Zhang *et al. Soft Sci.* **2025**, *5*, 23
**DOI:** 10.20517/ss.2025.05

**Soft Science**

**Perspective**

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# Polymer engineering in hydrogel-based moisture-electric generators for green energy harvesting

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**How to cite this article:** Zhang, H.; Sun, M.; Meng, Q.; Li, H.; Tian, Y. Polymer engineering in hydrogel-based moisture-electric generators for green energy harvesting. *Soft Sci.* **2025**, *5*, 23. https://dx.doi.org/10.20517/ss.2025.05

**Received:** 6 Mar 2025 **First Decision:** 8 Apr 2025 **Revised:** 11 Apr 2025 **Accepted:** 18 Apr 2025 **Published:** 13 May 2025

**Academic Editor:** Huanyu Cheng **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

## Abstract

Hydrogel-based moisture-electric generators (HMEGs) have emerged as a promising technology for sustainable energy harvesting by utilizing ambient moisture. This article highlights recent advancements in HMEG development, focusing on innovative hydrogel designs to enhance energy output and practical applicability. Hydrogels provide a highly efficient medium for water absorption and ion transport, but their limited moisture generation performance necessitates polymer engineering strategies. Protonation doping and the incorporation of other cations, such as sodium ions, have been shown to significantly improve electrical output. Furthermore, dual-network hydrogels enhance both mechanical robustness and energy conversion efficiency. Future research should focus on improving scalability through large-scale fabrication techniques, enhancing durability under varying environmental conditions, and optimizing hydrogel properties for wearable and implantable applications. With continued material and engineering innovations, HMEGs hold great potential for advancing self-powered electronics and sustainable energy solutions.

**Keywords:** Hydrogels, moisture-electric generators, energy harvesting, nanogenerators

## INTRODUCTION

As concerns over the energy crisis continue to rise, a diverse range of energy-harvesting technologies, such as osmotic energy harvesting[1,2], photovoltaic[3-5], piezoelectric[6-8], and thermoelectric systems[9-11], have been extensively studied. These technologies aim to meet the increasing demand for electricity required by biomedical devices[12-14], wearable electronics[15-18], smart city infrastructures[19-21], *etc*. Among these technologies, moisture-electric generators (MEGs) have emerged as a promising technology that harvests moisture from the environment to generate electricity without the need for mechanical, thermal, or solar inputs, which utilize the chemical potential difference induced by moisture absorption to drive ionic migration[22-25].

Since the phenomenon of moisture-generated electricity was first discovered in 2015 in a single graphene oxide (GO) film[26], recent years have witnessed the rapid development of MEGs. MEG offers significant advantages over conventional energy-harvesting methods[27-29]. For example, unlike solar cells that rely on sunlight or triboelectric devices that require mechanical input, MEGs can continuously generate electricity by utilizing ambient humidity, making them suitable for all-weather and indoor applications[30]. Moreover, MEGs can be fabricated from a wide range of materials, including polymers[31-33], metal oxides[34-36], carbon-based materials[37-40], and two-dimensional materials[41,42]. Their environmentally friendly and cost-effective fabrication process enables their widespread application in various fields, including sensing[43-46], medical treatment[47], and other cutting-edge technologies [Figure 1][18,47,48].

Hydrogels, as highly hydrophilic and ion-conductive materials[49-51], have received much attention in the development of high-performance MEGs. Their three-dimensional polymer network provides an efficient medium for fast water absorption and ion transport[52-55], making them ideal candidates for improving energy conversion efficiency. The excellent hydrophilicity and water retention capacity of hydrogels enable hydrogel-based MEGs (HMEGs) to sustain energy output even under extremely low ambient humidity conditions. Recent advances in HMEGs have focused on improving power output, operational stability, and mechanical robustness through innovative material designs, such as dual-network hydrogels, supramolecular hydrogels, and conductive hydrogels. HMEGs are engineered with more innovative designs, enabling them to be increasingly suitable for a wide range of practical applications. Here, we highlight the recent efforts in developing high-performance HMEGs and discuss future directions in developing next-generation HMEGs with better performance and wider applicability.

