraging the thermodiffusion (Soret) effect. That is, when a temperature gradient is applied to the ionogel, the ions migrate directionally from the high-temperature region to the low-temperature region. Because of the different interaction strengths between the cations or anions and the polymer networks, the migration rates of the ions differ, leading to an uneven distribution of ions, thus generating an electric potential.[63,65] For instance, the cation in 1-allyl-3-methylimidazolium chloride ([AMIM]Cl) IL can be effectively anchored by polymer networks *via* interactions, while Cl^- ions can move relatively freely (Fig. 3c). This yielded an n-type thermoelectric-responsive ionogel.[63] In addition, additives such as graphene oxide (GO) can be introduced to enhance the thermoelectric properties of ionogels by improving conductivity (*e.g.*, 2.2 $mS{\cdot}cm^{-1}$ without GO and 5.9 $mS{\cdot}cm^{-1}$ with 0.22 wt% GO) and optimizing the ion concentration gradient.[65]

2.3.2 Mechanical response

The mechanical response of ionogels refers to their ability to generate an instantaneous electrical response to mechanical stimuli, allowing them to be used as sensing elements. Under reversible mechanical deformation, the network structure of ionogels (*e.g.*, polymer chain orientation and ion migration pathways) undergoes dynamic changes. These structural rearrangements directly lead to significant changes in physical properties such as resistance, thus converting mechanical stimuli into quantifiable electrical signals.

The mechanical responsiveness of the ionogels is mainly attributed to four different mechanisms. The first mechanism is the piezoresistive effect, which means that during stretching, the ion migration pathways within the ionogel elongate and contract, leading to an increase in the ion migration resistance and consequently an increase in the total resistance. This feature can be applied in ionogel-based wearable sensors.[45] The second type is the piezoionic effect, which is similar to the piezoelectric effect and is caused by the asymmetry of ion migration under external forces. For example, the mobility of bis(trifluoromethylsulfonyl)imide ([TFSI]) anion is typically higher than that of 1-ethyl-3-methylimidazolium ([EMI]) cation in [EMI][TFSI] IL (Fig. 3d). This difference in mobility leads to spatial charge separation, thus forming an internal electric field within the ionogel and ultimately generating a voltage between the two electrodes.[62] The third type of effect is the capacitive effect. As shown in Fig. 3(e), the flexibility of the ionogel allowed it to change the contact area with the electrodes under pressure, leading to a change in the interfacial double-layer capacitance. This mechanism enables ionogel-based capacitive sensors to achieve higher sensitivity, especially when integrated with gradient microstructures.[66] The fourth mechanism is triboelectric effect. When the ionogel comes into contact with another dielectric material under an external force, charge transfer occurs on the surface owing to the difference in electron affinity (Fig. 3f).[67,68] After separation, a potential difference is generated, driving electrons through the external circuit, thus producing an alternating electrical signal.[67] This triboelectric mechanism endows ionogels with self-powering capabilities (*e.g.*, nanogenerators) and makes them particularly sensitive to dynamic mechanical stimuli.[67–71]

In addition to electrical responses, ionogels exhibit optical responses when subjected to mechanical stimuli.[34,39,72] A typical example is the preparation of ionogel composites using aligned clusters of magnetic nanocrystals.[72] When this ionogel is stretched or compressed, the lattice spacing between nanocrystal clusters changes, leading to a shift in the reflected wavelength, thus providing intuitive qualitative feedback.

2.3.3 Photoresponse and electroresponse

Photoresponse refers to the ability of a material to absorb photon energy when subjected to external light stimuli (*e.g.*, UV or visible light), leading to changes in its physicochemical properties (*e.g.*, structure, electrical conductivity, or chemical activity). Photoresponsive ionogels can be realized by introducing photoresponsive molecules or ILs, particularly photothermal agents with high photothermal conversion capabilities such as carbon-based materials, metal nanoparticles, and organic molecules. This property not only gives ionogels great potential in solar energy utilization, but also enables them to use the photothermal effect as a trigger to activate other functions (*e.g.*, power generation), thereby achieving intelligent multi-field coupled responses including light, heat, and electricity.[73–75] For example, carbon black has been introduced into ionogels to construct a double-layered photothermal response system consisting of an upper light-absorbing heating layer and a lower thermoelectric conversion layer.[74] Upon illumination, this system can absorb light and convert it into thermal energy, generating a temperature gradient within the ionogel, which drives the directional migration of ions and ultimately achieves cascaded conversion from an optical signal to an electrical output.

In addition, introducing photochromic additives into the ionogels can endow them with photoresponsive properties. Specifically, the introduction of ammonium molybdate tetrahydrate into the ionogel can induce a color change under UV light.[76] This type of ionogel has great potential for application in information recording and optical storage.[76,77] Moreover, photoresponsive ionogels can also be achieved by introducing photoluminescent materials (*e.g.*, carbon dots and triphenylen-2-ylboronic acid), enabling the ionogels to

exhibit luminescent properties under light stimulation, which will be discussed in detail in Section 2.5.[78–81]

The electroresponsive behavior of the ionogel mainly originated from the ions in the IL solvents. When a voltage is applied to an ionogel sandwiched between two electrodes, its cations and anions migrate towards oppositely charged electrodes, accumulating at the gel-electrode interface and forming an electrical double layer (EDL). The strong electric field generated within the EDL induces local strain and stress in the ionogel, leading to deformations, such as bending, contraction, or expansion.[83] A specific example is an ionogel containing 1-allyl-3-methylimidazolium bis((trifluoromethyl) sulfonyl)imide IL (where the anion mobility is higher than the cation mobility), which can be deformed by asymmetric electrostatic attraction on both sides, even without direct contact between the ionogel and electrodes.[84] Electroresponsive ionogels can also function *via* electrochemical redox reactions. For instance, embedding phosphotungstic acid clusters into ionogels allows reversible redox reactions under external electrical stimulation, leading to a color change from transparent (oxidized state) to dark blue (reduced state).[85]

2.3.4 Chemical response

In addition to physical stimuli, ionogels can also respond to chemical stimuli such as pH and gases (*e.g.*, CO_2, NH_3).[82,86] For example, functional groups such as tertiary amines or imidazolium groups can react with gas molecules (*e.g.*, CO_2). These functional groups can be introduced into ionogels, thereby imparting stimulus-responsive properties, such as swelling or shrinking and changes in electrical conductivity. In addition, some monomers (*e.g.*, 2-(dimethyl amino) ethyl methacrylate) can be used to prepare ionogels that can absorb and react with gas.[87,88] This feature can be used for gas sensing and CO_2 capture.

Introducing ionizable weak acids (*e.g.*, phenolic hydroxyl groups) or weak bases (*e.g.*, amino groups) into ionogels can achieve pH responsiveness *via* a mechanism involving reversible protonation and deprotonation of these groups. For example, ionogels containing phenol red (a pH indicator) produce noticeable color changes at different pH values (Fig. 3g).[86] This is highly attractive for health monitoring applications, such as the use of pH-sensitive ionogels in artificial tongues to monitor salivary pH.[86] Similarly, pH-responsive ionogels have been fabricated into microneedles for diagnosing respiratory alkalosis.[89] At low pH values, intramolecular charge transfer occurred from the benzene ring to the imidazolium moiety, producing fluorescence emission (Fig. 3h). As the pH increased, the charge-transfer process was disrupted, leading to fluorescence quenching. Therefore, an increase in the pH of the exhaled breath condensate results in a significant decrease in fluorescence intensity, enabling sensitive diagnosis based on pH.

2.3.5 Magnetic response

Magnetic ionogels belong to a class of smart materials. They can be prepared mainly by doping with magnetic additives (*e.g.*, Fe_3O_4, cobalt, or nickel nanoparticles) or utilizing inherent magnetic ILs.[90–94] Among these, Fe_3O_4 nanoparticles are among the most commonly used materials for preparing magnetic ionogels.[90,91] Magnetic responsiveness enables ionogels to deform and achieve remote, contactless, and reversible manipulation under the influence of magnetic fields. For instance, magnetic ionogels prepared with Fe_3O_4 nanoparticles can bend under a magnetic field (Fig. 4a).[90]

In addition to the traditional strategy of incorporating magnetic additives into ionogels, magnetic ionic liquids (MILs) provide an alternative method to achieve magnetic responsiveness.[92–94] Notably, the use of MILs avoids common drawbacks associated with traditional strategy, such as reduced transparency and impaired mechanical properties.[94] For example, 1-ethyl-3-methylimidazolium tetrachloroferrate(III) MIL imparts intrinsic magnetism to the ionogel, and magnetization increases with increasing MIL content (Fig. 4b).[92] When exposed to a magnetic field, the ionogel experienced a net magnetic force, leading to controllable movement (Fig. 4c). This magnetic driving capability makes ionogels promising for a wide range of applications such as contactless sensing, soft robotics, and biomedicine.

2.4 Luminescence

Luminescent materials can convert external stimuli such as light, electricity, and mechanical force into optical signals, which have broad application prospects in optical sensing, visual monitoring, and flexible optoelectronic devices, *etc.*[79,95–100] Ionogels can have luminescence by incorporating luminescent additives (*e.g.*, zero-dimensional hybrid metal halides, carbon dots, triphenylen-2-ylboronic acid).[78,80,81] Generally, depending on the type of luminescent additive, there are three luminescence mechanisms: photoluminescence (fluorescence and phosphorescence), electroluminescence, and mechanoluminescence.[64,78,96,99,101,102] These mechanisms represent the optical response of ionogels to the corresponding external stimuli, with photoluminescence being the most widely studied mechanism.

Photoluminescent ionogels are mainly obtained through two strategies: (i) introducing exogenous photoluminescent materials and (ii) using polymers or ILs that inherently have photoluminescent properties.[78,79,96,99] Exogenous photoluminescent materials include metal complexes, organic luminophores, and inorganic nanomaterial.[78,80,81] Taking metal complexes as an example, photoluminescence can be achieved by *in situ* formation of metal halides within the ionogel.[78] Specifically, luminescence originates from the d-d electron transitions of the metal centers under excitation at a specific wavelength. This *in situ* strategy effectively mitigates light scattering and luminescence inhomogeneity, which commonly occur in traditional metal halide-polymer composites.[103–105] Importantly, as shown in Fig. 5(a), the emission color can be finely tuned by changing the metal ion (Pb, Mn, or Sb) and halide species (Cl or Br).

The use of inherently photoluminescent polymers or ILs is a more direct method for achieving luminescent ionogels.[79,99] For instance, polymers such as poly(acrylic acid-*co*-2,2,3,4,4,4-hexafluorobutyl acrylate) exhibit clusterization-triggered emissions.[79] Ionogels containing 1-ethyl-3-methylimidazolium acetate IL showed excitation-wavelength-dependent (ExDe) emission due to the aggregation of imidazolium cations caused by electrostatic interactions (Fig. 5b).[79] The synergistic effect of these two components enabled the ionogel to ex-

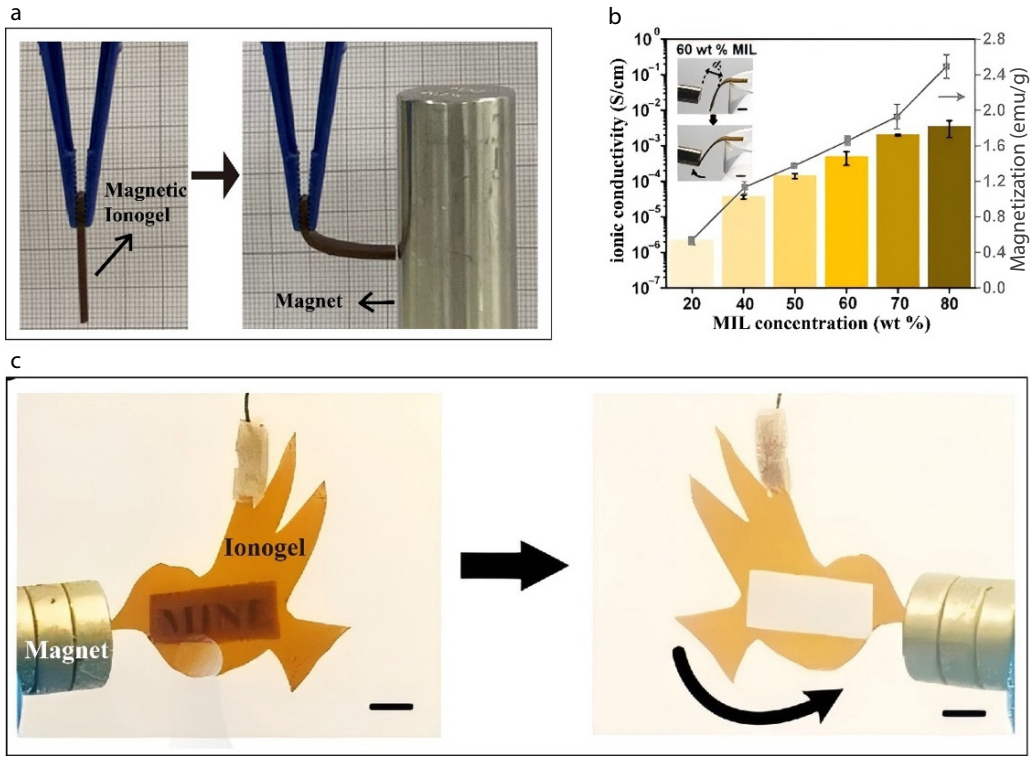


Fig. 4 Magnetic ionogels. (a) Magnetic response behavior is realized in ionogel by introducing Fe_3O_4 nanoparticles (Reproduced with permission from Ref. [90]; Copyright (2023), Elsevier); (b) The magnetization strength of ionogels can be enhanced by increasing the MIL content (Reproduced with permission from Ref. [92]; Copyright (2025), American Association for the Advancement of Science); (c) The movement of the magnetic ionogel can be easily controlled by the magnetic field (Reproduced with permission from Ref. [92]; Copyright (2025), American Association for the Advancement of Science).

