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Topical Review

Advances in magnetic-assisted triboelectric nanogenerators: structures, materials and self-sensing systems

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Abstract

Triboelectric nanogenerators (TENG), renowned for their remarkable capability to harness weak mechanical energy from the environment, have gained considerable attention owing to their cost-effectiveness, high output, and adaptability. This review provides a unique perspective by conducting a comprehensive and in-depth analysis of magnetically assisted TENGs that encompass structures, materials, and self-powered sensing systems. We systematically summarize the diverse functions of the magnetic assistance for TENGs, including system stiffness, components of the hybrid electromagnetic-triboelectric generator, transmission, and interaction forces. In the material domain, we review the incorporation of magnetic nano-composites materials, along with ferrofluid-based TENG and microstructure verification, which have also been summarized based on existing research. Furthermore, we delve into the research progress on physical quantity sensing and human-machine interface in magnetic-assisted TENGs. Our analysis highlights that magnetic assistance extends beyond the repulsive and suction forces under a magnetic field, thereby playing multifaceted roles in improving the output performance and environmental adaptability of the TENGs. Finally, we present the prevailing challenges and offer insights into the future trajectory of the magnetic-assisted TENGs development.

Keywords: triboelectric nanogenerator, magnetic assistance, tuning structure, controlled material preparation, self-powered system

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1. Introduction

Ensuring a reliable energy supply remains a considerable challenge for the sustained operation of Internet of things (IoT) terminals and monitoring systems in various fields. Conventional power methods prove insufficient to meet the demands of widespread sensor networks, thereby emphasizing the necessity for portable, sustainable, and decentralized carbon-free green energy solutions to power these devices [1]. In 2006, Wang and Song coined the term ‘micro-nano energy devices’ and introduced the nanogenerator, a device proficient in efficiently converting mechanical energy into electrical energy through displacement current [2]. Nanogenerators, renowned for their compact size and flexible design, have diverse applications and can effectively capture small amounts of ambient energy. These generators, including triboelectric nanogenerators (TENG) and pyroelectric, thermoelectric, piezoelectric, and electret generators, are categorized according to their effects [3]. Among nanogenerators, TENG and piezoelectric nanogenerators (PENG) stand out for their capability to harvest minimal mechanical energy from the environment [4]. TENG, is particularly adept at harvesting weak mechanical energy from sources such as wind [5–8], sound [9–12], small vibrations [13–16], temperature changes [17–21], and human movement [22–27], thereby leading the field owing to its cost-effectiveness, high output, and adaptability. To expand the opportunities for harvesting weak mechanical energy from different sources, four essential modes of operation have been introduced, namely contact-separation (CS), single-electrode (SE), lateral sliding (LS), and freestanding (FS) (figure 1). Over the last decade, researchers have focused their efforts on investigating the mechanisms, materials, structures, and applications of TENG and deploying them in diverse environments [28–34]. Versatile energy harvesting methods have become prevalent in marine exploitation [35–43], energy science [44–46], environmental protection [47–49], wearable electronics [50–53], self-powered sensors [54–57], biomedical applications [58–62], robotics [63–66], and artificial intelligence [67–70].

TENG serves as a transducer for converting mechanical energy into electrical energy, thereby representing a burgeoning field of research driven by the quest to improve capture and conversion efficiency. Central to this pursuit is the optimization of the TENGs’ ability to capture maximum mechanical energy input from diverse environmental sources such as wind, waves, and other kinetic forms. Here, researchers have devoted considerable efforts to expanding the dynamic response range of TENGs, a task fraught with challenges in energy capture structure design. Among the strategies employed, mechanical tuning [83, 84], fluid-structure coupling [85, 86], and magnetic assistant have emerged as promising avenues. Magnetic-assisted TENGs, leveraging the forces between magnets and their interactions with ferromagnetic objects, offer a particularly intriguing approach to enhancing system performance. The first TENG was invented by Fan *et al* in 2012 [87], while Yang *et al* introduced the first magnetic-assisted TENG in the same year [88]. Hu *et al* presented the initial

