Progress in Energy

Check for updates

TOPICAL REVIEW

RECEIVED
2 October 2025

REVISED
2 December 2025

ACCEPTED FOR PUBLICATION
14 April 2026

PUBLISHED
27 April 2026

Recent progress in iontronic power sources based on nanoconfined ion modulation

Puguang Peng[1,2], **Han Qian**[1,2], **Zhonglin Wang**[1,3,*] and **Di Wei**[1,*]

[1] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, People's Republic of China
[2] School of Nanoscience and Engineering, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[3] Beijing Key Laboratory of Micro-Nano Energy and Sensor, Center for High-Entropy Energy and Systems, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, People's Republic of China
[*] Authors to whom any correspondence should be addressed.

E-mail: zlwang@binn.cas.cn and weidi@binn.cas.cn

Keywords: iontronics, nanoconfined, ion modulation, field-effect, iontronic power, ion dynamics

Abstract

Iontronic power sources exploit the coupled transport of ions and electrons within liquids, gels, and nanoconfined architectures to realize energy harvesting, conversion, and storage beyond the scope of conventional electronics. Unlike systems governed solely by electron flow, iontronics harnesses the dynamic, selective, and field-responsive nature of ionic transport, offering unique advantages in flexibility, bio-integration, and multifunctionality. This review delineates the nanoconfined ion dynamics and the principal mechanisms underlying iontronic power sources, including osmotic gradients, moisture-driven nanoconfined ion transport, and field-modulated ionic dynamics. We then examine recent technological advances that leverage nanoconfined ion modulation to enhance performance metrics. Finally, we outline emerging opportunities and future directions for iontronic power sources, highlighting their potential to transform energy technologies at the interface of materials science, bioelectronics, and nanotechnology.

1. Introduction

The past decade has witnessed a paradigm shift in energy science, driven by the demand for sustainable, miniaturized, safety and bio-integrated power technologies [1]. Beyond conventional electrochemical batteries and capacitors, iontronic power sources have emerged as a new frontier for energy conversion and storage based on ion modulation [2, 3]. It directly exploits the mobility, selectivity, and spatiotemporal transport of ions, thereby enabling unique advantages such as operation in complex aqueous or moisture environments, compatibility with soft and flexible platforms, and intrinsic coupling with external fields and biological signals. Within this research landscape, diverse ionic materials, ranging from ionic liquids and ion gels to polymer-based ionic conductors, have provided valuable platforms for studying ion transport and electrical double layer (EDL) phenomena [4, 5]. These materials illustrate how tuning interfacial interactions and ionic environments can influence ionic mobility, interfacial capacitance, and charge screening, thereby enriching the conceptual foundation of iontronic processes.

Based on these established ionic systems, nanoconfined ion modulation is emerging as a central paradigm in the development of iontronic power sources, as it enables control over ion transport dynamics, enhances the efficiency of ionic energy conversion, and facilitates the seamless coupling of ionic processes with multifunctional electrical outputs [6]. Recent progress has demonstrated diverse strategies to modulate ion dynamics and expand the versatility and performance of iontronic power sources. These systems can be classified according to the fundamental transport behavior of ions (including diffusion, convection and migration), which leads to the emergence of iontronic power sources based on osmotic-driven ionic gradients, moisture-induced ion transport, and field-effects driven ion dynamics (such as photoelectric, piezoelectric and thermoelectric field-driven ion dynamics, etc). Among them, the field-effects driven ion dynamics is an important and rapidly developed method to enhance ion transport by ionic-electronic coupling [2, 7]. All these strategies and advances not only deepen the

© 2026 IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

understanding of fundamental ion dynamics, but also enable the development of devices that bridge energy harvesting, storage, and conversion with flexible electronics, bio-integrated interfaces and multi-functional energy to information applications.

Herein, this review first introduces the fundamental concepts and governing principles of nanoconfined ion dynamics, which underpin ion transport and modulation in nanoconfined systems. Second, we highlight recent progress in iontronic power sources based on nanoconfined ion modulation, including osmotic energy harvesting, moisture-enabled systems, and external-field-driven ion dynamics. Next, we summarize key technological advances, covering multi-field coupling strategies, device architecture design, and emerging scalable fabrication approaches. Finally, we provide a forward-looking outlook that discusses the opportunities and challenges for translating iontronic power sources into practical applications spanning high-performance energy harvesting, wearable and implantable iontronics, and intelligent bio-interfaces.

2. Nanoconfined ion dynamics

Nanoconfined ion dynamics describe the distinct behaviors of ions when confined within nanoscale spaces such as nanochannels, nanopores, and nanotubes, where conventional bulk transport laws break down and interfacial interactions become dominant [8]. Unlike in bulk solutions, ion dynamics under nanoconfinement are strongly influenced by the overlap of EDLs, geometric constraints, and surface charge distributions [9]. These effects collectively reshape ion-solvent interactions and ion-surface coupling, giving rise to unique transport phenomena that are foundational to emerging iontronic systems. The characteristic length scale of these effects is influenced by surface proximity, such as the size of pores or the shrinking of interspacing. These effects arise from different types of interactions, including steric and hydration interactions (typically in the 1–2 nm range), van der Waals forces (1–50 nm), and electrostatic interactions (1–100 nm) [10, 11]. In detail, hydration interactions, based on hydrogen bonding, are generally repulsive. To bring two hydrophilic surfaces closer, it is necessary to disrupt the hydrogen-bonding network between them. Van der Waals interactions arise from induced dipoles caused by instantaneous fluctuations in charge distribution around atoms and molecules. Electrostatic interactions occur in ionic solutions near charged surfaces, known as the EDL or Debye length, which typically ranges from 1 to 100 nm under most ionic conditions.

As shown in figures 1 (a), a central feature of nanoconfined ion dynamics is enhanced ion transport. When ions migrate through nanoconfined channels, overlapped EDLs generate strong local electrostatic fields that lower transport resistance and accelerate ion transport. In addition, nanoconfinement often induces partial or complete dehydration of hydrated ions, which reduces their effective size and facilitates faster passage through channels. These mechanisms jointly enhance ionic conductivity and transport efficiency beyond what is typically observed in bulk electrolytes [12]. Another defining feature is ion selectivity, whereby different ionic species display distinct transport behaviors governed by steric exclusion, dehydration energetics, electrostatic interactions, and the chemical specificity of channel surfaces (figure 1(b)). For example, channels with dimensions comparable to the hydration radius may preferentially allow smaller or weakly hydrated ions to pass, while charged surfaces can attract counter-ions and repel co-ions, creating selective ion transport. Surface functionalization and environmental factors such as pH, ionic strength, or applied fields further fine-tune selectivity, enabling precise ionic sieving and separation [10]. A third key phenomenon is ionic rectification, which refers to the asymmetric or unidirectional transport of ions under an external bias, analogous to electronic diodes (figure 1(c)). Rectification typically arises from geometric asymmetry (e.g. conical channels), uneven surface charge distributions, or nonuniform EDL overlap, which together create direction-dependent transport resistances. The interplay of these factors allows ions to flow preferentially in one direction, an effect that can be modulated by ion species, concentration, and temperature [13].

Beyond these passive behaviors, external-field modulation of nanoconfined ion dynamics provides an active way of ionic control. Optical, electrical, thermal, and mechanical fields can regulate ion transport by altering interfacial charge distributions, local electrostatic potentials, or ion hydration states [7]. Such external-field strategies enable the iontronic power sources to harvest energy from environments. Together, these phenomena define the essence of nanoconfined ion dynamics from nanoconfined materials and channels, interfacial engineering and field modulation, leading to enhanced performance and new functionalities in iontronic power sources.

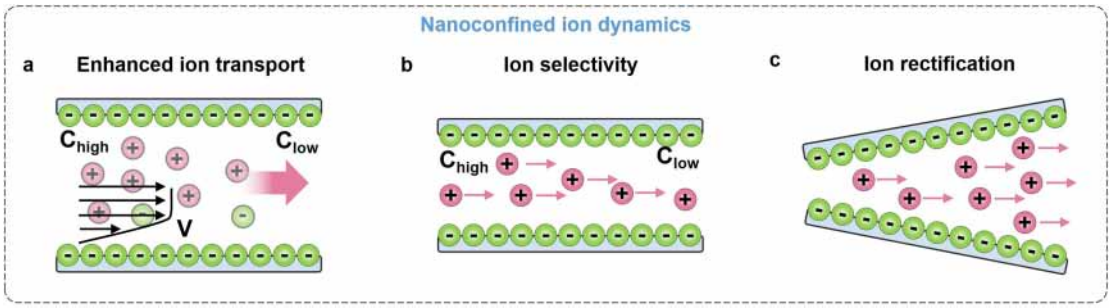

Figure 1. Nanoconfined ion dynamics. (a) Enhanced ion transport in nanoconfined channels based on overlapped EDLs. (b) Ion selectivity in nanoconfined channels. (c) Ion rectification in asymmetric nanoconfined channels.