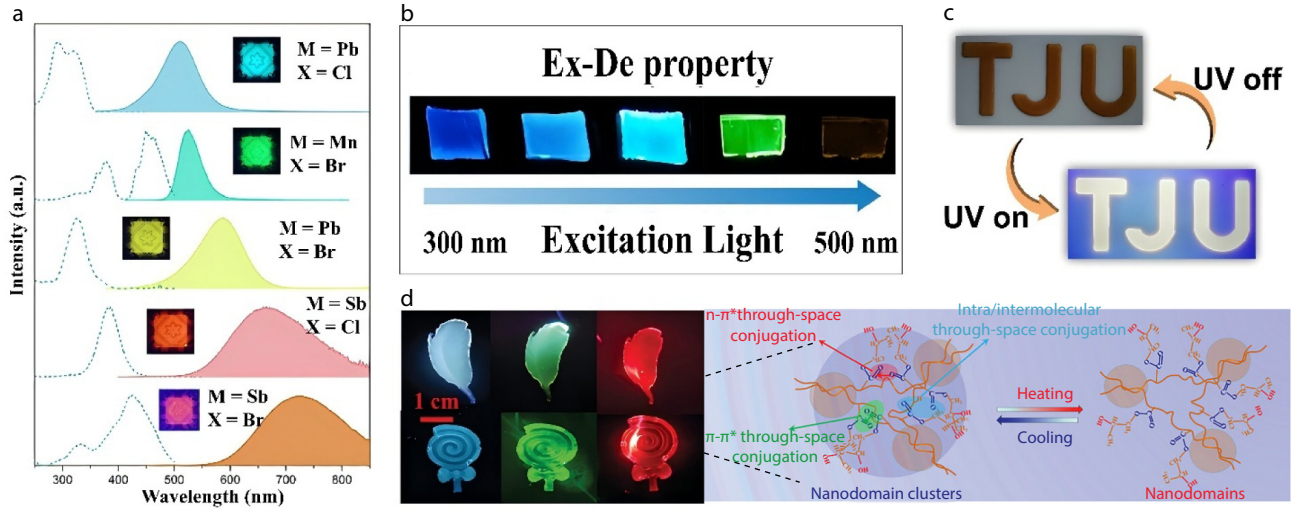


Fig. 5 Photoluminescent ionogels. (a) Photoluminescent ionogels with different emission colors are produced using different metal slats (Reproduced with permission from Ref. [78]; Copyright (2025), Wiley); (b) Photoluminescent ILs and polymers endow ionogels with Ex-De emission behavior (Reproduced with permission from Ref. [79]; Copyright (2025), Wiley); (c) Images of photoluminescent ionogels under UV light (Reproduced with permission from Ref. [99]; Copyright (2025), American Chemical Society); (d) Nanoscale phase separation enables multicolor fluorescence in ionogels by enhancing spatial n-π and π-π interactions (Reproduced with permission from Ref. [64]; Copyright (2024), Wiley).

hibit a broad range of Ex-De emission spectra. It is worth noting that the luminescent properties of the ionogels can be affected by external forces. Ionogels prepared using multi-arm crosslinkers with π-π conjugated structures showed photoluminescence intensity proportional to the applied stress (Fig. 5c).[99] This may be attributed to the decreased intermolecular distance during deformation, which enhances the π-π conjugation interaction and consequently increases the luminescence efficiency.

Interestingly, the photoluminescence in the ionogels may

also stem from their unique microstructures.[106] For example, photoluminescent ionogels are created by the *in situ* formation of nanoscale phase separation through the aggregation of solvophobic segments in polymer networks during polymerization.[64] Nanoscale phase-separated domains effectively confined non-conjugated subluminescent groups (*e.g.*, ester groups) within highly restricted spaces. This promotes the overlap of electron clouds in the domains, thereby enabling spatial n-π and π-π interactions, which in turn activates efficient multicolor fluorescence (Fig. 5d). The emission color can be easily controlled by changing the size of the phase-separated domains.

Photoluminescent lifetime is an important parameter in applications and is typically influenced by many factors, such as the excitation wavelength and mechanical properties of ionogels. For example, ionogels with ultralong phosphorescence lifetimes were obtained by increasing the stiffness of the ionogels.[81] This is because high stiffness effectively restricts the vibration and rotation of polymer chains in ionogels, which helps stabilize the triplet excitons, thereby significantly improving the phosphorescence intensity and lifetime. Electroluminescent ionogels can be achieved by adding electroluminescent additives (*e.g.*, such as tris(bipyridine)ruthenium(II)). These additives undergo redox reactions under external electric fields and generate high-energy unstable intermediates, which emit photons upon relaxation to the ground state.[102]

3 APPLICATIONS

In Section 2, we systematically discuss the design-enabled functionalities of ionogels that endow them with various performance advantages. This section focuses on applications enabled by these functionalities and the resulting performance improvements.

3.1 Wearable Sensors

The intrinsic (*e.g.*, ionic conductivity and nonvolatility) and additional properties (*e.g.*, self-healing and adhesion) of ionogels make them attractive for use as electrolytes in batteries, biomedicine, and wearable sensors.[106,107] In particular, wearable sensors have been widely used for health monitoring, including human motion detection and physiological signal monitoring.[108]

3.1.1 Human motion detection

Ionogels have demonstrated broad application prospects in human motion detection.[66,109,110] For example, biodegradable ionogels have been used as wearable sensors to monitor joint angles during robot-assisted rehabilitation training (Fig. 6a).[48] Note that biodegradability effectively moderates the concerns about electronic waste pollution. The ionogel also possesses shape-memory properties, allowing it to better conform to uneven surfaces, thus enabling shape adaptability. In addition, 3D printing technology can be used to fabricate precisely structured wearable sensors to monitor finger gestures (Fig. 6b).[111] Importantly, ionogels can be designed to be hydrophobic and can be used underwater. For instance, hydrophobic ionogels are used as sensors and exhibit long-term stable performance in motion monitoring, particularly in harsh marine environments (Fig. 6c).[112] In another related study, inspired by marine organisms, hydrophobic ionogels with bionic structures were developed and used as sensors to accurately record human underwater motions, such as subtle facial expressions and large-scale limb movements.[113]

3.1.2 Physiological signal monitoring

Ionogels with self-healing properties can stabilize their performance in various applications because they can automatically repair damage. A typical example is the use of self-healing and biocompatible ionogels as epidermal electrodes; they exhibit a signal-to-noise ratio 2.5 times higher than that of a commercial Ag/AgCl electrode in electrocardiogram (ECG) recording and 1.6 times higher in electromyogram (EMG) signal recording (Fig. 6d).[114] In addition, this ionogel can accelerate wound healing, enabling the integration of diagnostic and therapeutic functionalities. Similarly, ionogels with piezoelectric and pH-responsive properties have been used as wearable sensors for the real-time monitoring of pulses during various human activities (*e.g.*, rest, walking, and running) and the pH value of human sweat, respectively (Figs. 6e and 6f).[115,116] These studies highlight the progress of ionogels in applications for human motion detection and physiological signal monitoring. With continuous advancements in material design, device integration, and manufacturing technologies, ionogels are expected to play an increasingly important role in personalized healthcare, intelligent rehabilitation systems, and remote health-monitoring technologies.

3.2 Energy Storage Devices

The development of green and efficient renewable energy storage technologies is crucial for addressing global energy and environmental challenges.[117] Ionogels have emerged as highly attractive solid-state electrolyte materials for batteries because of their excellent properties (*e.g.*, ionic conductivity, high stability, and self-healing).[118] In particular, ionogels with good mechanical properties significantly mitigate the limitations of traditional liquid electrolytes (*e.g.*, leakage and flammability) and solid-state electrolytes (*e.g.*, brittleness).[13] Therefore, ionogels are emerging as ideal materials for high-performance, safe, and reliable energy-storage systems.[2]

3.2.1 Li-ion batteries

Enhancing the electrochemical stability and ion transport rate can yield Li-ion batteries with a high energy density.[119,120] For instance, an ionogel electrolyte with a layered heterogeneous structure has been designed, which can effectively adapt to the extreme operating potentials of the battery (Fig. 7a).[121] This provides a new strategy for developing solid-state Li-ion batteries with a high-voltage window. In addition, Li^+ ion transport can be improved by regulating the local Li^+ microenvironment in the ionogel electrolyte (Fig. 7b). This process shifts the primary transport mechanism from the traditional "carrier transport" mode to a faster "structural transport" mode. As a result, the battery exhibited significantly enhanced rate performance over a wide temperature range of 0–90 °C.[122] Moreover, tough ionogels exhibit better performance when they possess high ionic conductivity and high Li^+ ion transference number.[123]

3.2.2 Fuel cells

One major challenge facing fuel-cell technology is achieving stable operation at high temperatures without external humidification.[124] Proton-conducting ionogels have been proposed to

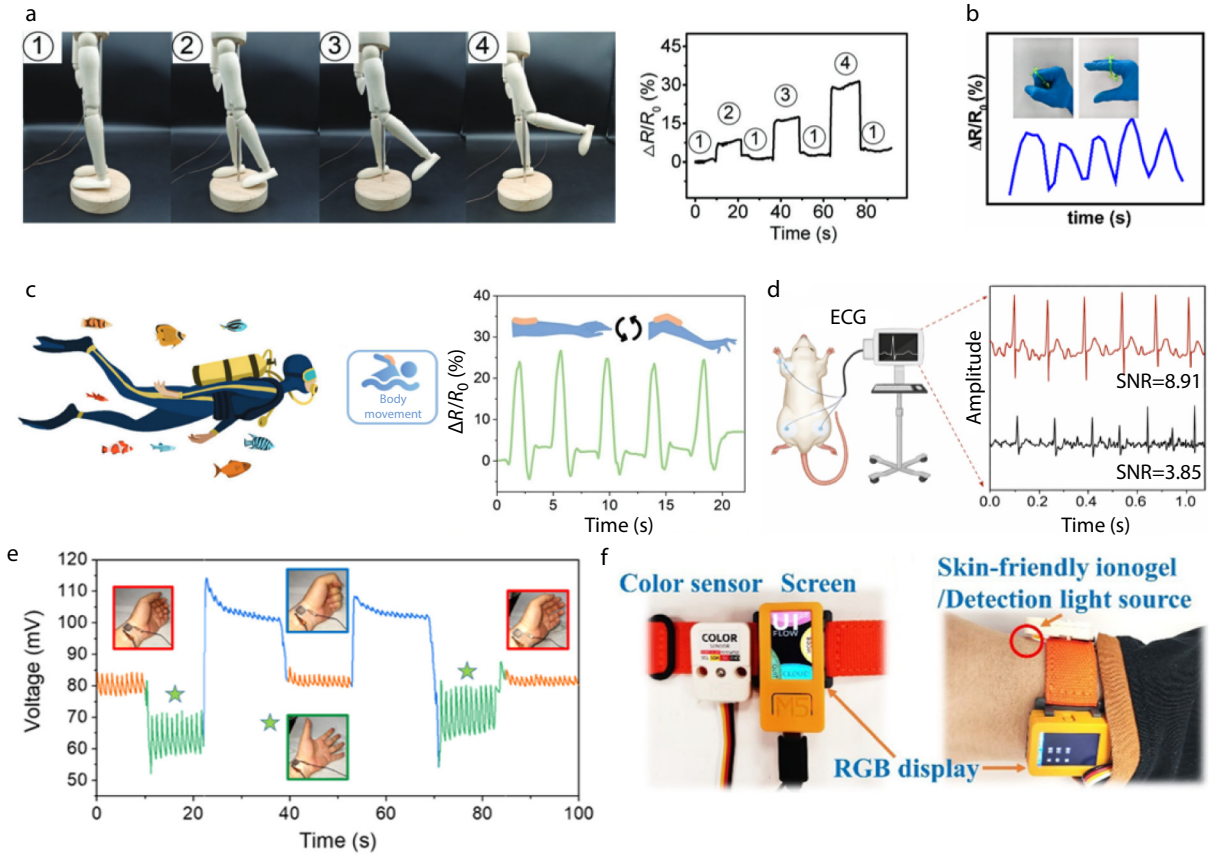


Fig. 6 Applications of ionogels in wearable sensors. (a) Wearable sensors are used to monitor knee joint motions (Reproduced with permission from Ref. [48]; Copyright (2023), Wiley); (b) 3D-printed wearable sensors record finger gestures (Reproduced with permission from Ref. [111]; Copyright (2025), American Chemical Society); (c) Hydrophobic ionogels are applied to detect underwater human motion (Reproduced with permission from Ref. [112]; Copyright (2024), Wiley); (d) Self-healing ionogels are used as epidermal electrodes to monitor ECG signals (Reproduced with permission from Ref. [114]; Copyright (2025), Elsevier); (e) Piezoelectric ionogel is integrated into wearable sensors to monitor pulse (Reproduced with permission from Ref. [115]; Copyright (2021), American Chemical Society); (f) pH-responsive ionogel is used to record the pH value of human sweat (Reproduced with permission from Ref. [116]; Copyright (2025), The Royal Society of Chemistry).

address this problem by poly(merizing vinyl) monomers in protic ILs (Fig. 7c).[125] The resulting ionogels exhibited a high proton conductivity of 17.1 mS·cm^{-1} under anhydrous conditions at 120 °C and were successfully applied in H_2/O_2 fuel cells. In addition, the battery was responsive to temperature and humidity. By adjusting the temperature and optimizing the humidification conditions, the water content of the membrane, proton transport efficiency, and reaction kinetics could be controlled, thereby achieving precise control over the power density and operational stability of the batteries. A maximum power density of 0.45 W·cm^{-2} was achieved when the temperature on both sides was 60 °C and a relative humidity of 100%. This work provides an effective strategy for developing high-temperature proton-conducting electrolytes for fuel-cell systems.

3.2.3 Zn-based batteries

Although Zn-based batteries are favored owing to their inherent low cost, Zn dendrite growth and parasitic side reactions (*e.g.*, hydrogen evolution reaction (HER)) severely hinder their practical application.[126,127] To address these issues, an ionogel electrolyte was developed with a gradient water distribution that effectively regulates Zn^{2+} ion transport and interfacial reactions.[128] Consequently, this design provided Zn-based batteries with good cycling stability (for example, over 7000 h at 0.2 mA·cm^{-2}). To further improve the Zn-based batteries, ionogel electrolytes are designed with self-healing property to stabilize device performance, in addition to high ionic conductivity (*e.g.*, 23.5 mS·cm^{-1} at 25 °C and 4.1 mS·cm^{-1} at –40 °C) (Fig. 7d).[129] These functionalities enable the stable operation of the battery from –20 °C to 40 °C.