hybrid electromagnetic-triboelectric generator (HETG), an innovative device that achieved both sliding and contact modes of TENG through a levitated magnetic structure [89]. Consequently, magnetic assistants have been widely used in TENG. Various reviews have delved into the applications of magnetic-assisted TENGs in hybridized systems, particularly in non-contact applications [90–92]. These studies demonstrate that the utilization of magnetic assistance extends beyond repulsive and suction forces under a magnetic field. However, the most key function of magnetic assistance lies in tuning the mechanical response. In terms of conversion efficiency, the triboelectric materials, as carriers for charge transfer and transport, are the very foundation of the TENG technique, which determines not only the electric output performance but also the diversified functions of the TENGs [93]. Magnetic-assisted materials have emerged as a groundbreaking approach to enhancing the functionality and efficiency of TENGs, heralding a new era of advancement in energy harvesting technology. Researchers have developed various magnetic-assisted materials, aimed to enhance their electric output [94], create micro or macro structures [95], and introduce novel forms of the TENGs (ferrofluid-based) [96]. The preparation of these materials is by the combination of magnetic nano-particles in a magnetic field for micro or macro alignment, which offers a non-contact approach with high responsiveness and minimal lag time. Overall, the magnetic assistant plays a key role in enhancing the system’s mechanical response and electrical output performance of TENGs. However, the relevant review has not been reported.

In this review, we extensively analyzed magnetic-assisted TENGs, thereby examining their structures, materials, and self-powered sensing systems from a unique perspective. Researchers have incorporated magnetic assistance to enhance the system stiffness, HETG components, transmission, and interaction forces, thereby resulting in structures with exceptional environmental adaptability. The preparation of magnetic nano-composites materials, implementation of ferrofluid-based TENG, and microstructure verification were identified as strategies to improve the TENG’s output performance and environmental adaptability of the TENG. Subsequently, we investigated the research progress on physical quantity sensing and human-machine interface (HMI) in magnetic-assisted TENGs. Finally, we addressed the prevailing challenges and anticipated the future trajectory of magnetic-assisted TENG development.

2. Magnetic-assisted structures in TENGs

TENGs offer unique advantages owing to their high efficiency at low frequencies, notably in harvesting wind and blue energy. Researchers have explored various structural designs to enhance the environmental resilience of the TENGs, regardless of wind or wave energy harvesting. These designs comprise bouncing-ball structures [97–99], multiple degrees

