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EDITORIAL

Powering the Future: Hydrogel-based Soft Ionic Conductors Energize Flexible and Wearable Triboelectric Nanogenerators

Yang Luo [1,2]

[1] *Department of Materials, ETH Zürich, Zürich, 8093, Switzerland*

[2] *Department of Physics, City University of Hong Kong, Kowloon, Hong Kong SAR, 999077, China*

In contemporary times, the escalating prominence of portable and wearable electronics of the next generation has instigated a surge in the need for power solutions [1]. However, conventional power supplies, characterized by their rigid and intricate configurations, substantial size, and ecologically detrimental characteristics, no longer meet the essential prerequisites of wearable electronics. Consequently, researchers have devoted significant efforts toward the advancement of pliable and environmentally sustainable power sources specifically tailored for wearable applications. In recent years, one particular avenue of exploration that has garnered attention is flexible triboelectric nanogenerators (TENGs). These devices have captivated interest owing to their uncomplicated structure and manufacturing processes, lightweight nature, impressive power output, and cost-effectiveness [2-5].

In addition to triboelectric materials, the integration of flexible and wearable TENGs relies on the selection of suitable electrodes. Generally, there exist four categories of electrodes in flexible TENGs: i) metal sheets; ii) carbon sheets; iii) conductive polymer films; and iv) hydrogel films. However, metal sheets, despite their high conductivity, are unsuitable for flexible and wearable applications due to their limited flexibility and stretchability. Similarly, carbon sheets exhibit drawbacks such as reduced conductivity despite being cost-effective. Although conductive polymer films can achieve stretchability when fabricated on flexible substrates, their synthesis process is often complex, and they tend to possess poor conductivity. In contrast, hydrogels offer distinct advantages, including high transparency, stretchability, biocompatibility, and minimal environmental impact. Most notably, hydrogels exhibit ionic conductivity

*CORRESPONDING AUTHOR:

Yang Luo, Department of Materials, ETH Zürich, Zürich, 8093, Switzerland; Department of Physics, City University of Hong Kong, Kowloon, Hong Kong SAR, 999077, China; Email: yluo24-c@my.cityu.edu.hk

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as opposed to the electronic conductivity observed in metal sheets, carbon sheets, and conductive polymer films. This unique property enables fine-tuning and optimization of resistance and charge-carrier density, selection of specific chemical ionic species utilized in the material, and integration of biological and electronic systems. Consequently, hydrogels hold significant potential for enhancing the performance and integration of soft electrodes and conductors in TENGs, particularly in the domains of wearable and biomedical electronics [6,7].

In 2017, Xu et al. [8] introduced the pioneering hydrogel-based triboelectric nanogenerator (H-TENG), employing polyvinyl alcohol (PVA) hydrogel as the conductor and polydimethylsiloxane (PDMS) as the triboelectric layer. This PVA-based H-TENG demonstrated its capability as a self-powered human motion sensor, adept at harnessing biomechanical energy from stretching, bending, and twisting motions. Similarly, in the same year, Pu et al. [9] presented the first ionic hydrogel composed of polyacrylamide (PAM) and LiCl, which exhibited excellent stretchability and transparency as the current collector. The skin-like PAM/LiCl H-TENG demonstrated significant potential in enhancing human motion energy harvesting and touch sensing, thereby finding promising applications in artificial skins, wearable electronics, and soft robots. Subsequently, the field of H-TENGs has garnered increasing attention, leading to rapid advancements in output performance and long-term stability, facilitating expanded possibilities for their applications.

In conventional TENGs, electrodes generally do not require specific characteristics beyond conductivity and attachment to the triboelectric layers. However, in the context of flexible and wearable applications, TENG electrodes must satisfy several additional requirements. These include i) tunable conductivity to achieve desirable output for detecting human motions and powering portable electronics; ii) flexibility and stretchability to effectively harness energy from bending and twisting movements while ensuring user comfort; iii) non-toxicity to prioritize user health and safety; and iv) transparency to facilitate visual information transmission and maintain aesthetic appeal. In this regard, hydrogels emerge as an optimal choice for flexible TENG electrodes, surpassing other alternatives such as metal sheets, carbon sheets, and conductive polymer films. Hydrogels utilized as electrode materials for flexible TENGs can be categorized into several types, including pure hydrogels, salt-modified hydrogels, carbon-modified hydrogels, and other variants.

H-TENGs, like other TENGs, encounter various challenges and obstacles that need to be addressed for commercial viability. **Figure 1** provides an overview of the key challenges and prospects of H-TENGs, with descriptions on key aspects including principles, mechanical properties, conductivity, output, stability, and applications summarized below.

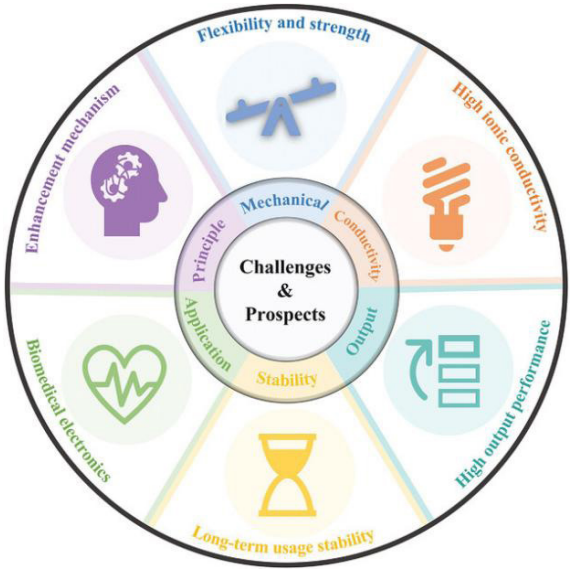

Figure 1. Challenges and prospects of H-TENGs [10].

The synthesis of hydrogels involves diverse components, complicating the understanding of internal mechanisms. Improving the mechanical strength of hydrogels while maintaining flexibility is a challenge that can benefit from insights from fields like tissue engineering. Despite enhancements through conductive additives, hydrogels still exhibit lower conductivity than flexible metal electrodes, necessitating the refinement of strategies for achieving higher conductivity. H-TENGs currently have lower output compared to other flexible TENGs due to single-electrode working modes, limiting integration

in applications requiring contact with human skin. Stability issues, such as limited mechanical strength and lack of polymer-polymer interaction, need to be addressed for long-term performance. H-TENGs find utility in wearable applications, but further development is required for biomedical applications, considering biocompatibility, biodegradability, and compatibility with triboelectric materials, as well as factors related to biosafety and body rejection in implantable settings.

The development of hydrogels as current collectors in TENGs has shown rapid progress in terms of ionic conductivity, stretchability, flexibility, and biocompatibility. Recent advances, such as environmental tolerance and self-healing capabilities, have narrowed the gap between research and commercial applications. However, there are still challenges in the commercialization of hydrogels and H-TENGs due to unclear chemical interfaces, relatively low conductivity and stability, and limited flexible and wearable applications. Nonetheless, hydrogels are expected to gain significant attention in the future, particularly in biomedical and implantable applications, thanks to their favorable biocompatibility and environmental friendliness. It is possible for H-TENGs to surpass other flexible TENGs in terms of conductivity and output. However, parameters such as performance and environmental stability will play crucial roles in realizing the commercial potential of H-TENGs. The development of highly conductive and durable hydrogels through simple fabrication methods will position H-TENGs as excellent alternatives for future wearable and biomedical applications.

Conflict of Interest

There is no conflict of interest.

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