3.2.4 Supercapacitors

High ionic conductivity and excellent mechanical properties are crucial for supercapacitors because they enable rapid ion transport to boost power density, ensure structural stability, and extend lifetime.[132,133] By introducing conductive nanofillers, such as two-dimensional MXene, the mechanical performance and ionic conductivity of ionogels can be improved (Fig. 7e).[130] The fabricated supercapacitors can operate stably for over 1×10^4 charge-discharge cycles within a wide operating temperature range of –20 to 90 °C. In addition to their excellent mechanical properties, ionogel electrolytes can be designed using biocompatible polymers (*e.g.*, hydroxyethyl cellulose) to achieve biocompatibility (Fig. 7f).[131] This is crucial for establishing sustainable and environmentally friendly supercapacitor systems. Thus, through rational material selection and precise structural de-

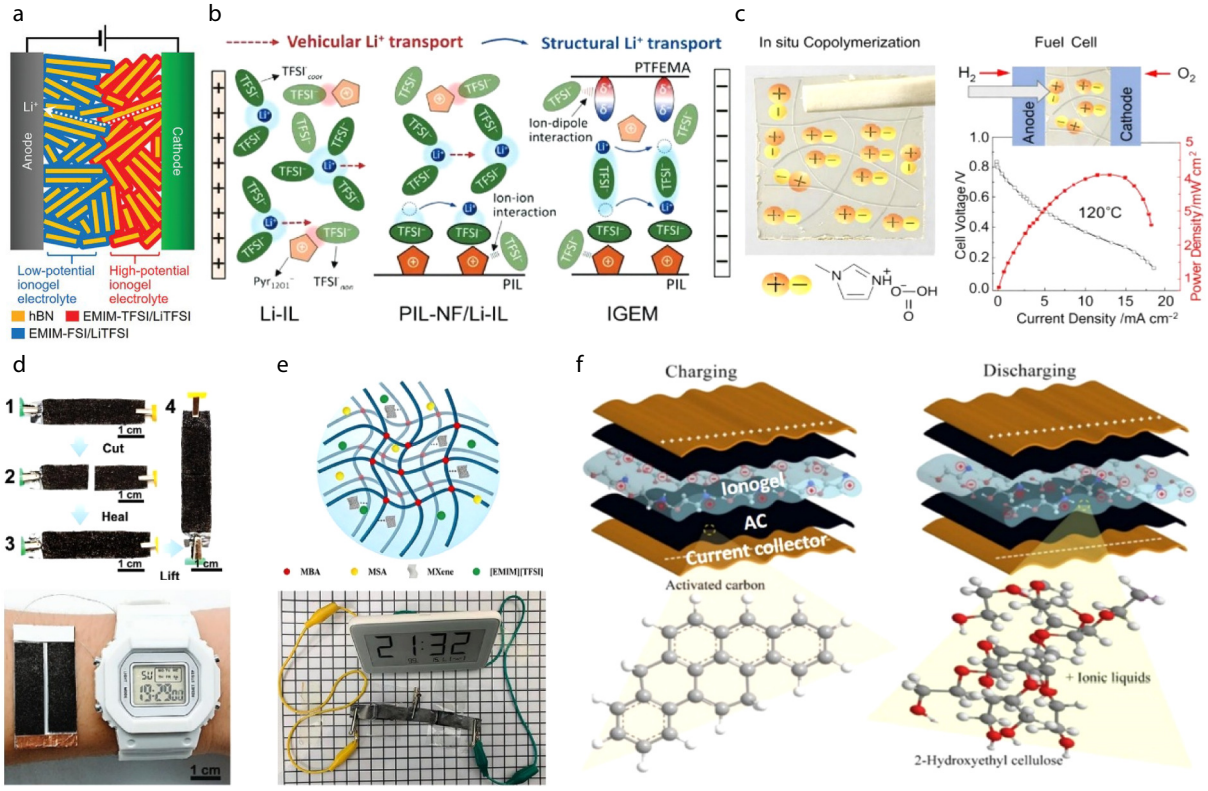


Fig. 7 Applications of ionogels in energy storage devices. (a) Ionogel-based electrolytes for Li-ion batteries (Reproduced with permission from Ref. [121]; Copyright (2021), Wiley); (b) Schematics showing the working mechanism of ionogels with high Li-ion transport performance (Reproduced with permission from Ref. [122]; Copyright (2022), Wiley); (c) Ionogel electrolytes for fuel cells and their performance at 120 °C (Reproduced with permission from Ref. [125]; Copyright (2021), American Chemical Society); (d) Self-healing ionogels are used as electrolytes for Zn-ion batteries (Reproduced with permission from Ref. [129]; Copyright (2024), Wiley); (e) MXene-doped ionogels are designed before use as electrolytes in supercapacitors (Reproduced with permission from Ref. [130]; Copyright (2023), MDPI); (f) Biocompatible ionogels are developed to enable sustainable and environmentally friendly supercapacitor systems (Reproduced with permission from Ref. [131]; Copyright (2025), Elsevier).

sign, high-performance multifunctional ionogel-based electrolytes can be created, accelerating the development of advanced energy storage systems with enhanced safety and reliability.

3.3 Electrochromic Devices

Electrochromic behavior originates from a voltage-induced reversible redox process, which is accompanied by ion-electron coupling, thereby altering the electronic structure and light absorption capability of the material. Electrochromic properties are promising for electrochromic devices, such as smart displays, optical devices, and smart windows.[134–136] By introducing electrochromic additives (*e.g.*, biphenyl polyviologen and viologen derivatives), ionogels can be endowed with electrochromic performance.[137] For example, the addition of biphenyl polyviologen to an ionogel can produce an electrochromic ionogel with reversible three-state color switching, exhibiting orange, green, and purple colors at 0, −1.4, and −1.9 V, respectively (Fig. 8a).[137] In addition, these ionogels can be effectively patterned into electrochromic displays using the electrostatic force-assisted dispensing printing technology.[137]

Importantly, electrochromic ionogels can also be prepared by curing electrochromic IL monomers (*e.g.*, 1-butyl-3-vinylimidazolium bis(trifluoromethylsulfonyl)imide).[138,139] It should be noted that this type of ionogel does not directly exhibit electrochromic properties; instead, it achieves electrochromic performance by providing mobile ions, ensuring charge balance, and supporting reversible redox reactions of the electrochromic material. These electrochromic ionogels have been used in curved goggles to protect the eye (Fig. 8b).[138] Similarly, a π-conjugated ionogel with a nanoporous sponge structure was applied to light-emitting electrochemical cells, which significantly reduced the turn-on voltage of the cells to 4 V (typically ≥6 V).[141] In addition, electrochromic ionogels can be designed to possess self-healing functionality, which can provide more reliable and stable performance for electrochromic applications (*e.g.*, maintaining a stable performance after 1000 bending cycles) (Fig. 8c).[139]. Furthermore, an electrochromic ionogel with high elongation (*e.g.*, about 1664% strain) was demonstrated for the fabrication of stretchable electrochromic devices, and it remained stable even under 50% strain (Fig. 8d).[140]

3.4 Biomedicine

Ionogels can be made biocompatible by using biocompatible ILs (*e.g.*, choline chloride) and polymers (*e.g.*, cellulose and alginate).[142,143] In a typical example, biocompatible ionogels with good tissue adhesion were prepared using a deep eutectic solvent (DES) and acrylic acid (AA) monomer or hydroxyethyl cellulose (HEC) polymer (Fig. 9a, upper).[144] In hemostasis tests, these ionogels obviously shortened the clotting time by activating coagulation factors, in addition to exhibiting good antibacterial

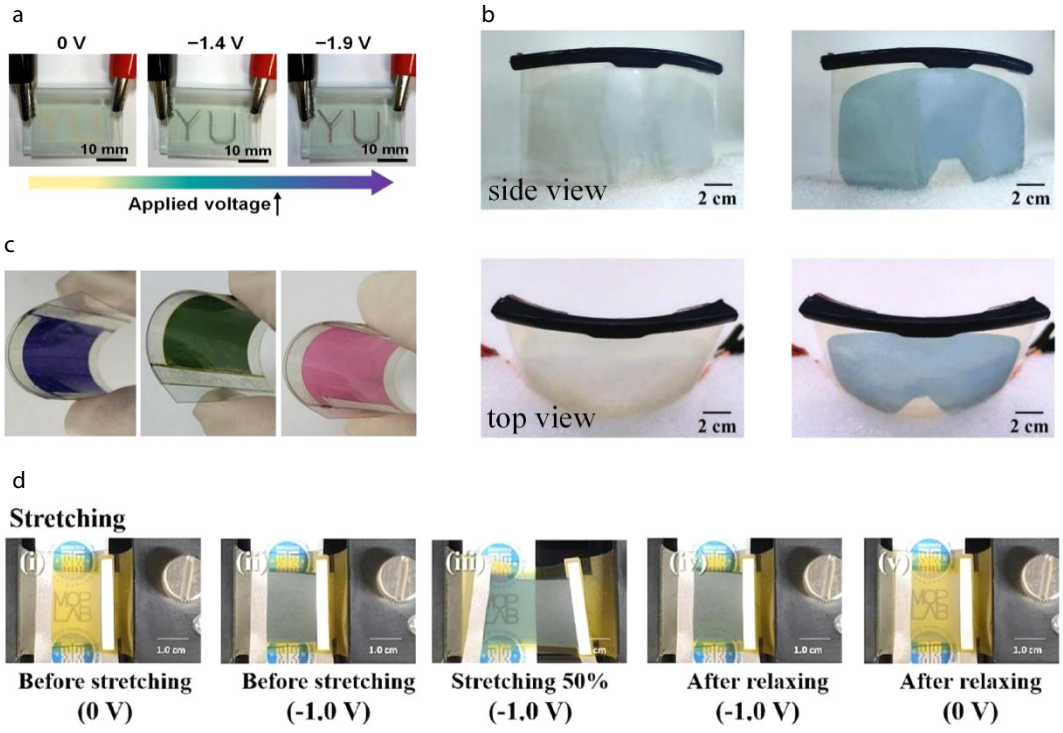


Fig. 8 Applications of ionogels in electrochromic devices. (a) Electrochromic ionogels exhibit different colors under different voltages (Reproduced with permission from Ref. [137]; Copyright (2022), Elsevier); (b) Ionogels are used in flexible electrochromic eye protection devices (Reproduced with permission from Ref. [138]; Copyright (2022), Wiley); (c) Self-healing ionogels enable flexible electrochromic devices to be bent 1000 times (Reproduced with permission from Ref. [139]; Copyright (2025), The Royal Society of Chemistry); (d) Highly stretchable ionogel allows the electrochromic device to function normally even under 50% strain (Reproduced with permission from Ref. [140]; Copyright (2023), Elsevier).

activity (Fig. 9a, lower). Similarly, ionogels prepared using bacterial cellulose and choline-amino acid-based poly(ionic liquids) showed efficient antibacterial properties while maintaining good biocompatibility.[145] These results indicate that this antibacterial and biocompatible ionogel provides a solution to the issue of antimicrobial resistance (Fig. 9b).[145] Furthermore, MXene-toughened ionogels containing phenol red as a pH indicator have been proposed and used as artificial tongues (Fig. 9c).[86] This artificial tongue exhibits excellent water retention, mechanical strength, and antibacterial stability in simulated saliva tests, offering a convenient and reliable platform for the early screening of diseases, such as gastric ulcers. Therefore, ionogels have great potential in biomedical applications through material innovation.

3.5 Other Applications

Because of their diverse physicochemical properties and additional functionalities, ionogels have found many applications beyond the aforementioned fields, including their use as coatings, protective materials, and encapsulation materials. This section focuses on the application of ionogels in emerging and promising areas.

3.5.1 Sunscreen coatings

Blocking ultraviolet B (UVB) radiation is crucial because high-energy ultraviolet rays can cause skin damage, premature aging, eye damage, and material degradation. Therefore, UV-protective coatings are essential for human health and lifespan. The potential of ionogels in this area has been explored because of their high compatibility with processing and patterning technologies (such as 3D printing and spring coating). For example, a polyurethane-based ionogel has been developed as a sunscreen coating that can completely block UVB radiation while maintaining a transmittance of over 80% with a thickness of 0.5 mm (Fig. 10a).[146] This performance stems from the fact that esterified rutin (acting as a crosslinker) retains its p-π conjugation system through conjugated double bonds and phenolic hydroxyl groups, thus strongly absorbing UVB radiation in the 275–320 nm wavelength range, whereas the amorphous structure of the ionogel maintains high visible light transmittance. In addition, this ionogel has excellent mechanical properties (*e.g.*, fracture strength of about 35 MPa and toughness of about 88 MJ·m^{-3}), making it suitable for use as a protective coating in applications such as umbrellas, car windows, and architectural glass.[146]

3.5.2 Lubrication

Lubrication can reduce the friction and wear between contacting surfaces, which minimizes energy loss, prevents mechanical failure, and extends the lifespan of components. Ionogels can serve as effective lubricants because their liquid IL solvents reduce friction, whereas the polymer networks provide stability and wear protection under stress. Studies have shown that biocompatible ionogels composed of DES and polyacrylamide polymers can significantly reduce wear rates and effectively protect metal surfaces from friction-induced damage (Fig. 10b).[147] Notably, this ionogel also exhibits excellent self-healing properties, with its repair mechanism driven by the synergistic action of hydrogen and ionic bonds, thus further extending its lifespan as a lubricant. This type of ionogel has potential for use in environmentally friendly industrial lubricants and