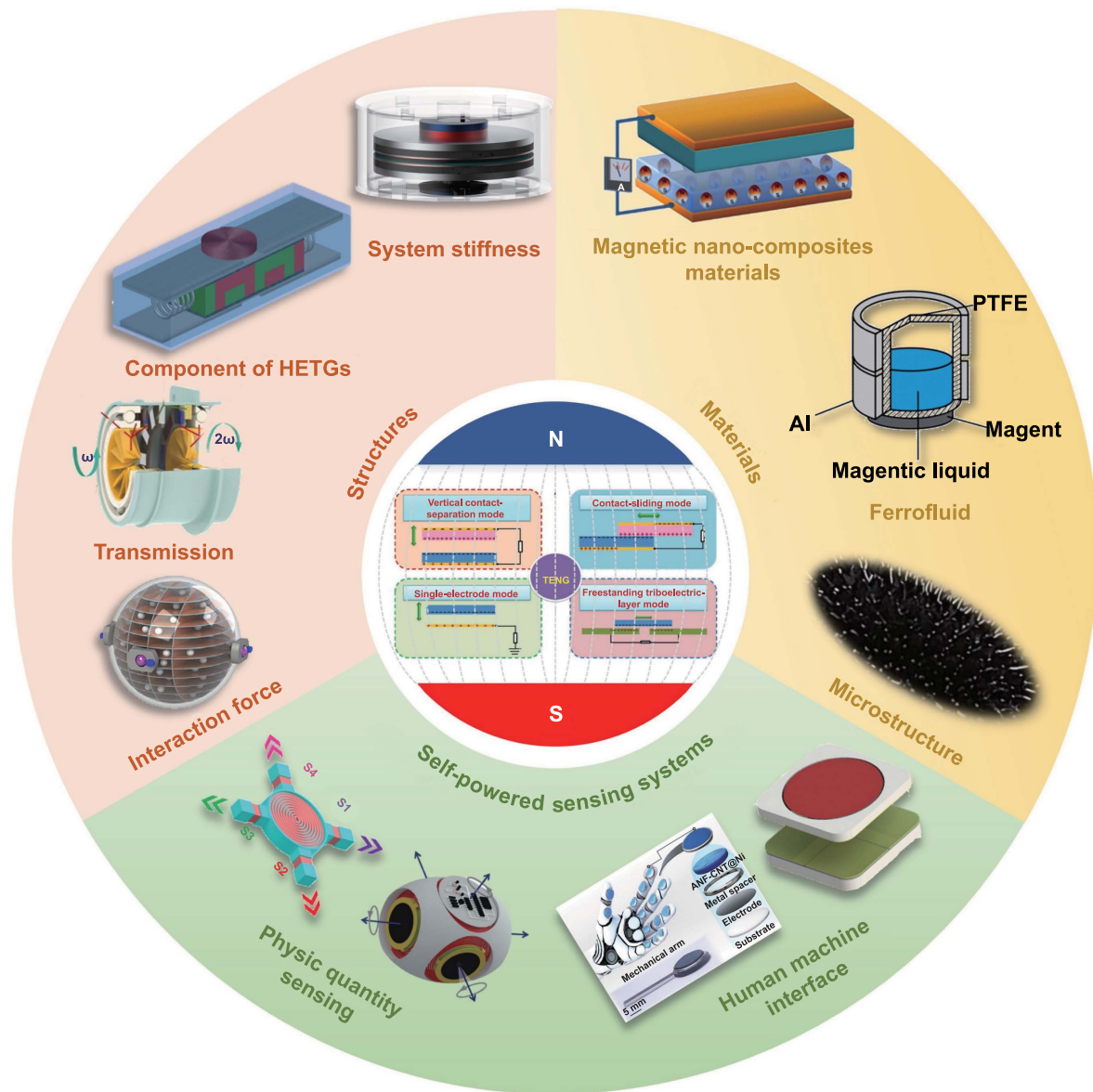


Figure 1. Summary of the magnetic-assisted TENGs in the structures, materials, and self-powered sensing systems. Reproduced from [71]. CC BY 4.0 [72]. John Wiley & Sons.© 2022 Wiley-VCH GmbH [73]. John Wiley & Sons.© 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim [74]. John Wiley & Sons.© 2022 Wiley-VCH GmbH [75]. John Wiley & Sons.© 2023 Wiley-VCH GmbH. Reprinted from [76],© 2023 Elsevier Ltd. All rights reserved. Reprinted from [77],© 2019 Elsevier Ltd. All rights reserved. Reprinted from [78],© 2022 Elsevier Ltd. All rights reserved. Reprinted from [79],© 2021 Elsevier Ltd. All rights reserved. Reprinted from [80], © 2014 Elsevier Ltd. All rights reserved. Reproduced from [81]. CC BY 4.0. Reproduced from [82] with permission from the Royal Society of Chemistry.

of freedom [100, 101], resonant structures [102–104], flexible structures [105, 106], and structures incorporating magnetic assistance [107, 108]. The incorporation of magnetic assistance enables non-contact force transfer, facilitating complex mechanical actions while remaining compatible with the required magnetic field of the HETGs. By categorizing the functions of the magnetic assistance in TENGs, these magnetic-assisted structures can be classified into four types: (i) system stiffness, (ii) HETG components, (iii) transmission and (iv) interaction forces. According to the relevant literature [71, 76], magnetic assistant exhibits excellent performance in maximum mechanical energy capture.

2.1. System stiffness in TENGs

TENG, as a transducer converting mechanical energy into electrical energy, can be simplified into mechanical dynamic systems of stiffness and mass. Stiffness plays a key role in the dynamics of mechanical systems. In mechanical systems, stiffness generally refers to the degree of response of the system to external forces or displacements. The resistance between different magnets, due to their non-contact, nonlinear characteristics, is widely utilized in TENGs. Recently, Wu *et al* have introduced a quasi-zero stiffness structure into the TENG to minimize the driving force by optimizing the parameters of

the magnets and weights (figure 2(a)) [71]. This study aims to address the pivotal question of designing a self-powered sensor capable of detecting a broader frequency range with higher sensitivity, thereby expanding its application. Further, the achieved results set a new standard for ultrawide frequency response and high sensitivity in triboelectric vibration sensors, thereby offering insights for the development of subsequent high-resolution triboelectric vibration sensors. Yang *et al* designed a non-encapsulated pendulum-like paper-based HETG comprising three components: a solar panel, two paper-based zigzag multilayered TENGs, and three electromagnetic generators (EMGs) (figure 2(b)) [109]. System stiffness was attained using the side magnet and main pendulum magnet, thereby creating a spring oscillator-like mechanism. This distinctive structure demonstrated superior robustness, thereby resulting in a maximum peak power of 22.5 mW for zigzag multilayered TENGs. This work has demonstrated the efficiency and effectiveness of their design in terms of harnessing energy from ambient sources. This level of power generation is significant, especially considering the lightweight and portable nature of the paper-based components. In another development, Zhao and Ouyang created an oscillatory TENG incorporating a bistable structure with two repulsion magnets to broaden the frequency bandwidth (figure 2(c)) [110]. This study delved into the nonlinear mechanism dynamics of a TENG featuring grating-patterned films. Moreover, it integrated these films with the bistable magnetic structure to enhance the output performance. Notably, the magnets also significantly contributed to the system stiffness on the inclined planes. Through magnetic supporting stiffness in two directions, the TENGs exhibited a good dynamic response, thereby serving as a reference for subsequent multi-directional oscillation designs. As illustrated in figure 2(d), Park *et al* demonstrated a TENG featuring a thoughtfully designed biaxial vibration-responsive magnetic configuration (BVMC) [111]. The system stiffness was provided by the two magnets, and their oblique placement imparted biaxial sensitivity to the system, thereby, providing design insights for vibration energy harvesters in rotational directions.