## RECENT PROGRESS IN HMEGS

Figure 2 schematically illustrates the key milestones in the development trajectory of HMEGs. In 2020, He *et al.* first reported an HMEG based on a tannic acid (TA)–carbon nanotube (CNT)–glycerol–polyvinyl alcohol (PVA) conductive hydrogel, which exhibits excellent anti-freezing (-30 °C), moisturizing (retaining 70% weight after 10 days), mechanical strength (~1,000 kPa) and conductivity (5.13 S/m) properties[56]. This hydrogel utilizes PVA as the functional component, which releases protons upon moisture absorption, creating a proton concentration gradient that drives ionic migration, leading to electricity generation. The fabricated HMEG achieved an open-circuit voltage of 80 mV. A similar phenomenon was also observed in cellulose or polyacrylamide (PAM)-based conductive hydrogels[57,58]. These studies demonstrate the feasibility of using hydrogels in the fabrication of MEGs; however, the electrical performance of the output still requires further improvement.

Subsequently, Yang *et al.* further introduced phytic acid and glycerol into the PVA network[59]. Phytic acid provides abundant protons for the hydrogel, while the hydrophilic properties of glycerol enhance the affinity between the hydrogel and moisture. The HMEGs developed from this material exhibit excellent


**Figure 1.** Overview of MEGs: efficient energy conversion and wide applications. Reproduced with permission[18]. Copyright©2023, Wiley-VCH. Reproduced with permission[47]. Copyright©2025, Wiley-VCH. Reproduced with permission[48]. Copyright©2023, Wiley-VCH. MEGs: Moisture-electric generators.

moisture collection ability and efficient ion transport, generating a stable direct current (DC) output of approximately 0.8 V for over 1,000 h. Its short-circuit current density reaches up to 0.24 mA·cm$^2$ with a maximum power density of 35 μW·cm$^2$, enabling power supply for small electronic devices such as calculators, electronic paper displays, and LED arrays. They found that in HMEG, proton conduction primarily arises from the vehicle mechanism. Under this mechanism, the transport of ions or protons is driven by the movement of mobile species such as $H_3O^+$ or $H^+\cdot(H_2O)n$, which are dissociated from acid within the HMEG. These water clusters serve as conductive channels, effectively acting as "vehicles" for proton transport. This finding also highlights the crucial role of ionic conductivity in the generation of moisture-enabled electricity. This approach has achieved high-performance and all-weather operation of HMEG, but the mechanical properties of the hydrogel remain limited. Cheng *et al.* incorporated phytic acid into PAM hydrogels and observed similar enhancements in MEG performance[60]. The generator demonstrated outstanding electrical properties across a humidity range of 40%-90%, with its open-circuit voltage increasing from 0.675 to 0.838 V and a short-circuit current reaching 635.543 μA. These findings underscore the growing importance of proton doping as a key strategy for optimizing the performance of HMEGs.

In addition to incorporating small molecule acids (such as phytic acid), hydrogels with a high proton content can be synthesized by directly copolymerizing organic acids into the network. For example, Zhang *et al.* developed a double-network (DN) hydrogel by copolymerizing 2-acrylamido-2-