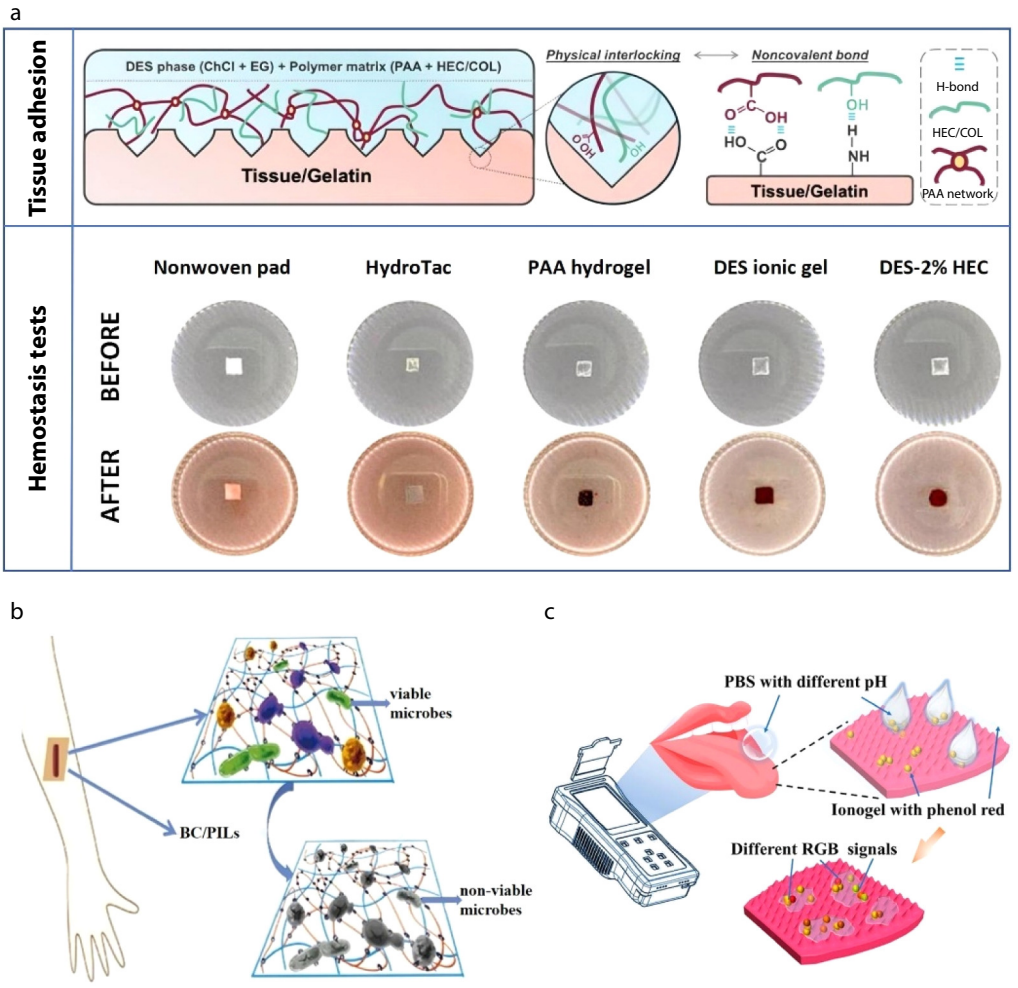


Fig. 9 Applications of ionogels in biomedicine. (a) Schematics illustrating the adhesion mechanism of the ionogel (upper) and its application in hemostasis (Reproduced with permission from Ref. [144]; Copyright (2025), Wiley); (b) Biocompatible ionogels exhibit excellent antibacterial activities (Reproduced with permission from Ref. [145]; Copyright (2024), Elsevier); (c) An artificial tongue made from ionogels that can function as a pH indicator (Reproduced with permission from Ref. [86]; Copyright (2022), American Chemical Society).

biomedical applications (*e.g.*, artificial cartilage and tendons).[148,149]

3.5.3 Food quality monitoring

Food quality monitoring can ensure food safety and prevent the spread of harmful contaminants. It also helps prevent food spoilage, reduces waste, and maintains the nutritional value of food, thus safeguarding human health. Ionogels can be used for food quality monitoring because their stable matrix can immobilize sensors and convert chemical changes into detectable signals. For instance, a pH-sensitive dye acting as a colorimetric sensor was introduced into an ionogel, which was then used to monitor meat spoilage at –4 °C (Fig. 10c).[150] The results showed that the ionogel exhibits reliable performance by exhibiting visually observable color changes caused by the total volatile basic nitrogen (TVB-N) produced during meat spoilage.

3.5.4 Smart adhesion

Smart adhesion is essential for applications that require reliable adhesion and debonding under varying mechanical and environmental conditions, such as wearable devices, protective coatings, and smart packaging.[151–154] In addition to ILs, the adhesion properties of ionogels are greatly influenced by polymer properties (*e.g.*, polarity and dissociation). An adhesive ionogel containing poly[(2-acryloyloxyethyl trimethylammonium bis(trifluoromethylsulfonyl)imide)]-*co*-*N*,*N*-dimethylacrylamide polymer was developed and integrated into an "impact protection-sensing" system for smart laminated glass (Fig. 10d).[155] This ionogel enhanced the stability of the glass, allowing it to withstand impact forces of up to 8000 N while maintaining structural integrity and without shattering into sharp fragments. In addition, biocompatible ionogels exhibiting excellent adhesive properties over a wide temperature range (*i.e.*, –80 °C to 80 °C) show promise for applications such as smart packaging.[156]

3.5.5 Fire safety

Fire safety protects our lives and property, especially in buildings and electronic systems, where flammable materials and heat accumulation pose continuous risks. Ionogels are ideally suited for fire safety applications because of their non-flammability and high thermal stability. For instance, ionogels enable treated wood to achieve an underwriters laboratories standard 94 V-0 flammability rating (UL-94 V-0 rating) and increase the limiting oxygen index to 31% (in contrast, the limiting oxygen index of normal wood is approximately 19%), significantly im-

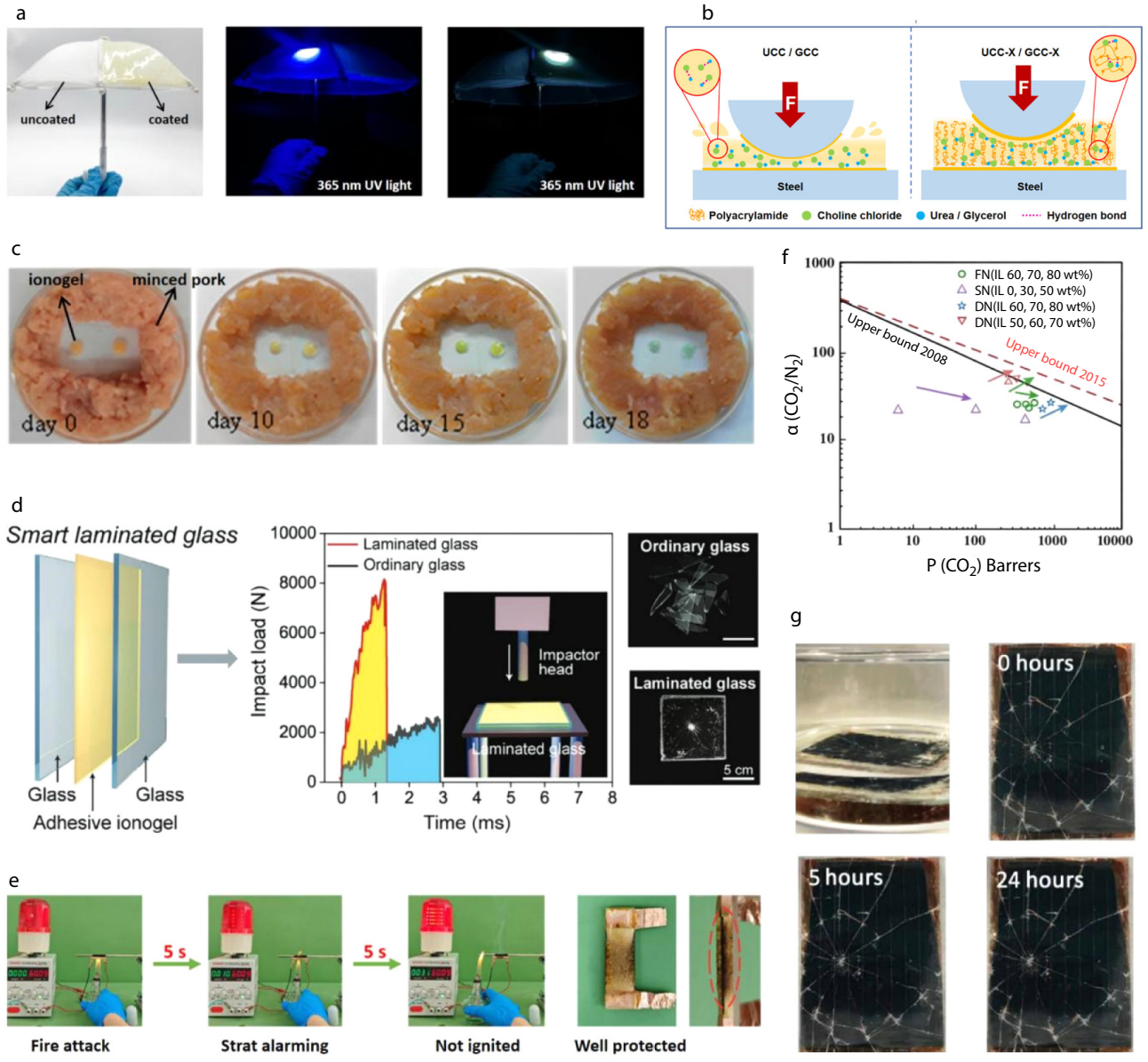


Fig. 10 Applications of ionogels in other fields. (a) Ionogels are used as sunscreen coatings (Reproduced with permission from Ref. [146]; Copyright (2024), Springer Nature); (b) Schematic diagram illustrating the mechanism of ionogels acting as lubricants (Reproduced with permission from Ref. [147]; Copyright (2021), American Chemical Society); (c) Ionogels-based for the detection of meat spoilage (Reproduced with permission from Ref. [150]; Copyright (2024), American Chemical Society); (d) Adhesive ionogels are used as smart laminated glass, significantly improving the impact resistance of the glass (Reproduced with permission from Ref. [155]; Copyright (2024), Wiley); (e) Ionogels are applied to flame-retardant materials (Reproduced with permission from Ref. [157]; Copyright (2025), Elsevier); (f) Comparison of the permeability and selectivity of ionogels for CO_2 capture with the 2008 Robeson Upper Bound (Reproduced with permission from Ref. [159]; Copyright (2024), Elsevier); (g) This ionogel-based encapsulation material significantly improves the impact resistance of the device and reduces lead leakage (Reproduced with permission from Ref. [160]; Copyright (2021), American Association for the Advancement of Science).

proving its flame-retardant properties (Fig. 10e).[157] In addition, this ionogel possessed self-healing capabilities. When damaged by a knife cut, it can be completely healed by simply heating at 75 °C for 5 min, thus ensuring the continuous stability of its flame-retardant properties. Ionogels with similar properties have been used in smart fire safety systems that integrate early warning and self-powered capabilities.[158]

3.5.6 CO_2 capture

CO_2 capture is crucial for mitigating climate change and reducing greenhouse gas emissions from industrial sources. Ionogels have been explored because they exhibit strong selective interactions with CO_2. Ionogels have attracted increasing attention in this field owing to their strong selective interactions with CO_2. High-performance ionogel membranes have been fabricated for efficient CO_2 capture and separation. These ionogels can efficiently separate CO_2 from CO_2/N_2 mixtures, with separation performance exceeding the Robeson upper bound of 2008 and outperforming traditional single-network membranes (Fig.

10f).[159]

3.5.7 Encapsulation

Encapsulation technology ensures the safety and reliability of devices in daily life because it prevents damage caused by environmental factors. In particular, encapsulation is crucial for protecting optoelectronic devices from mechanical damage and environmental influences while also preventing the leakage of harmful substances. As a typical example, a self-healing and lead-adsorbing ionogel was developed to encapsulate perovskite solar cells.[160] This ionogel-based encapsulation technology significantly reduces lead leakage by approximately 1000 times compared to commercial encapsulation materials, such as ethylene vinyl acetate (Fig. 10g). In addition, this ionogel possesses excellent mechanical properties (*e.g.*, Young's modulus of about 70 MPa), effectively resisting external impacts and thus ensuring the long-term stability and environmental safety of perovskite solar cell technology.

In addition to the above applications enabled by the additional functionalities, the inherent properties (*e.g.*, ionic conductivity and nonvolatility) of ionogels also greatly facilitate their use, especially compared to traditional gels such as hydrogels.[2,161] For example, high thermal stability and nonvolatility allow ionogel-based ionic skins to operate stably at extreme temperatures (*e.g.*, –60 to 200 °C) without solvent evaporation or freezing.[3,5,162] In addition, ionogels are intrinsically ionically conductive because of the cations and anions in ILs, whereas hydrogels are insolutors.[163] Thus, ionogels can be used as electrolytes without the need for added conductive media (for example, with ionic conductivities up to 22.1 $mS{\cdot}cm^{-1}$).[164] Ionogels also have high electrochemical stability (*e.g.*, about 4 V), whereas hydrogels undergo electrolysis at voltages above 1.29 V.[5] More importantly, ionogels are diverse because of the vast variety of ILs (about 10^{18} species), whereas water is the only solvent for hydrogels.[3] These unique features of ionogels make them ideal alternatives to hydrogels.

4 OUTLOOKS

Ionogels are an emerging class of multifunctional soft materials with broad application prospects in flexible electronics, energy-storage devices, biomedicine, sensing, and smart systems. This study provides a comprehensive overview of ionogels with design-enabled functionalities and their related applications. Despite significant progress, ionogels still face several key challenges, including precise control of structure-property relationships, balancing mechanical strength and multifunctionality, long-term environmental stability, and cost-effective manufacturing methods for practical applications.

Currently, exploration of additional functionalities of ionogels (such as magnetic properties) remains rare, thus requiring more systematic and in-depth research. For example, in addition to introducing magnetic additives or MILs, the development of magnetic ionogels through rational polymer design is a promising but underexplored direction. This strategy can achieve a more uniform magnetic response and a higher long-term stability. Stable and strong luminescence is crucial for ionogels used in applications such as information encryption, sensing, and medical diagnostics. However, fluorescence or phosphorescence quenching remains a major challenge and requires further effort in this field.