3. Iontronic power source based on nanoconfined ion modulation

3.1. Energy from osmotic effect

Iontronic power source driven by ionic gradients, commonly known as blue osmotic power, arises from the free energy released when ions diffuse spontaneously along a concentration gradient between two solutions of different salinity [14]. This chemical potential difference can be converted into electricity if ion transport is directed through selective membranes or channels, making osmotic power one of the most sustainable and continuous energy sources available (figure 2(a)). Since reverse electrodialysis (RED) system, the development of osmotic power has been nearly 120 years old and has become the origin of iontronic power sources [15]. The research on selectivity and permeability of ions through ion-exchange membranes is a continuous and cutting-edge direction in this field, which has been thoroughly reviewed by many literatures [16]. So far, inspired by biological ionic channels, materials with nanoconfined and charged structures have been widely employed to build nanoconfined channels that enhance ion selectivity and mobility [17, 18], such as molybdenum disulfide (MoS_2), graphene oxide (GO), and anodic aluminum oxide, etc. These channels are also generally classified as 0 dimensional nanopores, one dimensional nanochannels, two-dimensional (2D) nano-slits and three-dimensional (3D) nano-hierarchies based on ion transport pathways [19], as shown in figure 2(b). The overlapped EDLs in these nanoconfined systems enable continuous energy generation from asymmetric ion transport and rectification, with additional real-applications in desalination and self-powered iontronic system [11, 20]. For example, RED requires a highly concentrated solution and, thus, could be coupled with desalination processes for the simultaneous generation of renewable energy and drinking water, while minimizing the environmental impact of brine disposal [21]. Emblematically, the use of single-layer molybdenum disulfide (MoS_2) nanopores as osmotic nano-power generators could produce an estimated power density of up to 10^6 W m^{-2} and self-power a MoS_2 transistor [22].

Recently, ion channels have been engineered with increasing precision and complexity, leading to superior discharge performance for osmotic power. These strategies regulate ion transport pathways through structural design or by tuning the physicochemical properties of the channels, thereby enhancing ionic energy by influencing ion selectivity, mobility, and transport rate. For example, Turing-type nanochannel membranes have also been developed (figure 2(c)), in which extrinsically interwoven channels between adjacent lamellae markedly enlarge both the effective transport pathways and the active interfacial area. This structural feature enhances the ionic current by 23% while preserving a high cation selectivity of 0.91 [23]. Furthermore, an osmotic power source fabricated from lithographically defined double-walled carbon nanotubes with an inner diameter of 2.3 nm (figure 2(d)), which constrains ion transport through overlapped EDL and straight ionic pathway, achieving an impressive power density of 22.5 kW · m^{-2} [24]. Another attractive approach employs covalent organic framework (COF)-based nanochannels, where interfacial polymerization and specific coordination with various ions yield highly axially aligned frameworks (figure 2(e)). A representative Ca-COF exhibits a cation selectivity of 0.93, an ionic conductivity of 0.06 S · m^{-1}, and delivers a power density of 320.8 W · m^{-2} in a real seawater-/river water configuration [25]. In addition, tailoring the channel entrances can effectively facilitate directional ion transport and improve selectivity, enabling high-efficiency energy conversion. For instance, a robust mushroom-shaped (stem-and-cap) nanochannel array membrane incorporating an ultrathin selective layer and extremely high pore density has been developed (figure 2(f)), delivering a power density of up to 22.4 W · m^{-2} under a 500-fold salinity gradient [26].

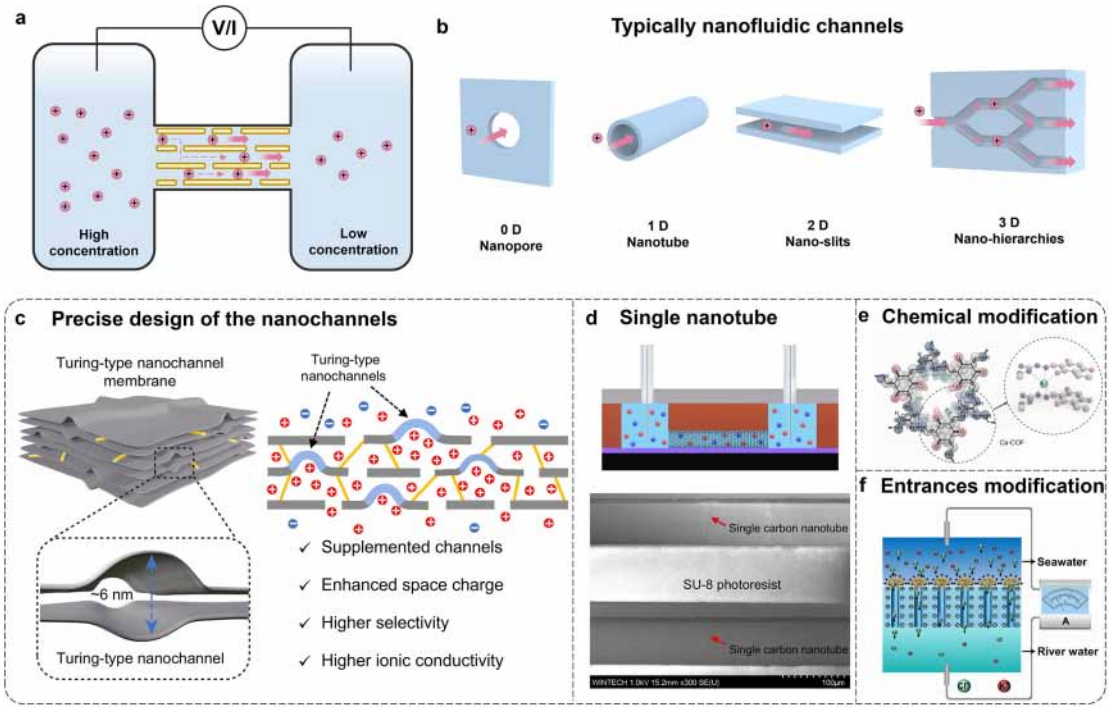

Figure 2. Iontronic power source based on osmotic effect. (a) Mechanism of the energy from osmotic effect. (b) Structure diagram of the typical nanoconfined channels. (c) Structure diagram and advantages of the Turing-type nanochannel. Reproduced with permission from [23]. CC BY-NC-ND 4.0 (d) device diagram and SEM photo of the single carbon nanotube. Reproduced from [24]. CC BY 4.0. (e) The pore and coordination structure of the Ca-COF. Reproduced from [25], with permission from springer nature. (f) Illustration of the osmotic power source based on the mushroom-shaped nanochannel array. Reproduced with permission from [26]. CC BY-NC-ND 4.0.

One of the current development trends in osmotic iontronics lies in harvesting energy from complex and harsh environments. For instance, NaX zeolite molecular sieve membranes can operate effectively under highly alkaline conditions. Under practical conditions, the devices yield power densities of 29.1 $W \cdot m^{-2}$, 81.0 $W \cdot m^{-2}$, and 380.1 $W \cdot m^{-2}$ for red sea/river, dead sea/river, and Qinghai brine/river configurations, respectively [27]. In addition, leveraging the chemical stability of MXene, a horizontally oriented MXene membrane featuring sequential ion-transport nanochannels has been developed. This architecture is engineered to remain stable in highly saline–alkaline environments while simultaneously improving ion selectivity and permeability. Under a 1000-fold salinity gradient in alkaline NaOH solution, it delivers a peak osmotic power density of 32.95 $W \cdot m^{-2}$ along with an impressive energy conversion efficiency of 48.67% [28].

3.2. Moisture-enabled iontronic power sources

Moisture-enabled iontronic power sources, as another kind of the osmotic power, capitalize on the strong correlation between environmental humidity and ion transport in hydrophilic or hygroscopic materials [3]. Such devices often do not have a liquid pool themselves, so they have the advantage of being all solid state compared to osmotic devices, and can be miniaturized and scalable. By absorbing water molecules from the environment, ion-containing hydrogels or hydrophilic materials generate an internal ionic flow or gradient that can be harvested as an electrical signal [29–32]. This mechanism not only allows for self-sustained energy generation from ambient humidity but also enables direct integration with soft, deformable substrates.

Recent developments have demonstrated programmable, moisture-activated iontronics, which may offer cost-effective, disposable, and environmentally adaptive energy solutions. For example, a heterogeneous moisture-enabled electric generator (HMEG) constructed from a polyelectrolyte bilayer is capable of producing a voltage of approximately 1.38 V per unit at 85% relative humidity (RH) [33]. Its operation relies on the spontaneous uptake of atmospheric water molecules and the resulting diffusion of oppositely charged ions (figure 3(a)). When multiple large-area HMEG units are sequentially stacked, the system can generate voltages exceeding 1000 V under ambient conditions (25% RH, 25 °C). Moreover, GO is a common material in this field, because of its rich surface hydrophilic functional groups, with hygroscopicity [32, 34] (figure 3(b)). A GO-based fully printable moisture power source was prepared