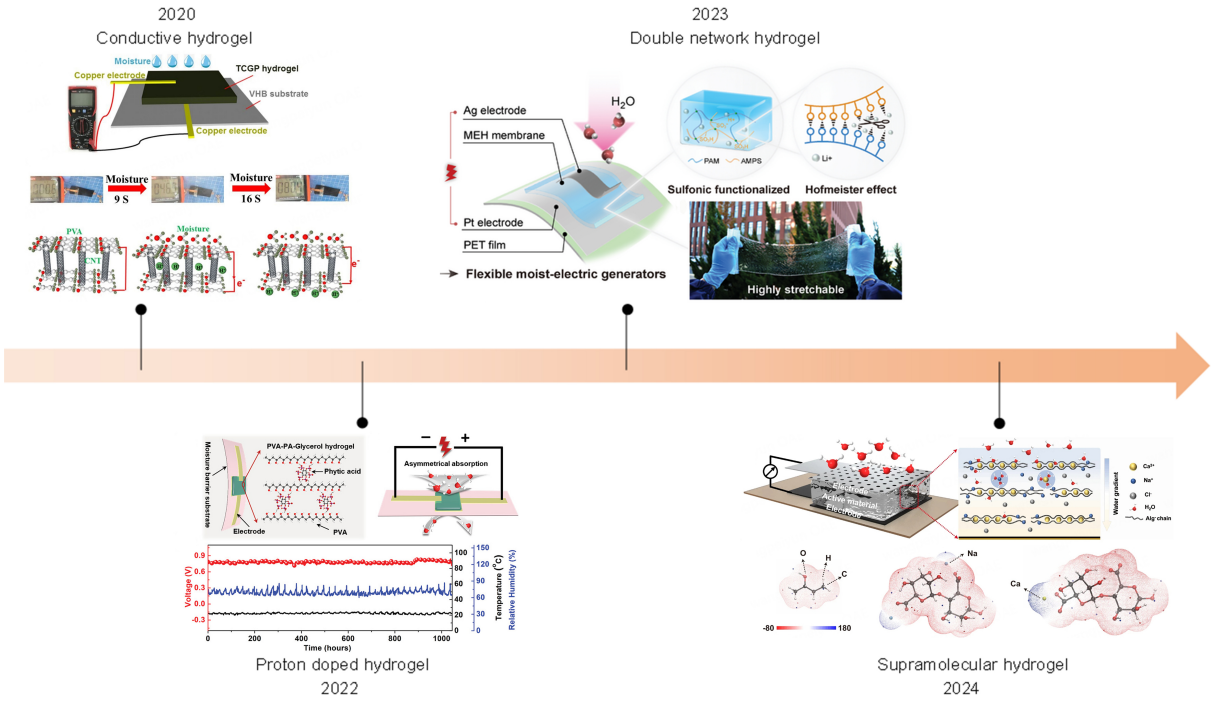


**Figure 2.** Representative advancements in the development trajectory of HMEGs. Reproduced with permission[56]. Copyright©2020, Royal Society of Chemistry. Reproduced with permission[59]. Copyright©2022, Wiley-VCH, under CC BY 4.0. Reproduced with permission[55]. Copyright©2023, Wiley-VCH. Reproduced with permission[62]. Copyright©2024, Nature Publishing Group. HMEGs: Hydrogel-based moisture-electric generators.

methylpropanesulfonic acid (AMPS), a sulfonic acid-containing monomer, with acrylamide[55]. To enhance water absorption and proton mobility, LiCl was further incorporated into the hydrogel matrix. The sulfonic acid groups in the dual-network hydrogel ensure adequate proton content and high ionic mobility (14.5 S/m). Notably, these DN hydrogels exhibit not only outstanding MEG performance - achieving up to 0.8 V and a short-circuit current of 480 μA/cm² at 80% humidity - but also excellent mechanical properties. Their remarkable stretchability makes the resulting MEGs well-suited for integration into wearable electronics, such as respiratory monitoring. Although the mechanical properties of hydrogels may not have a direct impact on the efficiency of moisture-induced power generation, they are essential for maintaining device stability by mitigating the risk of mechanical damage during operation. Likewise, Mo *et al.* discovered that high-performance HMEGs could also be fabricated using DN hydrogels composed of sulfated cellulose and PVA composite vegetation, achieving a maximum open-circuit voltage of 0.9 V[61].

Besides proton, Yang *et al.* found that other ions (e.g., $Na^+$) can similarly enhance power generation performance[62]. They reported that a supramolecular hydrogel composite of sodium alginate and PVA, featuring a high dissociable ion capacity, could achieve current output at the milliampere level (1.3 mA/cm²). This remarkable performance was attributed to the synergistic effects of enhanced hygroscopicity, a sustained water gradient, and an ample supply of dissociable ions contributing to ionic conductivity in the PVA-AlgNa-based hydrogel. Furthermore, the incorporation of inorganic materials into supramolecular hydrogels can enhance the performance of HMEGs. For instance, Huang *et al.* achieved a short-circuit current of 2.24 mA by incorporating $SiO_2$ and reduced GO into sodium alginate hydrogels, which may be attributed to the enhanced ion transport facilitated by these inorganic materials[63]. Integrating the generation of electricity from moisture with other power generation methods is also an important approach to enhancing performance. Li *et al.* present a novel hybrid energy harvesting device that