Despite their numerous potential applications, ionogels still face several key challenges, including limited long-term stability, mechanical fatigue under repeated deformation, and an inherent trade-off between ionic conductivity and mechanical strength. Addressing these issues is crucial for the reliability of their practical application. Simultaneously, these challenges present significant opportunities for innovation. Advances in the polymer structure, interactions in the gel matrix, and composite material design provide effective strategies for precisely controlling the ionogel properties. Furthermore, the integration of multiple functionalities, such as self-healing and stimulus responsiveness, can be further explored, offering broad prospects for expanding the application range of ionogels.

The multifunctional performance of ionogels is highly dependent on their precisely designed structures, including molecular-scale interactions, network topology, and mesoscale phase separation. Therefore, a deep understanding of the structure-property-function relationship is crucial, which should rely more on advanced theoretical simulations, multiscale modeling, and machine-learning-assisted material design. This will enable rational design rather than trial-and-error synthesis, thereby accelerating the development of ionogels with predictable and programmable functions.

Additional functionalities of ionogels (such as self-healing, shape memory, and multi-stimulus responsiveness) are often achieved at the expense of mechanical strength or long-term stability. However, mechanical performance is still essential for the application range of ionogels. Therefore, the mechanical performance and functional complexity should be balanced while ensuring environmental stability under extreme conditions (*e.g.*, high temperature and high vacuum) or repeated mechanical deformation. Notably, the shape memory behavior of the ionogels relies primarily on thermal activation. Thus, exploring nonthermal triggers, such as light, electric fields, magnetic fields, and chemical stimuli, will significantly broaden their application range.

Importantly, cost-effective manufacturing strategies must be carefully considered because of the high costs of ILs. In particular, challenges related to biocompatibility, environmental sustainability, and recyclability must be addressed to enable practical and economical production. This goal naturally promotes interdisciplinary collaboration across fields, such as materials science, chemistry, engineering, mechanics, data science, and biomedicine. With continued innovations in material design, processing strategies, and functional integration, ionogels have the potential to evolve from versatile laboratory materials into key enablers of next-generation smart, sustainable, and human-centered technologies.

We hope that this review inspires further exploration of the diverse functions and applications of ionogels. By systematically studying strategies for introducing specific properties and understanding how these properties influence the mechanical performance, a more comprehensive framework can be established for designing tough and multifunctional ionogels. This deeper understanding will facilitate the development of ionogels with specific properties, thereby broaden-

ing their applications.

BIOGRAPHIES

Xun Xiao received his Ph.D. degree from University of North Carolina at Chapel Hill (UNCCH), supervised by Prof. Jinsong Huang, in 2021. Then, he did postdoctoral research at the UNCCH and Linköping University. In 2025, he joined the School of Materials Science and Engineering, Peking University, as an assistant professor. Currently, he leads a group working on optoelectronics materials and devices, as well as functional encapsulant.

Mei-Xiang Wang received her Ph.D. degree from Xi'an Jiaotong University in 2018. She conducted postdoctoral research in Professor Michael D. Dickey's lab in the Department of Chemical and Biomolecular Engineering at North Carolina State University. In 2025, she joined the School of Chemistry at Beihang University as a professor. Her lab focuses on soft matter (gels, liquid metals) for str*etch*able and flexible devices (electronics, actuators, sensors, energy harvesters, and energy storage devices).

Conflict of Interests

The authors declare no interest conflict.

ACKNOWLEDGMENTS

This work was financially supported by the Beijing Natural Science Foundation (No. L252111), the National Natural Science Fund for Excellent Young Scientists Fund Program (Overseas), National Natural Science Foundation of China (No. 52503222), and State Key Laboratory of Advanced Waterproof Materials, Peking University (No. SKLAWM-2025YJXX), the State Key Laboratory of Silicon and Advanced Semiconductor Materials, Zhejiang University (No. SKL2025-03).

REFERENCES

1 Fan, X. T.; Liu, S. Q.; Jia, Z. H.; Koh, J. J.; Yeo, J. C. C.; Wang, C. G.; Surat'man, N. E.; Loh, X. J.; Le Bideau, J.; He, C. B.; Li, Z. B.; Loh, T. P. Ionogels: recent advances in design, material properties and emerging biomedical applications. *Chem. Soc. Rev.* **2023**, *52*, 2497–2527.
2 Yan, C.-C.; Li, W. Z.; Liu, Z. Y.; Zheng, S. J.; Hu, Y.; Zhou, Y. J.; Guo, J. N.; Ou, X.; Li, Q. N.; Yu, J. T.; Li, L. G.; Yang, M. C.; Liu, Q. B.; Yan, F. Ionogels: preparation, properties and applications. *Adv. Funct. Mater.* **2024**, *34*, 2314408.
3 Wang, M.; Hu, J.; Dickey, M. D. Tough ionogels: synthesis, toughening mechanisms, and mechanical properties—a perspective. *JACS Au* **2022**, *2*, 2645–2657.
4 Bideau, J. L.; Viau, L.; Vioux, A. Ionogels, ionic liquid based hybrid materials. *Chem. Soc. Rev.* **2011**, *40*, 907–925.
5 Wang, M.; Hu, J.; Dickey, M. D. Emerging applications of tough ionogels. *NPG Asia Mater.* **2023**, *15*, 66.
6 Wang, M. X.; Zhang, P. Y.; Shamsi, M.; Thelen, J. L.; Qian, W.; Truong, V. K.; Ma, J.; Hu, J.; Dickey, M. D. Tough and str*etch*able ionogels by *in situ* phase separation. *Nat. Mater.* **2022**, *21*, 359–365.
7 Luo, Z. H.; Li, W. J.; Yan, J. P.; Sun, J. Roles of ionic liquids in adjusting nature of ionogels: a mini review. *Adv. Funct. Mater.* **2022**, *32*, 2203988.
8 Rogers, R. D.; Seddon, K. R. Ionic liquids--solvents of the future *Science* **2003**, *302*, 792–793.
9 Li, Q.; Yan, F.; Texter, J. Polymerized and colloidal ionic liquids—syntheses and applications. *Chem. Rev.* **2024**, *124*, 3813–3931.
10 Wang, M.; Hu, J.; Dickey, M. D. Getting tough with ionogels. *Am. Sci.* **2023**, *111*, 144–147.
11 Marr, P. C.; Marr, A. C. Ionic liquid gel materials: applications in green and sustainable chemistry. *Green Chem.* **2015**, *18*, 105–128.
12 MacFarlane, D. R.; Forsyth, M.; Howlett, P. C.; Kar, M.; Passerini, S.; Pringle, J. M.; Ohno, H.; Watanabe, M.; Yan, F.; Zheng, W.; Zhang, S.; Zhang, J. Ionic liquids and their solid-state analogues as materials for energy generation and storage. *Nat. Rev. Mater.* **2016**, *1*, 15005.
13 Chen, N.; Zhang, H.; Li, L.; Chen, R.; Guo, S. Ionogel electrolytes for high-performance lithium batteries: a review. *Adv. Energy Mater.* **2018**, *8*, 1702675.
14 Ferbezar, A.; Zettl, R.; Hogrefe, K.; Fitzek, H.; Gadermaier, B.; Wilkening, H. M. R.; Hanzu, I. Tuning the ion conductivity of Zr-based metal–organic framework ionogels by linker functionalization. *J. Mater. Chem. A* **2024**, *12*, 12552–12563.
15 Wang, M.; Yang, L.; Adamson, J.; Li, S.; Huang, Y.; Shen, X.; Chen, Y.; Zhou, Q.; Tan, L. Ionogel microphones detect underwater sound with directivity and exceptional stability. *ACS Appl. Electron. Mater.* **2020**, *2*, 1295–1303.
16 Wang, M. Ionogels: from properties and synthesis to toughening, patterning, and applications. *Chem. Rev.* **2025**, *125*, 11815–11839.
17 Zhang, L.; Jiang, D.; Dong, T.; Das, R.; Pan, D.; Sun, C.; Wu, Z.; Zhang, Q.; Liu, C.; Guo, Z. Overview of ionogels in flexible electronics. *Chem. Rec.* **2020**, *20*, 948–967.
18 Huang, Y.; Zhu, H.; Zhang, Q.; Zhu, S. Ionogel adhesives: from structural design to emerging applications. *Macromol. Rapid Commun.* **2025**, *46*, 2400973.
19 Huang, Y.; Ming, X.; Tang, Z.; Chen, G.; Duan, X.; Zhu, H.; Zhu, S.; Zhang, Q. Ultra-strong ionogel adhesives *via in situ* microphase separation. *Adv. Funct. Mater.* **2025**, *35*, 2417011.
20 Wang, M. X.; Xiao, X.; Siddika, S.; Shamsi, M.; Frey, E.; Qian, W.; Bai, W. B.; O'Connor, B. T.; Dickey, M. D. Glassy gels toughened by solvent. *Nature* **2024**, *631*, 313–318.
21 Sun, Y. D.; Wang, C. H.; Guo, B. H.; Zhang, S. F.; Niu, W. B. Mussel-inspired tough ionogel with robust adhesion and mechanical adaptivity for impact resistance. *Chem. Eng. J.* **2024**, *498*, 155059.
22 Zhang, L. M.; He, Y.; Cheng, S.; Sheng, H.; Dai, K.; Zheng, W. J.; Wang, M. X.; Chen, Z. S.; Chen, Y. M.; Suo, Z. Self-healing, adhesive, and highly str*etch*able ionogel as a strain sensor for extremely large deformation. *Small* **2019**, *15*, 1804651.
23 Lebedeva, O.; Kultin, D.; Kustov, L. Advanced research and prospects on polymer ionic liquids: trends, potential and application. *Green Chem.* **2023**, *25*, 9001–9019.
24 Fu, J.; Zhang, L.; Liu, J. Y.; Zhang, G. H.; Wang, S. L.; Zhu, Q. H.; Qin, S.; He, L.; Tao, G. H. A spot ionogel for visual early-warning of illegal lead concentrations coupling inorganic perovskite crystallization and photoluminescence. *Adv. Opt. Mater.* **2023**, *11*, 2300617.
25 Ganguly, S.; Margel, S. Magnetic ionogel and its applications. *Gels* **2025**, *11*, 219.
26 Ren, Y.; Guo, J.; Liu, Z.; Sun, Z.; Wu, Y.; Liu, L.; Yan, F. Ionic liquid–based click-ionogels. *Sci. Adv.* **2019**, *5*, eaax0648.
27 Li, T. Q.; Wang, Y. T.; Li, S. H.; Liu, X. K.; Sun, J. Q. Mechanically robust, elastic, and healable ionogels for highly sensitive ultra-

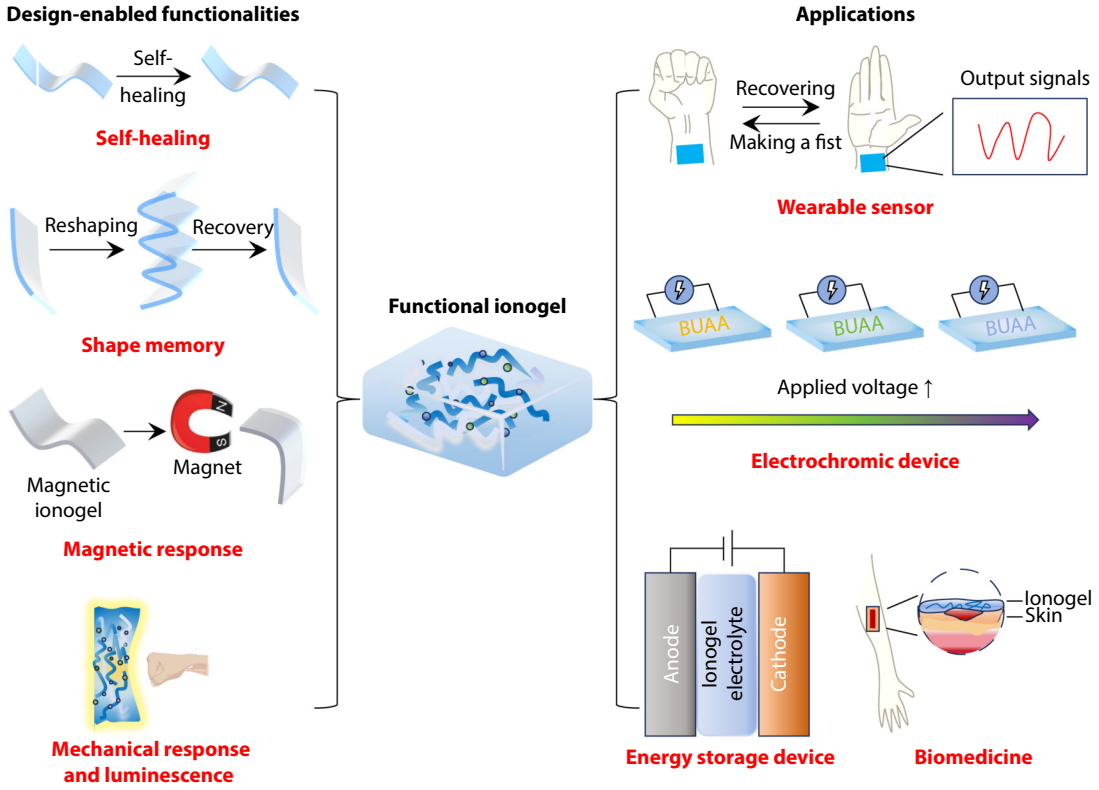
Graphical Abstract

Functional Ionogels: Design Principles and Applications

Rui Wu, Jin-Qi Zhang, Xun Xiao, and Mei-Xiang Wang

Beihang University, China; Peking University, China; Zhejiang University, China; North Carolina State University, United States

In addition to their inherent properties, ionogels can acquire additional functionalities (*e.g.*, self-healing, shape memory, and luminescence) through rational structural design and the introduction of functional additives. These functional ionogels have great potential in applications such as energy storage devices, wearable sensors, biomedicine, and electrochromic devices, *etc*.