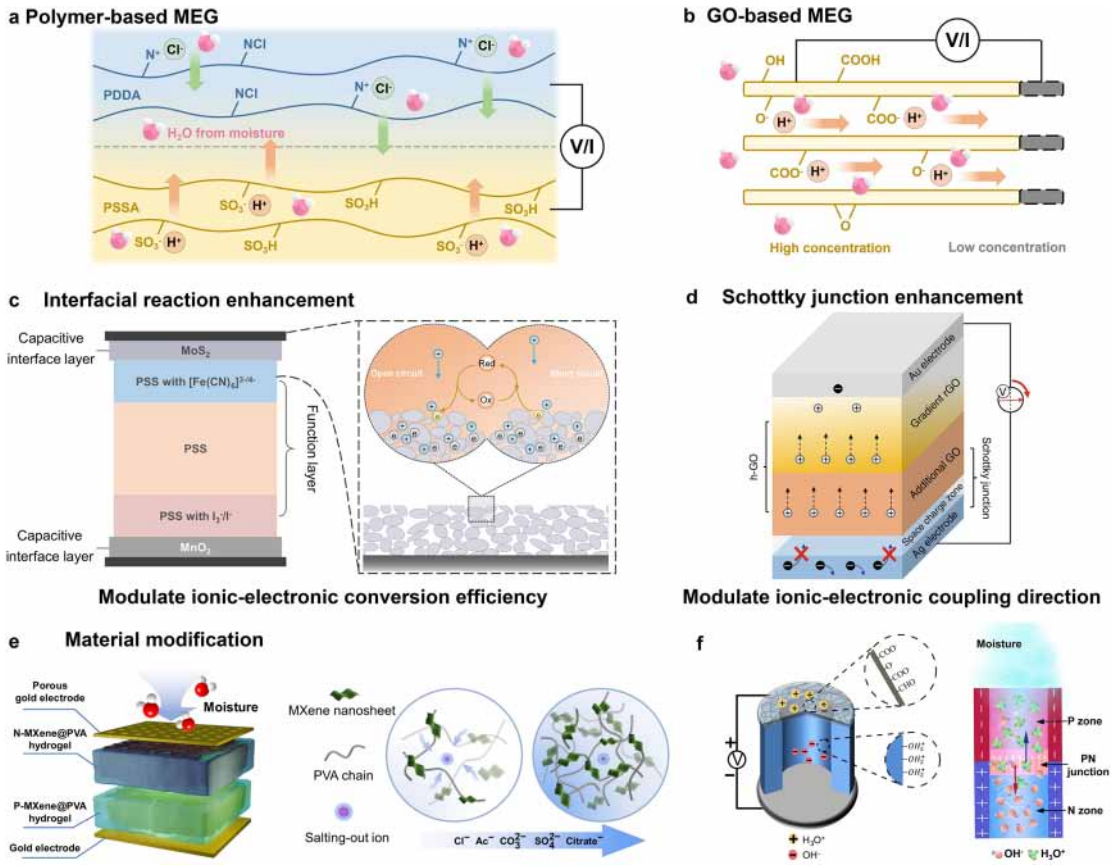

Figure 3. Moisture-enabled iontronic power sources. (a) Mechanism of the polymer-based MEG. (b) Mechanism of the GO-based MEG. (c) Schematic diagram of the interfacial reaction modulation for MEG performance enhancement. Reproduced with permission from [30]. CC BY-NC-ND 4.0. (d) Schematic diagram of the Schottky junction design to modulate the ionic-electronic coupling direction. Reproduced from [29]. CC BY 4.0. (e) Schematic diagram of the structural composition of polyvinyl alcohol/MXene hydrogel and the effect of salting-out ions on the cross-linking process of gel network. Reproduced with permission from [36]. CC BY-NC-ND 4.0. (f) Schematic diagram of the functional groups existing on the hybrid membrane surface and the mechanism of the PN junction realized MEG. Reproduced from [37]. CC BY 4.0.

with safe, disposable, and cost-effective properties. In the presence of moisture, cations are transported from the high-concentration side to the low-concentration side, creating a potential difference ∼1.2 V for single unit [35].

To enhance the performance of moisture-enabled ionic energy devices, holistic design is typically required, with the essential goal of improving the efficiency of ion storage, transport, and conversion into electricity. For example, to address the limited ion reservoir in hygroscopic functional materials, an ionic-electronic conversion-enhanced moisture energy harvester was developed by constructing an ion-rich storage interface while concurrently activating faradaic reactions via dual redox couples at the functional layer/electrode boundaries (figure 3(c)). This architecture delivers a record peak current of 9.2 mA cm^{-2} and a power density of 6.7 W m^{-2}, approximately 60 times higher than that of previously reported moisture-electricity generators [30]. Furthermore, a high-performance hydroelectric generator unit with an output voltage close to 1.5 V was achieved using hygroscopic heterogeneous GO integrated with Schottky junctions at the material/electrode interfaces [29] (figure 3(d)). Specifically, when hygroscopic GO absorbs moisture, a vertical proton gradient is established across the layered GO structure, driving proton migration upward. At the bottom Ag electrode, the lower work function forms a Schottky barrier with the GO layer, creating a space-charge region that restricts the backflow of electrons into the GO. The work function from Schottky junctions could efficiently tailor the flow of free electrons in an external circuit to be consistent with the direction of proton migration, greatly enhancing the final voltage output. These interfacial strategies provide new insights into the design and development of moisture-enabled iontronic power sources for practical applications.

From a materials perspective, a polyvinyl alcohol/MXene hydrogel with a multiscale ordered network was constructed, where the salting-out effect enables a synergistic enhancement of ionic conductivity, ion selectivity, and channel stability, all of which are critical for achieving high power densities [36] (figure 3(e)). In addition, a nanoconfined diode-type hybrid membrane was developed, in which the

built-in electric field from a PN junction facilitates selective ion separation and steady-state unidirectional ionic charge transfer (figure 3(f)). At 93% RH and 25 °C, this device delivered an open-circuit voltage (VOC) of 1.1 V and a short-circuit current of 7.7 μA, and the optimized system could operate stably over one month [37].

Since humidity is ubiquitous, moisture-powered generators have become well-recognized for applications in wearable electronics, such as masks, fibers, and smart textiles [3]. Recently, several novel mechanisms have been proposed that expand the application scope of moisture generators, particularly in environmental adaptability and electronic integration. For example, an anion-hybridized organic gel was developed that can operate in extreme cold environments at −30 °C, producing a voltage of 0.67 V and a stable output of 86.2 μA cm^{-2} [38]. This approach regulates the dynamics of the hydrogen-bond network via cooperative interactions between anionic salts and organic solvents, effectively inhibiting ice nucleation while enhancing ion dissociation. In addition, a simple method has recently been introduced to transform fallen leaves into moisture-powered energy harvesters by applying surface treatments and asymmetrically coating them with hygroscopic iron-based hydrogels. Exploiting the water absorption and retention capacity of leaf veins, iron-ion double layers form on the leaf surface, yielding an output of 49 μA cm^{-2} and 497 μW cm^{-3} [39]. In addition, an electromagnetic-moisture coupled wireless energy interactive system has been reported, which can synergistically harvest electromagnetic and moisture energy [40]. The absorbed electromagnetic energy drives directional migration of charge carriers and internal ionic currents. This energy interaction mechanism enables all-in-one device integration of antenna, rectifier, capacitor, and other components. Moisture generators can also serve as auxiliary units for conventional energy sources. For instance, a flexible moisture-driven supercapacitor has been fabricated that can spontaneously self-charge and stabilize its voltage by absorbing water from the air [31]. It provides a voltage output of ∼0.9 V under 90% RH and sustains continuous discharge for over 120 h at a current density of 10 μA cm^{-2}.

Osmotic power based on ion diffusion constitutes the foundation of iontronic power sources. Coupling osmotic power with other energy harvesting technologies, such as solar or mechanical energy, is also a current research hotspot in iontronic power sources. However, we categorize these approaches under field-driven ion dynamics, since most of them involve ionic-electronic coupling through external fields actively regulate ionic dynamics, which will be introduced in the following section. Besides, some devices rely solely on the motion of water molecules, converting the inherent energy of evaporation, rainfall, or small water flows into usable electricity. Based on solid-liquid contact electrification or triboelectric mechanisms, these devices transform the motion of water and vapor into electric power [41, 42]. Compared with ion-water interaction-based conversion, this approach offers higher water utilization efficiency and holds promise as a more efficient and sustainable method for clean energy harvesting in the future.

3.3. External field-driven ion dynamics for iontronic power sources

External field-driven ionic dynamics represents a novel paradigm for energy conversion, typically involving active regulation of ions through ionic-electronic interactions [2, 7]. This contrasts with conventional permeability and humidity ion electronics devices that rely on ion diffusion or ionic-water interactions to generate electricity. External field-driven iontronic systems utilize physical or chemical stimuli, such as electric fields, chemical reaction, light irradiation, thermal, mechanical pressure, or magnetic, etc, to actively modulate ion dynamics [2, 7]. These approaches enable the coupling of external field-effects with ion transport, resulting in tunable energy output. For instance, photoelectric effect can trigger electron and hole separation, and then induce local ionic redistribution by built-in photoelectric field [43]; mechanical pressure can modulate ionic migration through deformation or piezoelectric effect [44], etc. These strategies pave a way for the development of intelligent iontronic power sources that are high-performance, adaptive, and capable of multi-functionalities in distribute systems.

Specifically, recent studies have revealed that the built-in electric fields arising from interfacial chemical reactions can greatly enhance ion transport dynamics [45] (figure 4(a)). By tailoring interfacial redox reactions to couple with the efficient transport of alkali metal ions within GO-based 2D nanoconfined channels, iontronic power source has been developed with power densities as high as 15 900 W · m^{-2} [46]. Such devices can also be fabricated by printing on arbitrary substrates (e.g. polymers, paper, textiles) and integrated with diverse electronic systems to construct adaptive energy management systems (integrated with triboelectric nanogenerators) and wireless sensing systems (temperature sensors with NFC circuits), demonstrating enormous potential for soft, wireless, and conformable disposable electronics [47, 48].

In addition, benefiting from the mature development of photovoltaic, thermoelectric, and piezoelectric technologies, related strategies have also been widely employed in ionic energy harvesting [52, 53].