simultaneously generates electricity from both moisture and water-droplet-induced triboelectricity[64]. The device integrates an HMEG based on a citric acid-mediated polyglutamic acid (PGA) hydrogel and a triboelectric nanogenerator (TEG) using a porous waterproof expanded polytetrafluoroethylene (E-PTFE) film. The E-PTFE layer enables water vapor penetration for moisture electricity generation and enhances triboelectrification with water droplets. Under water droplet impacts, the device outputs a DC voltage of 0.55 V, a peak current density of 120 μA·cm$^{-2}$ (MEG), an alternating current (AC) voltage of 300 V, and a current of 400 μA (TEG).

The generator maintains high performance even in harsh environments (e.g., cold and salty water). It successfully powers optical alarms and wireless communication systems, demonstrating the potential for use in wearable electronics, Internet of Things (IoT), and emergency field applications. The work emphasizes the potential of multi-source energy harvesting from water and proposes a path for improving the practicality and output of moisture-based generators.

## SUMMARY AND OUTLOOK

In recent years, HMEGs have garnered significant attention due to their potential for sustainable energy harvesting from ambient moisture. This review highlights key advancements in HMEGs, with a focus on innovative designs in hydrogel materials. Hydrogels alone usually exhibit limited moisture generation performance and typically require polymer engineering to achieve superior energy output. Protonation doping has proven to be a highly effective approach, as the direct introduction of protons into the hydrogel network can significantly enhance both output voltage and current. Furthermore, copolymerizing proton-containing monomers with other mechanically robust monomers to form dual-network hydrogels results in HMEGs with outstanding mechanical properties and power generation capabilities. Existing studies also provide evidence that cations other than protons, such as sodium ions, can be incorporated into supramolecular hydrogel networks, enabling milliampere-level current outputs.

Although significant effort has been made, several key areas will require further development to unlock the full potential of HMEGs: Firstly, improving the output performance of HMEGs remains a critical objective (The output performance of reported HMEGs is summarized in Table 1)[56-75]. New strategies, such as combining concentration gradients with streaming potential or incorporating renewable energy sources such as solar or wind energy, may help improve voltage output and power density; Secondly, the development of flexible HMEGs suitable for wearable and even implantable electronics is crucial. While hydrogel materials are typically soft and stretchable, the fabrication of high-performance HMEGs still requires the integration of high-performance electrodes. The combination of novel flexible electrodes, such as silver nanowires, conductive polymers, and liquid metals, may prove to be beneficial; Thirdly, the compatibility of the fabrication processes of HMEGs with large-scale production technologies, such as screen printing and roll-to-roll printings. By aligning with these efficient and scalable manufacturing techniques, HMEGs can be produced at a significantly lower cost, enabling mass production and facilitating their integration into various industries. Indeed, the preparation of large-scale hydrogels still faces several challenges, including issues with uniformity, and stability, and the technical difficulties in achieving a stable interface with the electrodes. Additionally, the integration of circuit management techniques will play a crucial role in promoting practical applications; Fourthly, the durability and stability of HMEGs is a critical issue that requires attention. To ensure long-term performance, HMEGs must be capable of generating stable output across a range of temperatures and humidity levels. It is well known that hydrogels are highly sensitive to drying or freezing. Future efforts should focus on optimizing the water retention capacity of hydrogels and enhancing their ability to function reliably in both dry and extreme temperature conditions, whether high or low. Fifthly, ion migration plays an important role in moisture harvesting, which often