Chinese J. Polym. Sci. 2026, 44, 1645–1666 *https://doi.org/10.1007/s10118-026-3584-y*

durable ionic skins. *Adv. Mater.* **2020**, *32*, 2002706.
28 Kang, J.; B.-H. Tok, J.; Bao, Z. Self-healing soft electronics. *Nat. Electron.* **2019**, *2*, 144–150.
29 Li, H. L.; Xu, F. C.; Lin, X. R.; Li, Y. Self-healing ionogel with unprecedented high gel-sol transition temperature enables self-healing zinc-air battery operation at 100 °C. *Adv. Funct. Mater.* **2025**, *36*, e13459.
30 Yu, Z. C.; Wu, P. Y. Water-resistant ionogel electrode with tailorable mechanical properties for aquatic ambulatory physiological signal monitoring. *Adv. Funct. Mater.* **2021**, *31*, 2107226.
31 Gao, J.; Chen, E. P.; Yuan, W. J.; Meng, C. Z.; Wu, J. D.; Guo, S. J. Intrinsically conductive, optical transparent, and underwater self-healing ionogel with on-demand bonding triggered by skin temperature. *Small* **2025**, *21*, 2502449.
32 Wang, S. X.; Li, J. J.; Li, S.; Wu, X. C.; Guo, C.; Yu, L. M.; Murto, P.; Wang, Z. H.; Xu, X. F. Self-contained underwater adhesion and informational labeling enabled by arene-functionalized polymeric ionogels. *Adv. Funct. Mater.* **2023**, *33*, 2306814.
33 Chen, Z. J.; Sun, Y. Q.; Xiao, X.; Wang, H. Q.; Zhang, M. H.; Wang, F. Z.; Lai, J.; Zhang, D. S.; Pan, L. J.; Li, C. H. An ultra-tough and ultra-sensitive ionogel pressure/temperature sensor enabled by hierarchical design of both materials and devices. *J. Mater. Chem. A* **2023**, *11*, 8359–8367.
34 Sun, Y. D.; Wang, X. C.; Li, H. Y.; Zhang, S. F.; Niu, W. B. Mechanically robust photonic-ionic skin cross-linked by metal–imidazole interactions. *Adv. Funct. Mater.* **2024**, *34*, 2405345.
35 Wu, J. T.; Huang, L.; Wang, S. P.; Li, X. R.; Wen, L.; Li, X. M.; Feng, T. T.; Li, P. Y.; Fang, Z. X.; Wu, M. Q.; Lv, W. Ionogel electrolyte with

dynamic metal-ligand interactions enabled self-healable supercapacitor with high energy density. *Energy Storage Mater.* **2023**, *57*, 549–556.
36 Sahraeeazartamar, F.; Terryn, S.; Sangma, R. N.; Krack, M.; Peeters, R.; Van den Brande, N.; Deferme, W.; Vanderborght, B.; Van Assche, G.; Brancart, J. Diels–Alder network blends as self-healing encapsulants for liquid metal-based stretchable electronics. *ACS Appl. Mater. Interfaces* **2024**, *16*, 34192–34212.
37 Zhang, M. W.; Zhao, L. Y.; Tian, F.; Zhao, X. J.; Zhang, Y.; Yang, X.; Huang, W.; Yu, R. Bionic artificial skin based on self-healable ionogel composites with tailored mechanics and robust interfaces. *Adv. Mater.* **2024**, *36*, 2405776.
38 Zhang, M. W.; Tao, X. L.; Yu, R.; He, Y. Y.; Li, X. P.; Chen, X. Y.; Huang, W. Self-healing, mechanically robust, 3D printable ionogel for highly sensitive and long-term reliable ionotronics. *J. Mater. Chem. A* **2022**, *10*, 12005–12015.
39 Sun, Y. D.; Li, X. F.; Hu, T.; Zhang, S. F.; Niu, W. B. Dynamic acylhydrazone bonds cross-linked chromotropic photonic-ionic skin with self-healing and high resilience for interactive human-machine interface. *Chem. Eng. J.* **2023**, *475*, 146188.
40 Li, B.; Xu, F. C.; Guan, T. T.; Li, Y.; Sun, J. Q. Self-adhesive self-healing thermochromic ionogels for smart windows with excellent environmental and mechanical stability, solar modulation, and antifogging capabilities. *Adv. Mater.* **2023**, *35*, 2211456.
41 Sun, L. J.; Huang, H. F.; Zhang, L. Z.; Neisiany, R. E.; Ma, X. P.; Tan, H.; You, Z. W. Spider-silk-inspired tough, self-healing, and melt-spinnable ionogels. *Adv. Sci.* **2024**, *11*, 2305697.
42 Xu, L. G.; Huang, Z. K.; Deng, Z. S.; Du, Z. K.; Sun, T. L.; Guo, Z.-H.; Yue, K. A. Transparent, highly stretchable, solvent-resistant, recyclable multifunctional ionogel with underwater self-healing and adhesion for reliable strain sensors. *Adv. Mater.* **2021**, *33*, 2105306.
43 Zhang, Z. P.; Qian, L.; Zhang, B.; Ma, C. F.; Zhang, G. Z. Jellyfish-inspired polyurea ionogel with mechanical robustness, self-healing, and fluorescence enabled by hyperbranched cluster aggregates. *Angew. Chem. Int. Ed.* **2024**, *63*, e202410335.
44 Hunt, P. A.; Ashworth, C. R.; Matthews, R. P. Hydrogen bonding in ionic liquids. *Chem. Soc. Rev.* **2015**, *44*, 1257–1288.
45 Jia, S.; Feng, Z. X.; Yan, X. Q.; Zhang, Z. G.; Rao, J.; Shi, Z. J.; Ren, J.; Peng, F. Multifunctional bio-based wearable ionogel with hierarchical dynamic covalent crosslinked double networks enabled by surface active xylan. *Carbohydr. Polym.* **2025**, *368*, 124187.
46 Zhao, W.; Zheng, Y. W.; Huang, A. B.; Jiang, M.; Wang, L. J.; Zhang, Q. H.; Jiang, W. Metal-halogen interactions inducing phase separation for self-healing and tough ionogels with tunable thermoelectric performance. *Adv. Mater.* **2024**, *36*, 2402386.
47 Xia, Y. L.; He, Y.; Zhang, F. H.; Liu, Y. J.; Leng, J. S. A review of shape memory polymers and composites: mechanisms, materials, and applications. *Adv. Mater.* **2021**, *33*, 2000713.
48 Wu, S. S.; Huang, J. H.; Jing, S. R.; Xie, H.; Zhou, S. B. Biodegradable shape-memory ionogels as green and adaptive wearable electronics toward physical rehabilitation. *Adv. Funct. Mater.* **2023**, *33*, 2303292.
49 Hao, S.; Li, T. C.; Yang, X. M.; Song, H. Z. Ultrastretchable, adhesive, fast self-healable, and three-dimensional printable photoluminescent ionic skin based on hybrid network ionogels. *ACS Appl. Mater. Interfaces* **2022**, *14*, 2029–2037.
50 Li, F. Y.; Wu, K. F.; Zhang, X.; Fu, Y. M.; Sun, T. L.; Guo, H. L.; Wang, X. L.; Guo, H.; Meng, Y. "Frozen" ionogels with high and tunable toughness for soft electronics. *Small* **2025**, *21*, 2500477.
51 Zhao, Q.; Qi, H. J.; Xie, T. Recent progress in shape memory polymer: new behavior, enabling materials, and mechanistic understanding. *Prog. Polym. Sci*. **2015**, *49–50*, 79–120.
52 Zhao, Z.; Cao, Z.; Wu, Z.; Du, W.; Meng, X.; Chen, H.; Wu, Y.; Jiang, L.; Liu, M. Bicontinuous vitrimer heterogels with wide-span switchable stiffness-gated iontronic coordination. *Sci. Adv.* **2024**, *10*, eadl2737.
53 Wang, J. W.; Zheng, Y. P.; Cui, T. Y.; Huang, T. Y.; Liu, H. D.; Zhu, J. X.; Song, L.; Hu, Y. Bioinspired ultra-robust ionogels constructed with soft-rigid confinement space for multimodal monitoring electronics. *Adv. Funct. Mater.* **2024**, *34*, 2312383.
54 Zhuo, S. Y.; Song, C.; Rong, Q. F.; Zhao, T. Y.; Liu, M. J. Shape and stiffness memory ionogels with programmable pressure-resistance response. *Nat. Commun.* **2022**, *13*, 1743.
55 Yang, X. P.; Li, N. Y.; Wang, B. B.; Chen, P. Y.; Ma, S.; Deng, Y. F.; Lü, S. Y.; Tang, Y. Mechanics-photophysics correlation in tough, stretchable and long-lived room temperature phosphorescence ionogels deciphered by dynamic mechanical analysis. *Angew. Chem. Int. Ed.* **2025**, *64*, e202419114.
56 Zhou, Z. J.; Bai, Y. K.; Niu, L. Z.; Lv, C. Z.; Li, Y. Q.; Niu, L. N. Versatile ionogels with tailoring performance for strain sensors, temperature alarm and self-powered wearable devices. *Chem. Eng. J.* **2024**, *488*, 150982.
57 Li, T.; Liu, F.; Yang, X. M.; Hao, S.; Cheng, Y.; Li, S. J.; Zhu, H. N.; Song, H. Z. Muscle-mimetic highly tough, conductive, and stretchable poly(ionic liquid) liquid crystalline ionogels with ultrafast self-healing, super adhesive, and remarkable shape memory properties. *ACS Appl. Mater. Interfaces* **2022**, *14*, 29261–29272.
58 Wang, S. B.; Zhang, D.; Zhou, J. H.; He, X. M.; Zheng, S. Y.; Yang, J. T. Zwitterionic ionogels with water-mediated stiffness transition for shape memory and moisture electric generation. *Nano Energy* **2024**, *120*, 109166.
59 Li, S.; Cheng, Y.; Zhu, H. N.; Xu, M.; Lv, H. Y.; Wang, Z. E.; Liu, G. M.; Song, H. Z. Strain-induced phase separation and mechanomodulation of ionic conduction in anisotropic nanocomposite ionogels. *ACS Appl. Mater. Interfaces* **2024**, *16*, 13103–13113.
60 Choi, W. Y.; Kwon, J. H.; Kim, Y. M.; Moon, H. C. Multimodal wearable ionoskins enabling independent recognition of external stimuli without crosstalk. *Small* **2023**, *19*, 2301868.
61 Zhou, H. F.; Zhao, W. C.; Zhao, L. Radiation synthesis of covalently/non-covalently coupled all ionic liquid-based ionogels with rapid self-healing, environmental tolerance for multifunctional ionic skin. *Chem. Eng. J.* **2024**, *489*, 151163.
62 Lv, D.; Li, X.; Huang, X.; Cao, C. yan; Ai, L. qing; Wang, X. jiao; Ravi, S. K.; Yao, X. Microphase-separated elastic and ultrastretchable ionogel for reliable ionic skin with multimodal sensation. *Adv. Mater.* **2024**, *36*, 2309821.
63 Zhen, W. C.; Lu, C. S.; Li, D.; Meng, G. F.; Wang, H. Q.; Jiang, Y. F.; Lou, J.; Han, W. J. Cation-anchoring-induced efficient n-type thermo-electric ionogel with ultra-high thermopower. *Adv. Sci.* **2025**, *12*, 2414389.
64 Li, X.; Yang, X. M.; Li, S. J.; Lv, H. Y.; Wang, Z. E.; Gao, Z. Y.; Song, H. Z. 3D printing of thermo-mechano-responsive photoluminescent noncovalent cross-linked ionogels with high-stretchability and ultralow-hysteresis for wearable ionotronics and anti-counterfeiting. *Small* **2024**, *20*, 2403252.
65 Sun, S.; Shi, X.-L.; Lyu, W. Y.; Hong, M.; Chen, W. Y.; Li, M.; Cao, T. Y.; Hu, B. X.; Liu, Q.; Chen, Z. G. Stable, self-adhesive, and high-performance graphene-oxide-modified flexible ionogel thermoelectric films. *Adv. Funct. Mater.* **2024**, *34*, 2402823.
66 Xu, M.; Shen, X. C.; Li, S. J.; Zhu, H. N.; Cheng, Y.; Lv, H. Y.; Wang, Z. E.; Lou, C. G.; Song, H. Z. Skin-inspired gradient ionogels induced by electric field for ultrasensitive and ultrafast-responsive multifunctional ionotronics. *J. Mater. Chem. A* **2024**, *12*, 1036–1046.

67 Peng, W. X.; Zhao, J. M.; Li, Q. X.; Sun, Y.; Du, G. L.; Tang, F. Y.; Liu, Y. F.; Hu, Q. D.; Li, X. S.; Nie, S. X. A strong and tough ion-gel enabled by hierarchical meshing and ion hybridizations collaboration. *Adv. Funct. Mater.* **2025**, *35*, 2414682.

68 Xia, Y. F.; Zhu, Y.; Zhi, X. R.; Guo, W. Y.; Yang, B.; Zhang, S. Y.; Li, M. Y.; Wang, X.; Pan, C. F. Transparent self-healing anti-freezing ionogel for monolayered triboelectric nanogenerator and electromagnetic energy-based touch panel. *Adv. Mater.* **2024**, *36*, 2308424.

69 Wu, Y.; Cuthbert, T. J.; Luo, Y.; Chu, P. K.; Menon, C. Cross-link-dependent ionogel-based triboelectric nanogenerators with slippery and antireflective properties. *Small* **2023**, *19*, 2301381.

70 Fan, K.; Li, K.; Wang, Z.; Men, W.; Wu, X.; Cheng, J.; Zhang, J. An unprecedented strategy with electric double layer and adaptive ionic liquid in fully ionogel fiber-based TENG for enhanced output and dynamic stability. *Nano Energy* **2025**, *135*, 110658.

71 Li, H. L.; Xu, F. C.; Guan, T. T.; Li, Y.; Sun, J. Mechanically and environmentally stable triboelectric nanogenerator based on high-strength and anti-compression self-healing ionogel. *Nano Energy* **2021**, *90*, 106645.

72 Tang, A.; Wang, J. C.; Xu, J. L.; Liu, J. T.; Xu, T. P.; Zhang, Q.; Tian, Y. A high-performance photonic-ionic e-skin with synergistic electronic/optical sensing for motion tracking. *Biosens. Bioelectron.* **2025**, *278*, 117317.