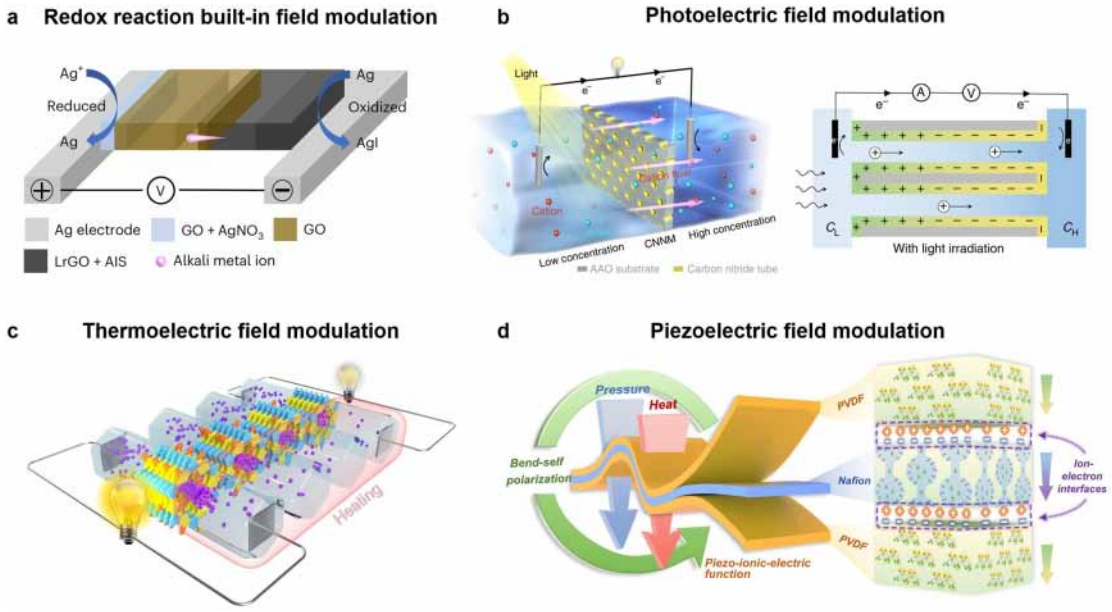

Figure 4. Field-driven ion dynamics for iontronic power sources. (a) Schematic diagram of the interfacial redox reaction modulates ion dynamics. Reproduced with permission from [45]. CC BY-NC-ND 4.0. (b) Schematic diagram and mechanism of the photoelectric field-driven ion dynamics. Reproduced from [49]. CC BY 4.0. (c) Working mechanism of the thermoelectric field-driven ion dynamics. [50] John Wiley & Sons. [© 2022 Wiley-VCH GmbH]. (d) Schematic diagram and mechanism of the piezoelectric field-driven ion dynamics. Reproduced from [51]. CC BY 4.0.

For instance, a carbon nitride nanotube membrane was used to construct an artificial light-driven ion pump system that drives ions thermodynamically uphill against concentration gradients up to 5000-fold under illumination [49] (figure 4(b)). When applied for solar energy harvesting, it reliably generated a sustained VOC of 550 mV and a current density of 2.4 $\mu A \cdot cm^{-2}$. Thermal ionic energy could be harvested by thermal ion diffusion (Soret effect) under the temperature difference [50, 54, 55]. To improve the thermal ionic modulation performance, general strategy is developing the materials with high Seebeck coefficient. For example, recently developed polymer electrolyte, with large Seebeck coefficient of ~10 000 μVK^{-1}, could be used as a low-voltage ionic thermoelectric gate to process the thermal information [56]. In the nanoconfined system, COF membranes could enable direct conversion of thermal and osmotic energy into electricity (figure 4(c)). The enhanced charge density within the channels improves both osmotic selectivity and ionic conductivity, resulting in increased osmotic voltage and current. When operating under simulated estuarine temperature differences of 60 K, the optimal COF membrane achieves a power density of approximately 231 W m^{-2} [50]. In addition, by applying a temperature gradient in the solution to enhance the thermal mobility of ions, the effect of concentration polarization can be significantly reduced, achieving an output power density up to 24.7 mW cm^{-2} at a temperature difference of ~40 K [57].

The piezoelectric effect of materials such as polyvinylidene difluoride (PVDF) also holds great promise for applications in flexible sensing and energy harvesting. For example, an all-polymer piezo-iontronic system has been reported, highlighting the impact of interfacial ordering and strong polarization effects between piezoelectric polymers and mobile organic ions on device performance [51] (figure 4(d)). By employing a PVDF/Nafion/PVDF sandwich structure with regularized ionic-electronic interfaces, the device achieved a pressure sensitivity of 51.50 $mV \cdot kPa^{-1}$ and a maximum peak power of 34.66 $mW \cdot m^{-2}$. Herein, Nafion utilizes the migration of protons released from its sulfonate groups within nanoscale ion channels to produce a piezoionic response under mechanical stress. This proton movement establishes an ionic-driven electric field, enabling the material to generate corresponding electrical signals [51]. Notably, recent studies have also demonstrated frontier approaches for regulating ion dynamics via triboelectricity. Through contact electrification, the dynamic modulation of dielectric-liquid interfacial EDLs has given rise to triboiontronics. In this case, the ionic charge density within the nanoconfined diffuse layer is regulated by CE-induced charges, enabling the realization of a direct-current triboelectric nanogenerator with an ultra-high peak power density of 126.40 $W \cdot m^{-2}$ [58].

Similarly, strategies that harness pH gradients, magnetic fields, and other external stimuli to modulate ion dynamics for energy harvesting have also been reported [59–62]. Looking ahead, it is expected that new approaches will continue to emerge, leveraging multifunctional coupling between chemical,

electrical, and mechanical fields to further enhance ion selectivity, transport efficiency, and device integration. Such progress will not only expand the diversity of iontronic power sources but also pave the way for their practical deployment in self-powered, adaptive, and multifunctional electronic systems.

4. Technological advances in iontronic power sources

As iontronic power sources advance from fundamental concepts toward practical applications, several technological breakthroughs are driving their evolution, including the integration of multiple external fields to dynamically control ion behavior, the role of architecture engineering in enhancing device performance and functionality, and the transition from single-unit iontronics to scalable, integrated platforms. These developments not only improve the efficiency and versatility of iontronic power sources but also expand their usability across various domains such as wearable electronics, intelligent sensing, and biomedical interfaces.

4.1. Towards multi-field-driven iontronic dynamics

The convergence of multiple physical or chemical stimuli into a single iontronic platform enables more precise and efficient modulation of ion dynamics. These hybrid systems not only offer higher energy conversion efficiency but also improve the adaptability of iontronic devices to various environmental or physiological conditions, marking a significant step toward intelligent and multi-functional energy platforms.

Recent advances include the use of photo-responsive materials for light-induced charging processes, triboelectric interfaces for mechanical-to-ionic conversion, and synergistic combinations of thermal, electrical, or mechanical fields to enhance energy output. For example, by coupling osmotic effects with electrochemical and photochemical reactions, an ultrafine iontronic power source with a diameter of only 120 μm was achieved, comparable to a human hair [63] (figure 5(a)). This filament harnesses ion transport through GO nanoconfined channels with interfacial silver-halide redox reactions, yielding exceptional gravimetric power and energy densities of 884.95 $W \cdot kg^{-1}$ and 108.7 $Wh \cdot kg^{-1}$, respectively. Following discharge, the reversible photochemical behavior of the silver halides enables ultrafast photo-recharging: the device restores 99% of its voltage in only 10.8 s, achieving a photo-recharging efficiency nearly reaching 100%.

On another front, light-gated ion transport governed by a synergistic photoelectric and photothermal effect was demonstrated in a heterogeneous 2D Ti_3C_2Tx/g–C_3N_4 nanochannel system, achieving a maximum output power density of 21.93 $mW \cdot m^{-2}$ [64] (figure 5(b)). Upon illumination, the separation of photogenerated charge carriers within the confined channels directly triggered spontaneous ion migration, while the efficient light-to-heat conversion of the Ti_3C_2Tx layer further strengthened the driving force through a locally elevated temperature field. In addition, a GO /molybdenum disulfide/sulfonated cellulose nanocrystal (GO/MoS_2/CNC) ion-channel membrane was developed, which delivered an output power density of 8.74 $W \cdot m^{-2}$ under light irradiation via combined photoelectric and photothermal contributions, representing a 78.4% increase compared to the dark condition, and produced an ultrahigh photo-responsive current of 71.5 μA in 1 m KCl solution [66].

Electrical and mechanical field-driven ion transport was also investigated in a COFs monolayer membrane [65] (figure 5(c)). The findings reveal an unusual decrease in conductance and identify a unique electro-mechanical coupling mechanism governed by the competition between ion diffusion from the boundary layer to the membrane surface and ion transport across the membrane itself. Providing new insights into the interplay between electrical and mechanical forces in ultra-permeable systems, such as osmotic power harvesting.