**Table 1. Summary of the output performance of HMEGs**

| Ref. | Materials | RH (%) | Output voltage (V) | Current density ($mA/cm^2$) | Maximum power density ($\mu W/cm^2$) | Internal resistance |
|---|---|---|---|---|---|---|
| [56] | TCGP | / | 0.08 | / | / | / |
| [57] | ICOH | 90 | 0.17 | / | / | / |
| [58] | MCTP | / | 0.164 | / | / | / |
| [59] | PVA-phytic acid-glycerol hydrogel | 80 | 0.8 | 0.24 | 35 | 10 kΩ |
| [60] | PAAGLE | 90 | 0.838 | 0.635 | 31.9 | 2 kΩ |
| [55] | PAM-AMPS | 80 | 0.8 | 0.48 | 53.3 | 10 kΩ |
| [61] | SCNF-PVA | 90 | 0.9 | 0.09 | 24 | 200 kΩ |
| [62] | Sodium alginate-PVA | 80 | 1.3 | 1.31 | 110 | 1 kΩ |
| [63] | SSG | 80 | 0.6 | 0.14 | / | / |
| [65] | PAM-AMPS | 90 | 0.89 | 0.173 | / | / |
| [66] | PPC/Li-PMC | 80 | 1 | / | 26.5 | 10 MΩ |
| [67] | Natural rubber latex with acrylamide | 95 | 0.24 | 0.161 | 3.86 | / |
| [68] | PAM-AMPS | 93 | 1.25 | 0.3 | 71.35 | 6 kΩ |
| [69] | CPVPN | 80 | 0.34 | 0.033 | / | / |
| [70] | LTH | 90 | ~0.8 | 0.065 | 14.35 | 12 kΩ |
| [71] | Agarose-PAM | 40 | 0.3 | / | 0.7 | 2 kΩ |
| [72] | PCP | 80 | 0.815 | 0.101 | 15.7 | 50 kΩ |
| [73] | PAM | 60 | 1.28 | / | / | / |
| [74] | Polyacrylic acid | 55 | 0.55 | 0.003 | / | 200 kΩ |
| [75] | Poly(acrylamide-acrylamide) | 90 | 1.3 | 55.7 | 2.34 | 500 kΩ |

HMEGs: Hydrogel-based moisture-electric generators; RH: relative humidity; TCGP: tannic acid-carbon nanotube-glycerol-PVA hydrogel; ICOH: cellulose nanofibrils-PVA-glycerol hydrogel; MCTP: MXene-cellulose nanocrystals-tamarind gum polyacrylamide; PVA: polyvinyl alcohol; PAAGLE: polyacrylamide-phytic acid-photosensitizers (Erythrosin B, E)-LiCl; PAM-AMPS: poly acrylamide and 2-acrylamide-2-methyl propane sulfonic acid; SCNF-PVA: sulfated cellulose nanofibers-PVA; SSG: $SiO_2$-sodium alginate-reduced graphene oxide; PPC/Li-PMC: PVA, cellulose nanofibrils, phytanic acid, LiBr, and multi-walled carbon nanotubes; CPVPN: calcium chloride-poly(vinyl alcohol)-poly(N-isopropylacrylamide); LTH: PVA-polyaniline-glycerol-ethyl cellulose ether-terpineol; PCP: PVA-cellulose nanofibrils-phytanic acid.

results in slower response times for HMEGs. Therefore, further development of hydrogels with enhanced ion migration rates is needed. Sixthly, the process of moisture harvesting lacks a precise theoretical model description. The establishment of an energy harvesting equation will provide important theoretical guidance for future technological innovations.

In summary, the future of MEGs holds immense potential, with significant prospects for further improvements in performance, durability, and versatility. Ongoing innovation in material design, fabrication techniques, and integration strategies will be key to ensuring that MEGs meet the diverse demands of applications ranging from wearable electronics to environmental sensors. At the same time, these advancements will contribute to the global shift toward more sustainable energy solutions.

## DECLARATIONS

### Authors' contributions

Data analysis and interpretation: Zhang, H.; Sun, M.; Meng, Q.; Li, H.
Provided administrative, technical, and material support: Tian, Y.
Wrote and reviewed draft: Zhang, H.; Sun, M.; Tian, Y.
Funding aquarian: Tian, Y.; Zhang, H.

### Availability of data and materials
Not applicable.

### Financial support and sponsorship
This work was supported by the National Natural Science Foundation of China (Grant No. 52175300), Heilongjiang Province Key Research and Development Program (Grant No. 2022XJ03C07), and State Key Laboratory of Precision Welding & Joining of Materials and Structures (MSWJ-24M11).

### Conflicts of interest
All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate
Not applicable.

### Consent for publication
Not applicable.



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