73 Luo, X.; Chen, C.; He, Z.; Wang, M.; Pan, K.; Dong, X.; Li, Z.; Liu, B.; Zhang, Z.; Wu, Y.; Ban, C.; Chen, R.; Zhang, D.; Wang, K.; Wang, Q.; Li, J.; Lu, G.; Liu, J.; Liu, Z.; Huang, W. A Bionic self-driven retinomorphic eye with ionogel photosynaptic retina. *Nat. Commun.* **2024**, *15*, 3086.

74 Sun, J. L.; Liu, Y.; Wei, J. J.; Wei, P.; Chen, T. Pseudo-photoelectric cascade conversion endowing photosensitive Janus ionogel for solar energy harvesting and sensing. *Chem. Eng. J.* **2024**, *485*, 149836.

75 Liu, Z.; Wu, J.; Wang, M.; Wang, K.; Zeng, Y.; Dong, X.; Wang, K.; Liu, J. A light-driven ionogel fabric synapse with strain-insensitivity and broadband response for textile photoperception. *Adv. Funct. Mater.* **2026**, *36*, e10021.

76 Zhang, J. Y.; Guo, M. R.; Su, Y. T.; Wu, W. X.; Wang, S. C.; Yang, R.; Xu, C.; Yin, H. Z.; Xu, J. H.; Wang, X. L. Photochromic ionogel with a wide temperature range and fatigue resistance for high-resolution rewritable information record. *Chem. Eng. J.* **2024**, *495*, 153263.

77 Yu, M.; Liu, X.; Gao, Z.; Chen, S.; Yu, X. Excitation-dependent ionogels based on lanthanide-terpyridine coordination for dynamic and controllable orthogonal information encryption. *ACS Macro Lett.* **2025**, *14*, 1694–1700.

78 Li, B.; Han, K.; Wang, Y. Z.; Sun, Y. S.; Xia, Z. G.; Xu, Y. Mn(II)-based hybrid halide ionogel scintillator film for large-area and high-resolution X-ray imaging. *Angew. Chem. Int. Ed.* **2025**, *64*, e202502440.

79 Zhang, Q. Q.; Ma, S.; Yang, X. P.; Li, N. Y.; Chen, P. Y.; Deng, Y. F.; Huo, L. X.; Lü, S. Y. Ionogels with excitation wavelength dependent emission and dynamic light-tracking for potential extreme rescues. *Adv. Funct. Mater.* **2025**, *35*, 2503287.

80 Wang, Y.; Kalytchuk, S.; Zhang, Y.; Shi, H. C.; Kershaw, S. V.; Rogach, A. L. Thickness-dependent full-color emission tunability in a flexible carbon dot ionogel. *J. Phys. Chem. Lett.* **2014**, *5*, 1412–1420.

81 Xu, Z. R.; Huang, Y. F.; Sun, S. Y.; Wang, P.; He, Z. Y.; Tian, H.; Ma, X. Programmable ultralong phosphorescent ionogels for intelligent monitoring. *Angew. Chem. Int. Ed.* **2025**, *64*, e202518340.

82 Vuuren, R. D. J. V.; Naficy, S.; Ramezani, M.; Cunningham, M.; Jessop, P. CO_2-Responsive gels. *Chem. Soc. Rev.* **2023**, *52*, 3470–3542.

83 Liu, G.; Deng, Y.; Ni, B.; Nguyen, G. T. M.; Vancaeyzeele, C.; Brûlet, A.; Vidal, F.; Plesse, C.; Li, M.-H. Electroactive Bi-functional liquid crystal elastomer actuators. *Small* **2024**, *20*, 2307565.

84 Liu, Z. W.; Li, B. B.; Liu, Y. D.; Liang, Y. R. Integrated bending actuation and the self-sensing capability of poly(vinyl chloride) gels with ionic liquids. *Adv. Funct. Mater.* **2022**, *32*, 2204259.

85 Mu, C. L.; Chen, Y.; Dai, Z.; Li, W.; Wang, J. F.; Jiao, X. L.; Chen, D. R.; Wang, T. Pom Functionalized ionogels with tunable optical, mechanical, electrical, and sensory properties. *Adv. Funct. Mater.* **2024**, *34*, 2313957.

86 Zhi, H.; Zhang, X. B.; Wang, F. Y.; Feng, L. A pH-sensitive, stretchable, antibacterial artificial tongue based on MXene cross-linked ionogel. *ACS Appl. Mater. Interfaces* **2022**, *14*, 52422–52429.

87 Zhang, J.; Xu, D.; Guo, J. N.; Sun, Z.; Qian, W. J.; Zhang, Y.; Yan, F. CO_2 responsive imidazolium-type poly(ionic liquid) gels. *Macromol. Rapid Commun.* **2016**, *37*, 1194–1199.

88 Zhang, L. H.; Shi, W. T.; Wang, J. Q.; Jin, L. M.; Hu, G.; Zheng, Q.; Xie, H. B.; Chen, P. Unique gelation and rheological properties of cellulose/CO2-based reversible ionic liquid/DMSO solutions. *Carbohydr. Polym.* **2019**, *222*, 115024.

89 Zhang, T.; Sun, B.; Qian, J.; Wang, T. Y.; Zhang, Y. S.; Xie, H. J.; Hua, C.; Qiang, Z.; Ren, J. Ultrabroad pressure sensing, ultrasensitive, multi-signal ionogel-based microneedles for wearable respiratory health monitoring. *Adv. Funct. Mater.* **2026**, *36*, e10723.

90 Rotjanasuworapong, K.; Lerdwijitjarud, W.; Sirivat, A. Dual electro- and magneto-induced bending actuators of magnetite-loaded agarose ionogels. *Carbohydr. Polym.* **2023**, *310*, 120741.

91 Fischer, L.; Menzel, A. M. Magnetostriction in magnetic gels and elastomers as a function of the internal structure and particle distribution. *J. Chem. Phys.* **2019**, *151*, 114906.

92 Zhang, X.; Zhang, L. S.; Liu, M. L.; Chng, C. B. Self-healing and hyperelastic magneto-iono-elastomers through molecular confinement of magnetic anions. *Sci. Adv.* **2025**, *11*, eadq7441.

93 Li, C. J.; Zhang, S. X.; Zhao, F.; Ye, Z. W.; Fu, Y. H.; Xiong, C. X.; Jiang, X. L.; Yao, J. L. Magnetic iongel/carbon nanotube composites for ultra-broadband electromagnetic wave absorption. *J. Mater. Chem. C* **2025**, *13*, 21383–21393.

94 Xie, Z.-L.; Jeličić, A.; Wang, F.-P.; Rabu, P.; Friedrich, A.; Beuermann, S.; Taubert, A. Transparent, flexible, and paramagnetic ionogels based on PMMA and the iron-based ionic liquid 1-butyl-3-methylimidazolium tetrachloroferrate(III) [Bmim][FeCl4]. *J. Mater. Chem.* **2010**, *20*, 9543.

95 Li, B. H.; Wang, Y. Z.; Xu, Y.; Xia, Z. G. Emerging 0D hybrid metal halide luminescent glasses. *Adv. Mater.* **2025**, *37*, 2415483.

96 Zhao, X. J.; Xu, J. H.; Zhang, J. Y.; Guo, M. R.; Wu, Z. L.; Li, Y. Y.; Xu, C.; Yin, H. Z.; Wang, X. L. Fluorescent double network ionogels with fast self-healability and high resilience for reliable human motion detection. *Mater. Horiz.* **2023**, *10*, 646–656.

97 Zhang, J. W.; Wang, Z. J.; Huo, X. X.; Meng, X.; Wang, Y.; Suo, H.; Li, P. L. Anti-counterfeiting application of persistent luminescence materials and its research progress. *Laser Photonics Rev.* **2024**, *18*, 2300751.

98 Yu, X. L.; Ryadun, A. A.; Pavlov, D. I.; Guselnikova, T. Y.; Potapov, A. S.; Fedin, V. P. Ln-MOF-based hydrogel films with tunable luminescence and afterglow behavior for visual detection of ofloxacin and anti-counterfeiting applications. *Adv. Mater.* **2024**, *36*, 2311939.

99 Zhang, T.; Li, Y.; Dunn, C. B.; Qian, J.; Wei, Z.; Tao, S. J.; Xie, H. J.; Zhang, C.; Qiang, Z.; Ren, J. Ultrabroad pressure sensing and highly sensitive gradient ionogel-based fluorescent flexible wearable bracelet. *ACS Sens.* **2025**, *10*, 7412–7426.

100 Xu, J.; Yang, Y.; Yang, J.; Yang, J.; Wang, Z. Mechanofluorescent

double network ionogels. *ACS Appl. Mater. Interfaces* **2025**, *17*, 47466–47473.
101 He, Z.; Song, J.; Wu, Z.; Jiang, P.; Zhou, L.; Huang, Z.; Tian, H.; Ma, X. Room temperature phosphorescence polymer ionogel with nucleation-induced dynamic reversible behavior. *Adv. Funct. Mater.* **2026**, *36*, e27649.
102 Kim, W.; Lee, K.; Choi, S.; Park, E.; Kim, G.; Ha, J.; Kim, Y.; Jang, J.; Oh, J. H.; Kim, H.; Jiang, W.; Yoo, J.; Kim, T.; Kim, Y.; Kim, K. N.; Hong, J.; Javey, A.; Rha, D. W.; Lee, T. W.; Kang, K.; Wang, G.; Park, C. Electrochemiluminescent tactile visual synapse enabling *in situ* health monitoring. *Nat. Mater.* **2025**, *24*, 925–934.
103 Xu, X. W.; Xie, Y.-M.; Shi, H. Y.; Wang, Y. Q.; Loh, X. J.; Li, B.-X.; Liu, S. J.; Chen, B.; Zhao, Q. Light management of metal halide scintillators for high-resolution X-ray imaging. *Adv. Mater.* **2024**, *36*, 2303738.
104 Wang, H.; Wang, J.-X.; Song, X.; He, T. Y.; Zhou, Y.; Shekhah, O.; Gutiérrez-Arzaluz, L.; Bayindir, M.; Eddaoudi, M.; Bakr, O. M.; Mohammed, O. F. Copper organometallic iodide arrays for efficient X-ray imaging scintillators. *ACS Cent. Sci.* **2023**, *9*, 668–674.
105 Han, J. H.; Samanta, T.; Park, Y. M.; Kim, H. J.; Manikanta Viswanath, N. S.; Kim, H. W.; Cha, B. K.; Cho, S. B.; Im, W. B. Highly stable zero-dimensional lead-free metal halides for X-ray imaging. *ACS Energy Lett.* **2023**, *8*, 545–552.
106 Gao, Z. Y.; Lv, H. Y.; Wang, Z. E.; Zhang, J. L.; Liu, Y. S.; Li, Y. J.; Zuo, F. Z.; Song, H. Z. Ultra-high stretchable, self-adhesive, and self-healable luminescent organogels with excellent anti-freezing and anti-fatigue performances for wearable sensors. *Chem. Eng. J.* **2025**, *514*, 163344.
107 Heng, W. Z.; Solomon, S.; Gao, W. Flexible electronics and devices as human–machine interfaces for medical robotics. *Adv. Mater.* **2022**, *34*, 2107902.
108 Chung, M.; Nirmale, V. S.; Reddy, V. S.; Koutsos, V.; Ramakrishna, S.; Radacsi, N. Enhancing the performance of wearable flexible sensors *via* electrospinning. *ACS Appl. Mater. Interfaces* **2025**, *17*, 39747–39771.
109 Xiao, W. Z.; He, T.; Cui, X. Y.; Wang, J.; Zhang, Y. Q.; Zhao, W. D.; Yan, J. P.; Sun, J. Ionogel-dominated wearable sensors for reliable health monitoring. *SusMat* **2025**, *5*, e70026.
110 Zhou, Q.; Zhu, C.; Xue, H. Y.; Jiang, L. M.; Wu, J. G. Flexible, wearable wireless-charging power system incorporating piezo-ultrasonic arrays and MXene-based solid-state supercapacitors. *ACS Appl. Mater. Interfaces* **2024**, *16*, 35268–35278.
111 Cao, W.; Lin, L. F.; Lammer, H.; Zhai, H. R.; Kuzhandaivel, D.; Huang, X. M.; Zhou, X.; Weng, Z. X.; Wu, L. X. Ultra-tough, high-strength ionogels enabling DLP 3D printing for wearable flexible electronics. *ACS Appl. Polym. Mater.* **2025**, *7*, 10860–10867.
112 Li, H. jing; Li, L.; Wei, J. jie; Chen, T.; Wei, P. Salt-adaptively conductive ionogel sensor for marine sensing. *Small* **2024**, *20*, 2305848.
113 Yu, Z. C.; Wu, P. Underwater communication and optical camouflage ionogels. *Adv. Mater.* **2021**, *33*, 2008479.
114 Shen, L. B.; Kong, T. T.; Yu, J. H.; Nan, F. C.; Wu, Z. L.; Li, B.; Li, J. H.; Yu, W. W. Self-polymerized metal-phenolic ionogel with multifunctional properties towards theranostic wearable electronics. *Acta Biomater.* **2025**, *199*, 154–165.
115 Chun, K. Y.; Seo, S.; Han, C.-S. Self-powered, stretchable, and wearable ion gel mechanoreceptor sensors. *ACS Sens.* **2021**, *6*, 1940–1948.
116 Zhi, H.; Qin, Y. X.; Li, Y.; Wang, F. Y.; Feng, L. A flexible, water anchoring, and colorimetric ionogel for sweat monitoring. *Biomater. Sci.* **2025**, *13*, 677–687.
117 Fan, L. Q.; Tu, Q. M.; Geng, C. L.; Wang, Y. L.; Sun, S. J.; Huang, Y. F.; Wu, J. H. Improved redox-active ionic liquid-based ionogel electrolyte by introducing carbon nanotubes for application in all-solid-state supercapacitors. *Int. J. Hydrog. Energy* **2020**, *45*, 17131–17139.
118 Zhou, J. Y.; Jiang, S.; Wang, Z. H.; Wang, C. H.; Tan, S.; Wu, Y. Propylene carbonate activated electrochemical performances of *in situ* polymerized ionogel electrolytes. *J. Power Sources* **2024**, *620*, 235243.
119 Sun, G. C.; Gao, J.; Li, H.; Chen, L. Q. Oxidized kinetic normal distribution models for sophisticated electrochemical windows. *J. Phys. Chem. C* **2023**, *127*, 9554–9561.
120 Khan, A.; Al Rashid, H.; Roy, P. K.; Chowdhury, S. I.; Sathi, S. A. Challenges and the way to improve lithium-ion battery technology for next-generation energy storage. *ENERGY Environ. Mater.* **2025**, *8*, e70088.
121 Hyun, W. J.; Thomas, C. M.; Luu, N. S.; Hersam, M. C. Layered heterostructure ionogel electrolytes for high-performance solid-state lithium-ion batteries. *Adv. Mater.* **2021**, *33*, 2007864.
122 Yu, L.; Yu, L.; Liu, Q.; Meng, T.; Wang, S.; Hu, X. L. Monolithic task-specific ionogel electrolyte membrane enables high-performance solid-state lithium-metal batteries in wide temperature range. *Adv. Funct. Mater.* **2022**, *32*, 2110653.
123 Igbaroola, B.; Demarthe, N.; Howlett, P.; Forsyth, M.; Kvasha, G.; Kvasha, A.; Sananes Israel, S.; Meatza, I. D.; Dupré, N.; Le Bideau, J. *in situ* phase separated ionogel electrolytes with enhanced properties for lithium metal batteries. *Chem. Eng. Sci.* **2025**, *316*, 121965.
124 N, A. B. J.; Sen, A. K.; Das, S. K. Effect of humidification and cell heating on the operational stability of polymer electrolyte membrane fuel cell. *Int. J. Hydrog. Energy* **2023**, *48*, 35267–35279.
125 Zou, M. D.; Luo, J.; Wang, X. R.; Tan, S.; Wang, C. H.; Wu, Y. *In situ* polymerized protic ionogels for fuel cells at elevated temperatures. *Ind. Eng. Chem. Res.* **2021**, *60*, 3589–3596.
126 Fan, X. Y.; Tian, C.; Xiao, H.; Gao, J.; Wang, Z. Q.; Song, C. Y.; Li, F.; Li, G. X. Synergizing interfacial passivation and ion-solvation engineering enables high-performance aqueous zinc-ion batteries. *J. Alloys Compd.* **2025**, *1038*, 182755.
127 Liu, X. R.; Li, H.; Liang, J. H.; Yin, J. Y.; Li, Z. Q.; Lu, Z. G. Advancing highly reversible zinc electrode: principles and strategies for electron and ion transport kinetics regulation. *Energy Storage Mater.* **2025**, *81*, 104446.
128 Zheng, R.; Jiang, N.; Wang, B. J.; Hou, C. Y.; Zhang, Q. H.; Wang, H.; Li, Y. G.; Li, K. R. Regulating the gradient water distribution *via* hydro-philic/phobic compositional design in ionogels for stable zinc ion batteries. *Chem. Eng. J.* **2025**, *513*, 162991.
129 Li, H. L.; Xu, F. C.; Li, Y.; Sun, J. Q. Self-healing ionogel-enabled self-healing and wide-temperature flexible zinc-air batteries with ultra-long cycling lives - Li 2024 Advanced Science Wiley Online Library. *Adv. Sci.* **2024**, *11*, 2402193.
130 Pan, F.; Wang, S.; Yong, Z. P.; Wang, X. D.; Li, C. L.; Liang, D.; Wang, X. R.; Sun, H.; Cui, Y. H.; Wang, Z. An all-solid-state flexible supercapacitor based on MXene/MSA ionogel and polyaniline electrode with wide temperature range, high stability, and high energy density. *Molecules* **2023**, *28*, 1554.
131 Mirzaei Saatlo, M.; Asghari, E.; Shekaari, H. Fabrication of solid state supercapacitors using phase change ionogel electrolytes based on 2-hydroxyethyl cellulose and protic ionic liquids with formate, acetate, and propionate as anions. *J. Energy Storage* **2025**, *108*, 115069.
132 Dai, H. L.; Zhang, G. X.; Rawach, D.; Fu, C.; Wang, C.; Liu, X. H.; Dubois, M.; Lai, C.; Sun, S. H. Polymer gel electrolytes for flexible supercapacitors: recent progress, challenges, and perspectives. *Energy Storage Mater.* **2021**, *34*, 320–355.
133 Tang, W. Y. ang; Dong, K. Y.; Chen, Z. L.; Duan, Y.; Sun, Q. H.; Li, X.; Zhai, D. M.; Lv, T.; Chen, T. A microphase-separation ionogel