Research on multi-field regulation of ion dynamics for iontronic power sources is still in its infancy. Most strategies rely on external-field modulation coupled with interfacial electrochemical reactions or capacitive processes, as this facilitates ionic-electronic charge transfer at the interface and mitigates ion polarization, thereby enhancing the efficiency of ion-to-energy conversion. For example, an ion-based thermoelectric gelatin was developed that enables thermal ion diffusion combined with a redox couple for thermogalvanic conversion [54] (figure 5(d)). It demonstrated a giant positive thermopower of 17.0 $mV \cdot K^{-1}$ and generated over 2 V and a peak power of 5 μW using body heat by assembling 25 unipolar units. Another study exploited the thermal ion diffusion and thermogalvanic effects of a dual-network ionic gel, where selective complexation/desorption of $Fe^{2+}/^{3+}$ ions occurred at the cold and hot ends, respectively [67]. This coupling effectively boosted thermopower by 700% (from -1.04 to -7.24 $mV \cdot K^{-1}$). At a temperature gradient (ΔT) of 25 K, the device delivered an energy density of 17.93 $kJ \cdot m^{-2}$ over 90 min. In triboiontronic nanogenerators, incorporating redox reactions into the

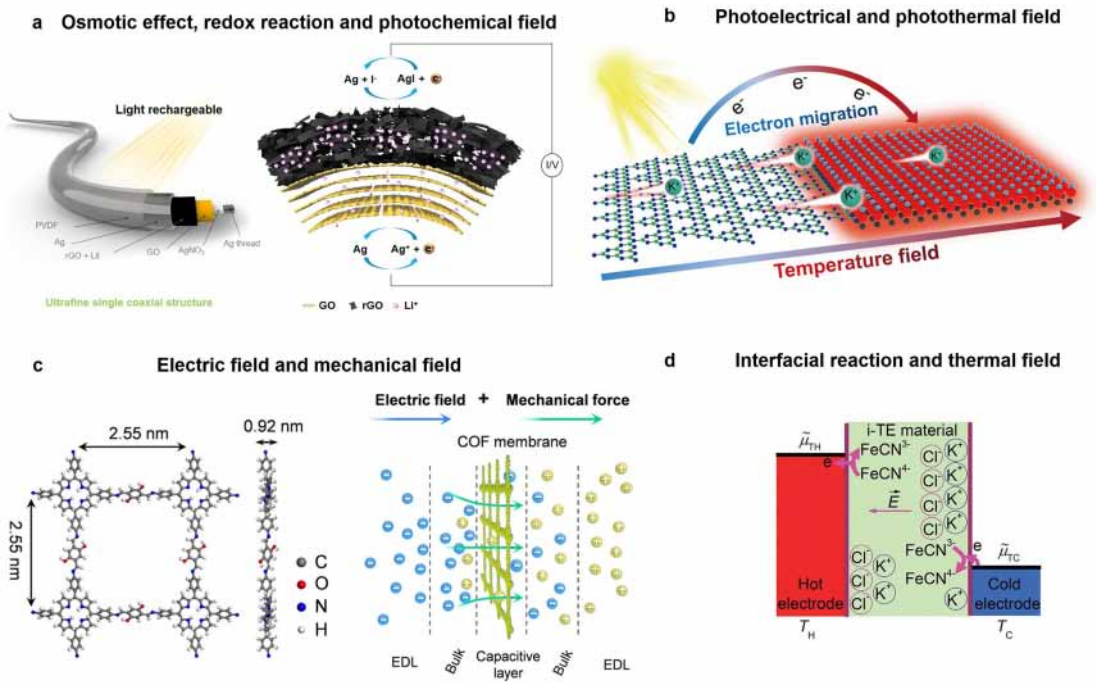

Figure 5. Multi-field driven iontronic dynamics for iontronic power sources. (a) Schematic diagram and mechanism of the fiber iontronic battery based on osmotic effect, interfacial redox and photochemical reactions. [63] John Wiley & Sons. [© 2025 Wiley-VCH GmbH]. (b) Schematic diagram of the enhanced ion dynamics based on photoelectrical and photothermal field. Reproduced from [64] with permission from the royal society of chemistry. (c) The synergistic principle of dynamically controlling ion dynamics by electric and mechanical fields. Reprinted with permission from [65]. Copyright (2023) American Chemical Society. (d) Synergistic effect and the corresponding voltage distribution of the interfacial reaction and thermal field-driven ion dynamics. Reprinted with permission from [54]. Copyright (2020) American Chemical Society.

dynamic modulation of asymmetric nanoconfined EDLs increased the peak power and charge transfer density to 38.64 W · m^{-2} and 540.70 mC · m^{-2}, respectively [68]. This improvement arises from the participation of interfacial chemical reaction fields in EDL formation, which amplifies both ionic current and voltage.

With the continuous growth of application demands and scenarios, multi-field coupled ion energy harvesting technologies are expected to achieve broader tunability, higher integration, and adaptive functionalities, ultimately advancing the development of next-generation self-powered iontronic systems.

4.2. Device architecture design

Device architecture and material microstructure critically govern the performance of iontronic systems. Recent advances generally focus on material and channels design, demonstrating that vertically confined nanochannels, in contrast to planar configurations, significantly accelerate ion transport by minimizing tortuosity and enhancing electrostatic interactions [28]. Hierarchically porous membranes, such as metal-organic frameworks, enable rapid and selective ion conduction [19], while Janus membranes with asymmetric wettability or charge distribution facilitate directional ion flow [69, 70]. However, the architectural design of iontronic power sources is often overlooked. Recent studies have shown that architectural optimization enables the regulation of ion dynamics at the microscale confinement and reveals promising prospects for advanced bio-compatible applications.

For example, droplet-based iontronics was developed by depositing lipid-supported networks of nanoliter hydrogel droplets, which utilize internal ion gradients to generate energy [71] (figure 6(a)). This architecture can reduce the volume of a power unit by more than 10^5-fold and store energy for over 24 h, enabling on-demand operation with a 680-fold increase in power density, reaching ∼1300 W m^{-3}. It can also function as a biocompatible ionic current source to modulate neuronal network activity in 3D neural microtissues and *ex vivo* mouse brain slices (figure 6(b)). By coupling with ionic-electronic interfacial electrochemical reactions, droplet-based miniature soft lithium-ion batteries were further developed, achieving a higher energy density of ∼46 μWh cm^{-2} and an instantaneous output power density of ∼10 μW cm^{-2}, sufficient for defibrillation and pacing in *ex vivo* mouse hearts [72]. In addition, ion circuit modules based on droplet iontronics have been employed to record electrophysiological

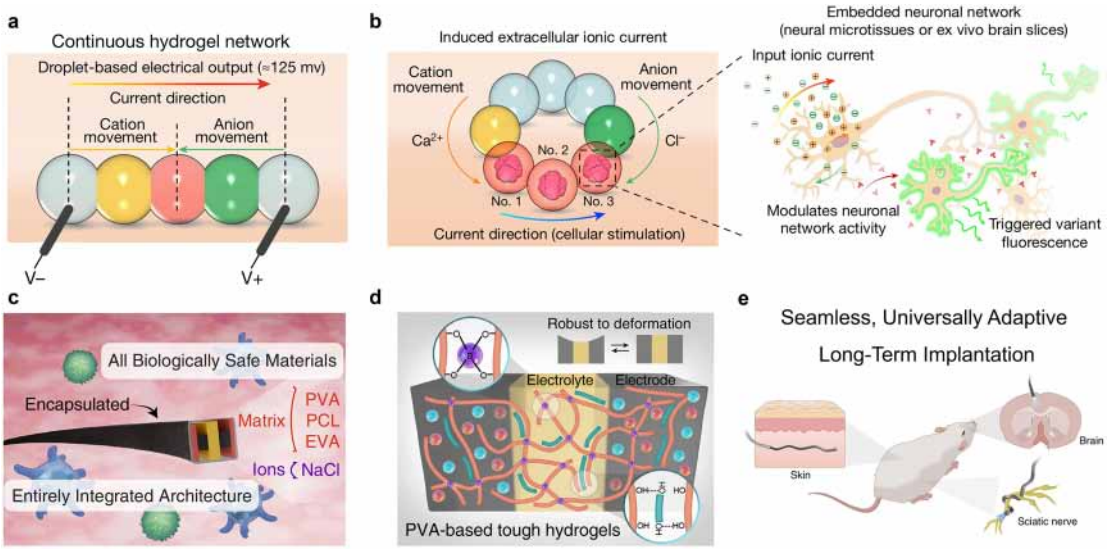

Figure 6. Device architecture design of the iontronic power sources. (a) Schematic diagram and mechanism of the droplet-based iontronic power source. (b) Neuronal modulation induced by the droplet-based iontronic power sources (a) and (b) reproduced from [71]. CC BY 4.0. (c) Schematic illustration about THBS fiber's biocompatibility. (d) Schematic illustration and mechanism of the tough hydrogel network. (e) Illustration of the universally implantable THBS fibers. Their fiber-shaped form factor enables minimally invasive insertion and flexible positioning within tissue for biomedical applications. (c)–(e)Reproduced with permission from [74]. [© 2025, The Author(s)] CC BY-NC-ND 4.0.

signals from human cardiomyocyte sheets, paving the way for constructing miniature bio-ionic electronic systems [73].

On the other hand, fiber-structured iontronic energy devices exhibit safer and more stable performance than traditional electronics in implantable medical and neural interface applications (figure 6(c)). A tough hydrogel-based supercapacitor (THBS) fiber was fabricated as a next-generation, fully biocompatible energy storage device for advanced implantable bioelectronic systems [74]. In this device, NaCl serves as the electrolyte ion source, enabling rapid migration to the electrode surface for efficient charge-discharge operations (figure 6(d)). It has been successfully applied in optogenetic stimulation of both central and peripheral nervous systems in freely moving mice, and its long-term functionality was maintained for more than five weeks with minimal immune response (figure 6(e)).

These developments underscore the importance of rational device architecture design in optimizing the functionality of iontronic power sources. In the future, it is anticipated that iontronic organs conforming to physiological structures could be constructed to achieve functional repair or enhancement. Such advances would not only enable seamless integration with living systems but also open pathways toward next-generation biohybrid platforms, where energy harvesting, storage, and signal modulation can be performed in a manner closely aligned with natural biological processes.

4.3. Scalability

To meet real-world application demands, iontronic power sources must evolve from isolated lab-scale units to scalable, manufacturable platforms. A central challenge in this transition lies in maintaining the continuity or translatability of ion transport pathways, ensuring that nanoscale transport advantages can be preserved in macroscopic device architectures. This requires strategies that bridge the gap between fundamental ion dynamics and practical engineering, such as modular integration of flexible nanoconfined channels and ionic gels assembly, and printing or weaving technologies that enable large-area yet efficient iontronic power sources. Addressing these challenges will be essential for advancing iontronic power sources toward wearable, implantable, and distributed energy applications.