electrolyte for highly stretchable all-solid-state supercapacitors. *Chem. Eng. J.* **2024**, *501*, 157726.
134 Wang, B.; Zhang, W.; Zhao, F. F.; Yu, W. W.; Elezzabi, A. Y.; Liu, L. H.; Li, H. Z. An overview of recent progress in the development of flexible electrochromic devices. *Nano Mater. Sci.* **2023**, *5*, 369–391.
135 Qian, C.; Wang, P.; Guo, X.; Jiang, C. Y.; Liu, P. High-contrast energy-efficient flexible electrochromic devices based on viologen derivatives and their application in smart windows and electrochromic displayers. *Sol. Energy Mater. Sol. Cells* **2024**, *266*, 112669.
136 Kim, S.; Yeo, J.; Kim, S. J.; Park, S.; Cho, K. G.; Paeng, K.; Lee, K. H.; Kim, M. Photopatternable and self-healable ionogels for organic thin-film transistors. *Org. Electron.* **2023**, *122*, 106895.
137 Vinh Quy, V. H.; Kim, K.-W.; Yeo, J.; Tang, X.; In, Y. R.; Jung, C.; Oh, S. M.; Kim, S. J.; Lee, S. W.; Moon, H. C.; Kim, S. H. Tunable electrochromic behavior of biphenyl poly(viologen)-based ion gels in all-in-one devices. *Org. Electron.* **2022**, *100*, 106395.
138 Poh, W. C.; Eh, A. L.-S.; Wu, W.; Guo, X.; Lee, P. S. Rapidly photocurable solid-state Poly(ionic liquid) ionogels for thermally robust and flexible electrochromic devices. *Adv. Mater.* **2022**, *34*, 2206952.
139 Zhou, K. J.; Tang, L.; Kuang, G. Q.; Zhang, J.; Li, Z. Y.; Xing, G. Q.; Jiang, X. A.; Chen, Z. Y.; Tao, Y. J.; Zhang, Y.; Zhang, S. G. Supramolecular ionogels enable highly efficient electrochromism. *Mater. Horiz.* **2025**, *12*, 1992–2001.
140 Oh, S. J.; Bae, J. W. All-in-one plasticized ionogel-based stretchable electrochromic devices. *Chem. Eng. J.* **2023**, *467*, 143367.
141 Kushida, S.; Kebrich, S.; Smarsly, E.; Strunk, K.-P.; Melzer, C.; Bunz, U. H. F. Light-emitting electrochemical cells based on conjugated ion gels. *ACS Appl. Mater. Interfaces* **2020**, *12*, 38483–38489.
142 Gomes, J. M.; Silva, S. S.; Reis, R. L. Biocompatible Ionic Liquids: fundamental behaviours and applications. *Chem. Soc. Rev.* **2019**, *48*, 4317–4335.
143 Morandeira, L.; Danho, M.; Markiewicz, M.; Stolte, S.; Sanromán, M. Á.; Rodríguez, A.; Deive, F. J. Sketching a suitable immobilization strategy for ionic liquid removal in a fixed-bed bioreactor. *ACS Sustain. Chem. Eng.* **2019**, *7*, 4307–4314.
144 Yang, J. Y.; Zhou, E.-Y.; Cheng, T.-H.; Liu, P.-H.; Hsieh, W.-C.; Cheng, H. C.; Hong, Y.-K.; Lin, Y.-C.; Hsu, Y.-C.; Yang, C.-C.; Hsu, C.-K.; Kuo, L.-C.; Hsieh, S.-C.; Chuang, C.-H. Injectable deep eutectic solvent-based ionic gel with rapid gelation and broad hemostatic functionality. *Adv. Healthc. Mater.* **2025**, e03038.
145 Su, Q. Q.; He, X. L.; Wang, S.; Song, H. D.; Dong, J. Choline-amino acid-based polyionic liquids and ionogels for antimicrobial infections. *Mater. Today Commun.* **2024**, *40*, 109593.
146 Zhang, Z. Y.; Peng, D. J.; Shang, X. Y.; Zhao, X.; Ren, S. X.; Pang, J. Y.; Li, S. J. Ultra-tough light-curing ionogels for UV shielding. *Commun. Mater.* **2024**, *5*, 259.
147 Zhou, Q. L.; Dong, L. S.; Wu, J.; Shi, Y. J.; Feng, X.; Lu, X. H.; Zhu, J. H.; Mu, L. W. Versatile ionic gel driven by dual hydrogen bond networks: toward advanced lubrication and self-healing. *ACS Appl. Polym. Mater.* **2021**, *3*, 5932–5941.
148 Arafune, H.; Watarai, Y.; Kamijo, T.; Honma, S.; Sato, T.; Arafune, H.; Watarai, Y.; Kamijo, T.; Honma, S.; Sato, T. Mechanical and lubrication properties of double network ion gels obtained by a one-step process. *Materials* **2022**, *15*, 2113.
149 Yu, Q. L.; Wu, Y.; Li, D. M.; Cai, M. R.; Zhou, F.; Liu, W. M. Supramolecular ionogel lubricants with imidazolium-based ionic liquids bearing the urea group as gelator. *J. Colloid Interface Sci.* **2017**, *487*, 130–140.
150 Yu, M. Q.; Chen, S. R.; Yu, X. D. Reusable, green, portable ionogels based on terpyridine-imidazole salt for visual monitoring of pork spoilage. *Langmuir* **2024**, *40*, 11713–11722.
151 Chun, S.; Son, W.; Kim, D. W.; Lee, J.; Min, H.; Jung, H.; Kwon, D.; Kim, A.-H.; Kim, Y.-J.; Lim, S. K.; Pang, C.; Choi, C. Water-resistant and skin-adhesive wearable electronics using graphene fabric sensor with octopus-inspired microsuckers. *ACS Appl. Mater. Interfaces* **2019**, *11*, 16951–16957.
152 Long, F.; Zhang, X. W.; Li, X.; Sun, F.; Zhou, T.; Liu, L. Ultrathin water-responsive zwitterionic hydrogel brush coatings for long-term corrosion protection. *ACS Appl. Mater. Interfaces* **2024**, *16*, 1416–1427.
153 Yang, J.; Shen, M. Y.; Luo, Y.; Wu, T.; Chen, X. X.; Wang, Y. X.; Xie, J. H. Advanced applications of chitosan-based hydrogels: from biosensors to intelligent food packaging system. *Trends Food Sci. Technol.* **2021**, *110*, 822–832.
154 Delisi, D.; D'Amora, U.; Scarpa, E.; Sodano, F.; Schiano, M. E.; Pinheiro, N.; Engevik, M.; Gentile, S.; Fasolino, I. A smart injectable hydrogel packaged with an ion channel activator molecule as a targeted delivery system for the treatment of cancer. *ACS Appl. Mater. Interfaces* **2025**, *17*, 38947–38959.
155 Shi, Y. K.; Wu, B. H.; Sun, S. T.; Wu, P. Y. Peeling–stiffening self-adhesive ionogel with superhigh interfacial toughness. *Adv. Mater.* **2024**, *36*, 2310576.
156 Ge, G.; Mandal, K.; Haghniaz, R.; Li, M. C.; Xiao, X.; Carlson, L.; Jucaud, V.; Dokmeci, M. R.; Ho, G. W.; Khademhosseini, A. Deep eutectic solvents-based ionogels with ultrafast gelation and high adhesion in harsh environments. *Adv. Funct. Mater.* **2023**, *33*, 2207388.
157 Yi, Y. X.; He, H. F.; Liu, L.; Sun, N.; Zhou, K. Q.; Qian, X. D.; Shi, C.; Hu, Y.; Yu, B. Mechanically-robust phosphorus-contained ionogels by UV-curing for fire warning and fire protection. *Polymer* **2025**, *338*, 129058.
158 Zhao, Y. N.; Zeng, Q. T.; Jiang, C. C.; Lai, X. J.; Li, H. Q.; Wu, Z. Z.; Zeng, X. R. Self-powered, durable and high fire-safety ionogel towards internet of things. *Nano Energy* **2023**, *116*, 108785.
159 Yu, Y. F.; Yang, X.; Zhang, C. C.; Chen, J.; Lin, W.; Meng, J. Q. A tough double-network ion gel membrane based on poly (ionic liquid) for efficient carbon capture. *Sep. Purif. Technol.* **2024**, *331*, 125591.
160 Xiao, X.; Wang, M. X.; Chen, S. S.; Zhang, Y. H.; Gu, H. Y.; Deng, Y. H.; Yang, G.; Fei, C. B.; Chen, B.; Lin, Y. Z.; Dickey, M. D.; Huang, J. Lead-adsorbing ionogel-based encapsulation for impact-resistant, stable, and lead-safe perovskite modules. *Sci. Adv.* **2021**, *7*, eabi8249.
161 Tamate, R.; Ueki, T. Adaptive ion-gel: stimuli-responsive, and self-healing ion gels. *Chem. Rec.* **2023**, *23*, e202300043.
162 Yiming, B.; Guo, X.; Ali, N.; Zhang, N.; Zhang, X.; Han, Z.; Lu, Y.; Wu, Z.; Fan, X.; Jia, Z.; Qu, S. Ambiently and mechanically stable ionogels for soft ionotronics. *Adv. Funct. Mater.* **2021**, *31*, 2102773.
163 Zhang, M.; Yu, R.; Tao, X.; He, Y.; Li, X.; Tian, F.; Chen, X.; Huang, W. Mechanically robust and highly conductive ionogels for soft ionotronics. *Adv. Funct. Mater.* **2023**, *33*, 2208083.
164 Liu, X.; Taiwo, O. O.; Yin, C.; Ouyang, M.; Chowdhury, R.; Wang, B.; Wang, H.; Wu, B.; Brandon, N. P.; Wang, Q.; Cooper, S. J. Aligned ionogel electrolytes for high-temperature supercapacitors. *Adv. Sci.* **2019**, *6*, 1801337.