2D nanoconfined materials such as GO and MXene, owing to their excellent dispersibility and self-assembly capability for constructing 2D nanoconfined channels, can be rapidly processed via extrusion printing or spray-coating to form long-range ion pathways for large-scale manufacturing of iontronic power sources [47, 75, 76] (figures 7(a)–(c)). However, it is important to note that ion transport over extended distances faces significant resistance. A feasible strategy employed interfacial chemical reaction-induced built-in electric fields to restrict ion transport distance and enabled the scalable fabrication of iontronic fiber batteries [63, 77] (figure 7(b)). In this case, the presence of chemically induced electric fields limits the transverse ion transport distance along the fiber, ultimately leading to stabilization of

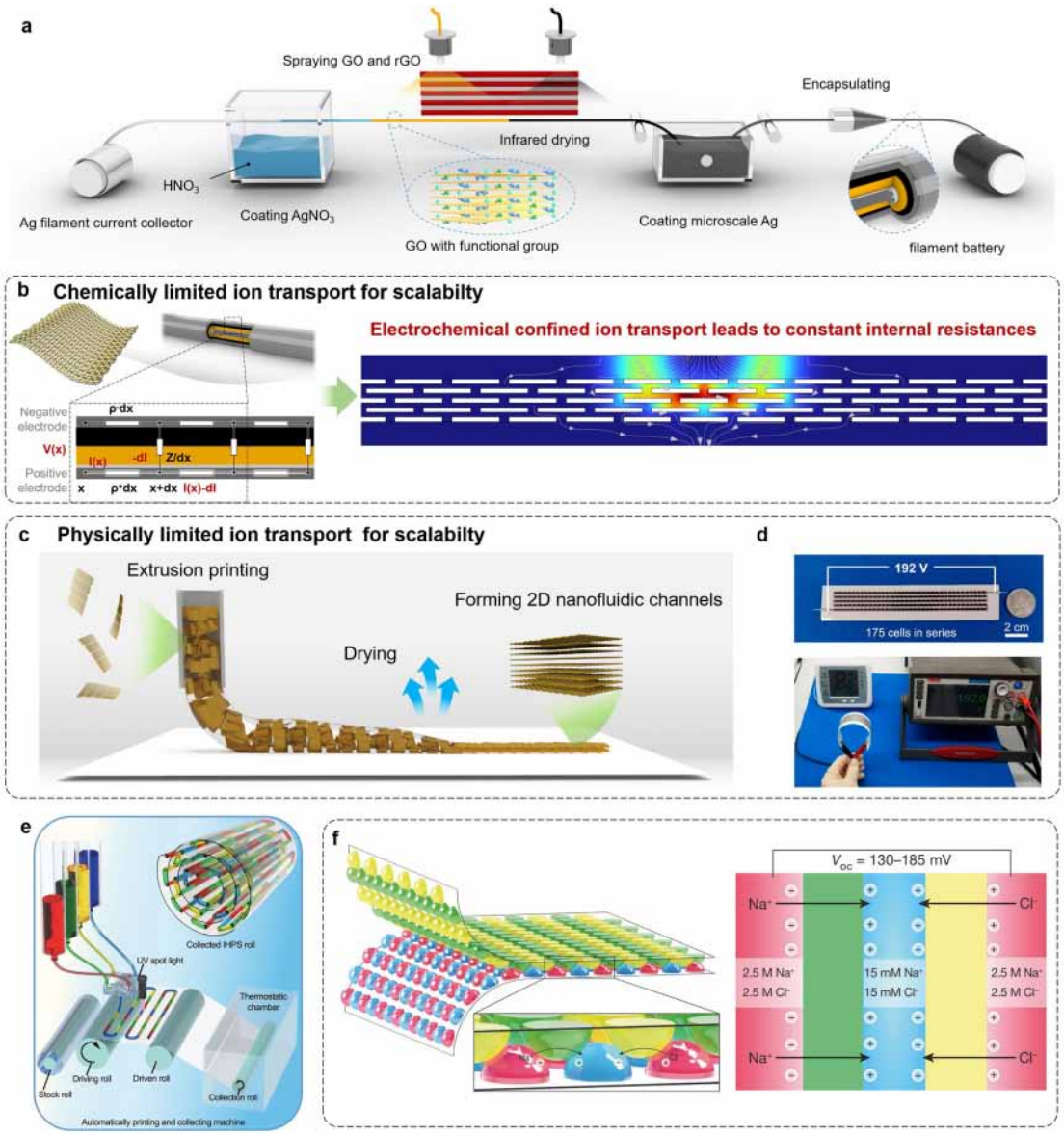

Figure 7. Scalable strategies for iontronic power sources. (a) Schematic illustration of the fabrication process for filament battery. (b) Schematic of long filament battery configuration, and the COMSOL simulation showing electrochemical nanoconfined ion transport along the fiber, contributing to stable internal polarization resistance. (a) and (b) [63] John Wiley & Sons. [© 2025 Wiley-VCH GmbH]. (c) The print process of the 2D nanoconfined channels of GO. [47] John Wiley & Sons. [© 2023 Wiley-VCH GmbH]. (d) Photographs of printed iontronic power units connected in series. A total of 175 cells were patterned onto a flexible paper strip, delivering an exceptionally high open-circuit voltage of 192 V under ambient conditions (15% RH, Beijing). Reproduced with permission from [35]. CC BY-NC-ND 4.0. (e) Schematic of the automated consecutive multi-material printing system with collection modules. Reproduced from [78]. CC BY 4.0. (f) Printed implementation and mechanism of the polyacrylamide hydrogel compartments, showing that ions are transported regionally between several gels to maintain the continuity of ionic current in large area. Reproduced from [79], with permission from springer nature.

the internal polarization resistance as fiber length increases. On the other hand, spray-coating combined with laser cutting to fabricate aligned and stacked large-scale iontronic power arrays, whose voltage output exhibited an almost linear relationship with the number of serially connected units [33, 35] (figures 7(c) and (d)). This effect is likely attributed to the asynchronous ionic-to-electric response of each unit and instantaneous electric generation [33]. By physically segmenting ion transport pathways and confining them within the distance of each unit, large-scale integration of humidity-driven generators becomes achievable.

Except for nanoconfined materials, scalable preparation is easier to achieve in confined gel iontronic power system. A promising study employed an aligned multichannel printing technique that enabled continuous, segmented multi-material deposition to construct linear ion-hydrogel power sources with a maximum stretchability of 137% [78] (figure 7(e)). Within just 30 min, the system could automatically print and assemble power units in parallel, achieving a maximum voltage of 208 V while maintaining

stable voltage output over 1000 stretching cycles under 100% strain. The interfaces of the ion-hydrogel assemblies were stabilized via ultraviolet crosslinking, thereby permitting continuous cation and anion transport through selectively designed gel components. Similarly, large-scale power generation was realized by establishing ion gradients across micro-scale polyacrylamide hydrogel compartments, formed by the alternating arrangement of cation- and anion-selective hydrogel membranes [79] (figure 7(f)). This system adopted a scalable stacked or folded architecture, where self-discharging was activated through mechanical contact, effectively preventing ion transport and energy loss prior to activation. Ultimately, it produced an VOC of 110 V or a power output of 27 mW per square meter per gel unit.

These strategies, spanning printing, spray-coating, compartmentalized architectures, and physicochemical regulation, have advanced the control of ion transport dynamics during large-scale fabrication. By mitigating long-distance transport resistance and enabling predictable performance, they accelerate the development of low-cost, customizable iontronic systems. Collectively, these approaches lay the foundation for integrated, multifunctional, and potentially disposable energy architectures, bridging laboratory concepts with real-world applications in soft, wearable, and sustainable formats.

5. Conclusion and outlook

Looking forward, iontronic power sources hold great promise for revolutionizing energy technologies in soft, bio-integrated, and intelligent systems. By harnessing the unique advantages of ionic carriers, such as high tunability, biocompatibility, and strong coupling with external stimuli, iontronics provides a fundamentally different approach to energy harvesting and storage compared to conventional electronics. The recent advances highlighted here demonstrate not only the feasibility of building scalable, multifunctional devices but also the potential to bridge artificial systems with biological environments. The synergy between materials innovation, nanoscale design, and external-field modulation will be the key driver in propelling iontronic power sources from laboratory prototypes toward practical applications. The development of scalable, low-cost, and customizable fabrication methods, such as printing, spray-coating, and compartmentalized assembly, will further accelerate their deployment in wearable, implantable, and disposable systems. As the boundaries between living systems and artificial devices continue to blur, iontronic power sources are poised to become the backbone of next-generation bio-integrated electronics, offering unprecedented opportunities for sustainable energy harvesting and intelligent human–machine interaction.

To achieve this goal, one critical direction for future research is achieving ion selectivity at a higher resolution. Beyond simply distinguishing between cations and anions, iontronic systems should be capable of discriminating ions of different types, valencies, hydration states, and mobilities [80, 81]. Such precision would allow energy conversion processes to be fine-tuned at the molecular level, improving both efficiency and stability. Moreover, enhanced selectivity would directly impact bio-interfaces, where signal fidelity depends on accurate recognition of physiologically relevant ions such as Ca^{2+}, K^{+}, and N^{+} [25]. Strategies combining nanoconfined channels, functional coatings, and bio-inspired architectures will be essential in advancing this goal.

Another key challenge lies in the continued optimization of ion transport dynamics. Advanced material synthesis and optimizations, including nanoconfined materials, adaptive hydrogels, and hierarchically porous frameworks, will play a central role in lowering transport resistance and reducing polarization effects. Equally important is the functional design of the channels and device architecture, from vertically aligned channels that minimize tortuosity to dynamically reconfigurable membranes capable of responding to external stimulations such as electric fields, light, or humidity. By coupling materials innovation with structural intelligence, future iontronic devices could achieve higher power densities, longer operational lifetimes, and improved integration with large-scale manufacturing.

In addition, the long-term reliability of iontronic power sources remains an essential consideration for their practical deployment. Iontronic systems inherently operate through dynamic ion redistribution, which makes them susceptible to several degradation pathways, including ion depletion at interfaces, swelling or shrinkage of hydrated nanochannels, contamination from environmental species, and gradual structural relaxation or chemical drift within soft ionic matrices. These failure modes can reduce ion selectivity, alter internal ionic resistance, and ultimately diminish overall energy-conversion efficiency. Addressing these issues requires a unified strategy that couples materials design with ion-transport engineering. For example, stabilizing confined channels against mechanical deformation, suppressing parasitic ionic adsorption, and designing self-regulating or self-healing ionic architectures. Incorporating

these reliability considerations alongside performance optimization will be crucial for translating iontronic power sources from laboratory prototypes to robust, long-term operational systems capable of functioning in complex real-world environments.

Finally, a particularly exciting frontier is the coupling of iontronic power sources with neural interfaces, soft robotics, and synthetic biology [82, 83]. In neural systems, ion-based power sources could directly interact with ionic currents in tissues, enabling closed-loop sensing, actuation, and stimulation without the need for bulky batteries or rigid electrodes. In soft robotics, iontronics may offer a pathway to self-sustained, compliant machines powered by environmental stimuli. Meanwhile, in synthetic biology, integrating ion-based power with engineered living systems could enable autonomous microscale platforms for sensing, therapeutic delivery, and bio-computation. Such interdisciplinary convergence underscores the transformative potential of iontronic power sources. However, to bridge the gap between laboratory demonstrations and practical deployment, some key technical support may be required. For improving long-term stability, the development of chemically robust ion conductors, mechanically reinforced nanoconfined channels, and encapsulation schemes may be effective in mitigating environmental degradation. For large-scale manufacturing, advances in printable inks, roll-to-roll patterning, and microstructure-controlled assembly may provide pathways to reduce device-to-device variation and ensure reproducibility. Furthermore, reliability in complex real-world environments, such as biological fluids, can be enhanced by using biocompatible interface coatings, antifouling layers, and ionic systems with buffered or self-regulating compositions that stabilize ion transport. Collectively, these strategies not only address key bottlenecks but also provide actionable routes toward enabling robust and application-ready iontronic power technologies.

Acknowledgments

This work was supported by the National Natural Science Foundation (Grant Number 22479016).

Data availability statement

All data that support the findings of this study are included within the article.

Author contributions

Puguang Peng 0000-0003-3709-7101
Investigation (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Han Qian 0009-0005-8692-2317
Investigation (equal), Validation (equal), Visualization (equal)

Zhonglin Wang 0000-0002-5530-0380
Funding acquisition (equal), Investigation (equal), Supervision (equal)

Di Wei 0000-0003-2670-6362
Investigation (equal), Supervision (equal), Writing – original draft (equal), Writing – review & editing (equal)

References

[1] Zhang B *et al* 2024 Nature-inspired interfacial engineering for energy harvesting *Nat. Rev. Electr. Eng.* **1** 218–33
[2] Liu P *et al* 2024 Ion transport in nanofluidics under external fields *Chem. Soc. Rev.* **53** 2972–3001
[3] Xu J *et al* 2024 Sustainable moisture energy *Nat. Rev. Mater.* **9** 722–37
[4] Shimizu S, Takahashi K S, Hatano T, Kawasaki M, Tokura Y and Iwasa Y 2013 Electrically tunable anomalous Hall effect in Pt thin films *Phys. Rev. Lett.* **111** 216803
[5] Kato T *et al* 2017 Transport of ions and electrons in nanostructured liquid crystals *Nat. Rev. Mater.* **2** 17001
[6] Xiao K, Jiang L and Antonietti M 2019 Ion transport in nanofluidic devices for energy harvesting *Joule* **3** 2364–80
[7] Peng P, Qian H, Liu J, Wang Z and Wei D 2024 Bioinspired ionic control for energy and information flow *Int. J. Smart Nano Mater.* **15** 198–221
[8] Sparreboom W *et al* 2009 Principles and applications of nanofluidic transport *Nat. Nanotechnol.* **4** 713–20

[9] Liu Y, Peng P, Qian H, Wang Z L and Wei D 2025 Nanoconfined iontronics and its electronic applications *Nano Res. Energy* **4** e9120156
[10] Bocquet L and Charlaix E 2010 Nanofluidics, from bulk to interfaces *Chem. Soc. Rev.* **39** 1073–95
[11] Daiguji H 2010 Ion transport in nanofluidic channels *Chem. Soc. Rev.* **39** 901–11
[12] Qian H, Wei D and Wang Z 2023 Bionic iontronics based on nano-confined structures *Nano Res.* **16** 11718–30
[13] Cheng L-J and Guo L J 2010 Nanofluidic diodes *Chem. Soc. Rev.* **39** 923–38
[14] Zhang Z, Wen L and Jiang L 2021 Nanofluidics for osmotic energy conversion *Nat. Rev. Mater.* **6** 622–39
[15] Veerman J, Saakes M, Metz S J and Harmsen G J 2010 Reverse electrodialysis: evaluation of suitable electrode systems *J. Appl. Electrochem.* **40** 1461–74
[16] Qian H, Peng P, Liu Y, Wang Z L and Wei D 2025 Balancing selectivity and permeability in nanofluidic membranes for osmotic power generation *Prog. Energy* **7** 042001
[17] Hou Y and Hou X 2021 Bioinspired nanofluidic iontronics *Science* **373** 628–9
[18] Hou X 2013 *Bio-inspired Asymmetric Design and Building of Biomimetic Smart Single Nanochannels* (Springer)
[19] Yang L *et al* 2024 MOFs/MXene nano-hierarchical porous structures for efficient ion dynamics *Nano Energy* **129** 110076
[20] Aluru N R *et al* 2023 Fluids and electrolytes under confinement in single-digit nanopores *Chem. Rev.* **123** 2737–831
[21] Mei Y and Tang C Y 2017 Co-locating reverse electrodialysis with reverse osmosis desalination: synergies and implications *J. Membr. Sci.* **539** 305–12
[22] Feng J, Graf M, Liu K, Ovchinnikov D, Dumcenco D, Heiranian M, Nandigana V, Aluru N R, Kis A and Radenovic A 2016 Single-layer MoS_2 nanopores as nanopower generators *Nature* **536** 197–200
[23] Zou K *et al* 2024 Turing-type nanochannel membranes with extrinsic ion transport pathways for high-efficiency osmotic energy harvesting *Nat. Commun.* **15** 10231
[24] Cui G, Zhi X, Han L, Zhang S, Luping X, Siria A and Ming M 2023 Enhanced osmotic transport in individual double-walled carbon nanotube *Nat. Commun.* **14** 2295
[25] Jiang W *et al* 2025 Axial alignment of covalent organic framework membranes for giant osmotic energy harvesting *Nat. Sustain.* **8** 446–55
[26] Li C *et al* 2021 Large-scale, robust mushroom-shaped nanochannel array membrane for ultrahigh osmotic energy conversion *Sci. Adv.* **7** eabg2183
[27] Wei R, Liu X, Cao L, Chen C, Chen I-C, Li Z, Miao J and Lai Z 2024 Zeolite membrane with sub-nanofluidic channels for superior blue energy harvesting *Nat. Commun.* **15** 10489
[28] Qian H *et al* 2024 Horizontal Transport in $Ti_3C_2T_x$ MXene for highly efficient osmotic energy conversion from saline-alkali environments *Angew. Chem., Int. Ed.* **63** e202414984
[29] Huang Y, Cheng H, Yang C, Zhang P, Liao Q, Yao H, Shi G and Liangti Q 2018 Interface-mediated hygroelectric generator with an output voltage approaching 1.5 volts *Nat. Commun.* **9** 4166
[30] Puying L, Hu Y, Wang H, He T, Cheng H and Qu L 2025 Interfacial ion-electron conversion enhanced moisture energy harvester *Nat. Commun.* **16** 6600
[31] Wang L, Wang H, Wu C, Bai J, He T, Li Y, Cheng H and Qu L 2024 Moisture-enabled self-charging and voltage stabilizing supercapacitor *Nat. Commun.* **15** 4929
[32] Yu X *et al* 2017 Graphene-based smart materials *Nat. Rev. Mater.* **2** 17046
[33] Wang H, Sun Y, Tiancheng H, Huang Y, Cheng H, Chun L, Xie D, Yang P, Zhang Y and Liangti Q 2021 Bilayer of polyelectrolyte films for spontaneous power generation in air up to an integrated 1,000 V output *Nat. Nanotechnol.* **16** 811–9
[34] Cheng H, Huang Y, Zhao F, Yang C, Zhang P, Jiang L, Shi G and Liangti Q 2018 Spontaneous power source in ambient air of a well-directionally reduced graphene oxide bulk *Energy Environ. Sci.* **11** 2839–45
[35] Yang L *et al* 2021 A moisture-enabled fully printable power source inspired by electric eels *Proc. Natl Acad. Sci. USA* **118** e2023164118
[36] Wang C, Duan P, Huang Y, Xulei L, Chunqiao F, Zhang Y, Qian L and Yang T 2025 Micro-meso-macroporous channels finely tailored for highly efficient moisture energy harvesting *Nat. Commun.* **16** 6568
[37] Zhang Y *et al* 2022 Sustainable power generation for at least one month from ambient humidity using unique nanofluidic diode *Nat. Commun.* **13** 3484
[38] Li L, Dong F, Miao P, He N, Wang B, Sun X, Miao J, Wang H and Tang D 2025 High-efficiency moisture energy harvesting at −30 °C via hybrid solute engineering *Energy Environ. Sci.* **18** 2985–94
[39] Guo S *et al* 2025 Leaf-based energy harvesting and storage utilizing hygroscopic iron hydrogel for continuous power generation *Nat. Commun.* **16** 5267
[40] Gao Z, Fang C, Gao Y, Yin X, Zhang S, Jian L, Guanglei W, Hongjing W and Bingang X 2025 Hybrid electromagnetic and moisture energy harvesting enabled by ionic diode films *Nat. Commun.* **16** 312
[41] Wu H *et al* 2024 Drinking-bird-enabled triboelectric hydrovoltaic generator *Device* **2** 100318
[42] Li S *et al* 2024 Transistor-like triboiontronics with record-high charge density for self-powered sensors and neurologic analogs *Device* **2** 100332
[43] Zhao C, Hou J and Zhang H 2023 Nanofluidic photoionic membranes for light energy harvesting and conversion *Ind. Eng. Chem. Res.* **62** 13734–47
[44] Dai B, Biesold G M, Zhang M, Zou H, Ding Y, Wang Z L and Lin Z 2021 Piezo-phototronic effect on photocatalysis, solar cells, photodetectors and light-emitting diodes *Chem. Soc. Rev.* **50** 13646–91
[45] Peng P, Yang F, Xiang L, Shaoxin L, Wang Z and Wei D 2024 High-power iontronics enabled by nanoconfined ion dynamics *Cell Rep. Phys. Sci.* **5** 101824
[46] Yang F *et al* 2024 Vertical iontronic energy storage based on osmotic effects and electrode redox reactions *Nat. Energy* **9** 263–71
[47] Peng P, Yang F, Wang Z and Wei D 2023 Integratable paper-based iontronic power source for all-in-one disposable electronics *Adv. Energy Mater.* **13** 2302360
[48] Wei D 2015 Writable electrochemical energy source based on graphene oxide *Sci. Rep.* **5** 15173
[49] Xiao K, Chen L, Chen R, Heil T, Lemus S D C, Fan F, Wen L, Jiang L and Antonietti M 2019 Artificial light-driven ion pump for photoelectric energy conversion *Nat. Commun.* **10** 74
[50] Zuo X, Zhu C, Xian W, Meng Q, Guo Q, Zhu X, Wang S, Wang Y, Shengqian M and Sun Q 2022 Thermo-osmotic energy conversion enabled by covalent-organic-framework membranes with record output power density *Angew. Chem., Int. Ed.* **61** e202116910
[51] Xu T *et al* 2024 All-polymer piezo-ionic-electric electronics *Nat. Commun.* **15** 10876
[52] Jia Y *et al* 2021 Wearable thermoelectric materials and devices for self-powered electronic systems *Adv. Mater.* **33** 2102990

[53] Liu R, Wang Z L, Fukuda K and Someya T 2022 Flexible self-charging power sources *Nat. Rev. Mater.* **7** 870–86
[54] Han C-G *et al* 2020 Giant thermopower of ionic gelatin near room temperature *Science* **368** 1091–8
[55] Prete D *et al* 2023 Heat-driven iontronic nanotransistors *Adv. Sci.* **10** e2204120
[56] Zhao D, Fabiano S, Berggren M and Crispin X 2017 Ionic thermoelectric gating organic transistors *Nat. Commun.* **8** 14214
[57] Zhu C, Zuo X, Xian W, Guo Q, Meng Q-W, Wang S, Shengqian M and Sun Q 2022 Integration of thermoelectric conversion with reverse electrodialysis for mitigating ion concentration polarization and achieving enhanced output power density *ACS Energy Lett.* **7** 2937–43
[58] Li X, Li S, Guo X, Shao J, Wang Z L and Wei D 2023 Triboiontronics for efficient energy and information flow *Matter* **6** 3912–26
[59] Cai J *et al* 2022 Magnetic field tuning ionic current generated by chiromagnetic nanofilms *ACS Nano* **16** 11066–75
[60] Wang D, Zheng S, Liu H, Tang J, Miao W, Wang H, Tian Y, Yang H and Jiang L 2019 A magnetic gated nanofluidic based on the integration of a superhydrophilic nanochannels and a reconfigurable ferrofluid *Adv. Mater.* **31** e1805953
[61] Laucirica G, Marmisolle W A, Toimil-Molares M E, Trautmann C and Azzaroni O 2019 Redox-driven reversible gating of solid-state nanochannels *ACS Appl. Mater. Interfaces* **11** 30001–9
[62] Zhang Z, Kong X-Y, Xiao K, Liu Q, Xie G, Pei L, Jie M, Tian Y, Wen L and Jiang L 2015 Engineered asymmetric heterogeneous membrane: a concentration-gradient-driven energy harvesting device *J. Am. Chem. Soc.* **137** 14765–72
[63] Peng P, Qian H, Yang F and Wei D 2025 Scalable, light rechargeable energy storage based on osmotic effects and photochemical reactions in a hair-thin filament *Adv. Energy Mater.* **15** 2405547
[64] Wang J, Wang D, Song Z, Jiang N, Shangzhen L, Zhang Y, Huang B, Zhou H, Cui Z and Wang L 2023 Efficient solar energy conversion via bionic sunlight-driven ion transport boosted by synergistic photo-electric/thermal effects *Energy Environ. Sci.* **16** 3146–57
[65] Zhang X *et al* 2023 Anomalous mechanical and electrical interplay in a covalent organic framework monolayer membrane *J. Am. Chem. Soc.* **145** 17786–94
[66] Li W, Li X, He J, Zhai J and Fan X 2025 Solar-enhanced blue energy conversion via photo-electric/thermal in GO/MoS2/CNC nanofluidic membranes *Small* **21** e06667
[67] Hu J, Wei J, Li J, Bai L, Liu Y and Li Z 2024 Double selective ionic gel with excellent thermopower and ultra-high energy density for low-quality thermal energy harvesting *Energy Environ. Sci.* **17** 1664–76
[68] Li X, Li R, Li S, Wang Z L and Wei D 2024 Triboiontronics with temporal control of electrical double layer formation *Nat. Commun.* **15** 6182
[69] Zhu X, Hao J, Bao B, Zhou Y, Zhang H, Pang J, Jiang Z and Jiang L 2018 Unique ion rectification in hypersaline environment: a high-performance and sustainable power generator system *Sci. Adv.* **4** eaau1665
[70] Qian H, Fan H, Peng P, Yan D, Xiang L, Liu Y, Yang F, Zhou Y, Wang Z L and Wei D 2025 Biomimetic Janus MXene membrane with bidirectional ion permselectivity for enhanced osmotic effects and iontronic logic control *Sci. Adv.* **11** eadx1184
[71] Zhang Y, Riexinger J, Yang X, Mikhailova E, Jin Y, Zhou L and Bayley H 2023 A microscale soft ionic power source modulates neuronal network activity *Nature* **620** 1001–6
[72] Zhang Y, Sun T, Yang X, Zhou L, Tan C M J, Lei M and Bayley H 2024 A microscale soft lithium-ion battery for tissue stimulation *Nat. Chem. Eng.* **1** 691–701
[73] Zhang Y, Tan C M J, Toepfer C N, Lu X and Bayley H 2024 Microscale droplet assembly enables biocompatible multifunctional modular iontronics *Science* **386** 1024–30
[74] Jeon S, Seo H, Kim Y, Choi Y, Lee Y, Jung Y, Lee S, Lee J T and Park S 2025 Fully biocompatible, thermally drawn fiber supercapacitors for long-term bio-implantation *Nat. Commun.* **16** 8207
[75] Hu G, Kang J, Ng L W T, Zhu X, Howe R C T, Jones C G, Hersam M C and Hasan T 2018 Functional inks and printing of two-dimensional materials *Chem. Soc. Rev.* **47** 3265–300
[76] Liu Y, Peng P, Yang F, Wang Z L and Wei D 2025 Printable high-performance iontronic power source based on osmotic effects *Energy Mater.* **5** 500059
[77] He J *et al* 2021 Scalable production of high-performing woven lithium-ion fibre batteries *Nature* **597** 57–63
[78] He P, Yue J, Qiu Z, Meng Z, He J and Li D 2024 Consecutive multimaterial printing of biomimetic ionic hydrogel power sources with high flexibility and stretchability *Nat. Commun.* **15** 5261
[79] Schroeder T B H, Guha A, Lamoureux A, VanRenterghem G, Sept D, Shtein M, Yang J and Mayer M 2017 An electric-eel-inspired soft power source from stacked hydrogels *Nature* **552** 214–8
[80] Chen W, Zhai L, Zhang S, Zhao Z, Yuhao H, Xiang Y, Liu H, Zhiping X, Jiang L and Wen L 2023 Cascade-heterogated biphasic gel iontronics for electronic-to-multi-ionic signal transmission *Science* **382** 559–65
[81] Peng P *et al* 2024 Photochemical iontronics with multitype ionic signal transmission at single pixel for self-driven color and tridimensional vision *Device* **3** 100574
[82] Shi J, Pengju L, Kim S and Tian B 2025 Implantable bioelectronic devices for photoelectrochemical and electrochemical modulation of cells and tissues *Nat. Rev. Bioeng.* **3** 485–504
[83] Rivnay J, Raman R, Robinson J T, Schreib C, Cohen-Karni T, Galloway K E and Veiseh O 2025 Integrating bioelectronics with cell-based synthetic biology *Nat. Rev. Bioeng.* **3** 317–32