Exploring the remarkable responsiveness of the BVMC to vibrations has led to the identification of further applications, particularly in harvesting multidirectional vibrational energy within a single device. The TENG, featuring a simple yet biaxially sensitive magnetic configuration, exhibits significant potential for efficiently capturing multidirectional and low-frequency vibrations in our surroundings. This provides avenues for practical applications in the future. As shown in figure 2(e), Tan *et al* have reported a battery-like self-powered universal module (SUM) comprising an energy harvesting unit (a '3-in-1' hybrid generator, EMG-PENG-TENG) and a power management (PM) unit. A magnet was situated in the polylactic acid (PLA) tube and centrally placed within the chamber through levitated magnets, which was achieved by two smaller repulsion magnets positioned at the ends of the tube. Compared to other mechanical energy harvesting devices, the levitated magnetic design renders the SUM more ingenious, efficient, and versatile as a battery. Similarly, Hu *et al* introduced a suspended mechanism based on two

repulsion magnets that simultaneously harvested mechanical energy using TENG and EMG (figure 2(f)) [89]. The design simultaneously achieves vibration energy harvesting in multiple operational modes (both PS-mode and CS-mode TENG).

Using a stiffness-parallel structure is also an effective approach for capturing vibrational energy. For example, Mu *et al* proposed a levitation magnet scheme in parallel with a spring-like TENG structure, as shown in figure 2(g) [113]. Additionally, He *et al* investigated a hybridized TENG-PENG-EMG with a levitated magnetic structure (figure 2(h)). This design demonstrated higher sensitivity than conventional spring or cantilever configurations, attributed to low energy loss [114]. Lu *et al* utilized a magnetic repulsion adjustment system (figure 2(i)) characterized by good robustness and a high signal-to-noise ratio within the measure range [115]. The practical application of the magnetic-assisted self-powered acceleration sensor was verified through real-time detection of remote-controlled car operation and collision acceleration, highlighting its potential for vehicle electronic systems. Qaseem and Ibrahim integrated a vibroimpact TENG with magnetic nonlinear stiffness to broaden the operational bandwidth to realize the efficiency enhancement of conventional TENGs [116]. This study used a cantilever beam with a magnet on one end aligned with a fixed magnet of the same polarity. This arrangement results in nonlinear magnetic repulsion. Additionally, a triboelectric collector is integrated into the system, which uses the underside of the upper magnet as the upper electrode. The electrodes are also put underneath and connected to the polydimethylsiloxane insulator (figure 2(j)). Finally, magnetically assisted TENGs have been used in nanogenerator-controlled drug delivery systems for cancer therapy [117]. Zhao *et al* have developed a new magnetic TENG that ensured contact and detachment cycles between the two tribolayers, effectively increasing the output of the TENG to 70 V compared to pre-implantation. The contact-mode magnet TENG, designed without a commonly used spacer, ensured high and stable electric output performance during packaging and unfolding. (figure 2(k)). This research indicates that magnetically assisted frictional electricity holds tremendous potential for implantable clinical therapies. In the future, the non-contact nature of magnetic forces could be utilized for external driving.

2.2. Component of HETGs

HETGs, as an innovative energy harvesting technology, have attracted widespread attention. They utilize the dual mechanisms of TENG and electromagnetic induction to capture mechanical energy from the surrounding environment and convert it into electrical energy. Compared to traditional single generators, HETGs have higher efficiency and broader applicability because they can capture a greater variety of mechanical energy under different conditions. Considering its intrinsic mechanical characteristics, wind energy, as a sustainable power source, must be efficiently harnessed. Lee *et al* introduced a self-adaptive HETG for wind energy harvesting by employing an analysis-based design strategy based on a

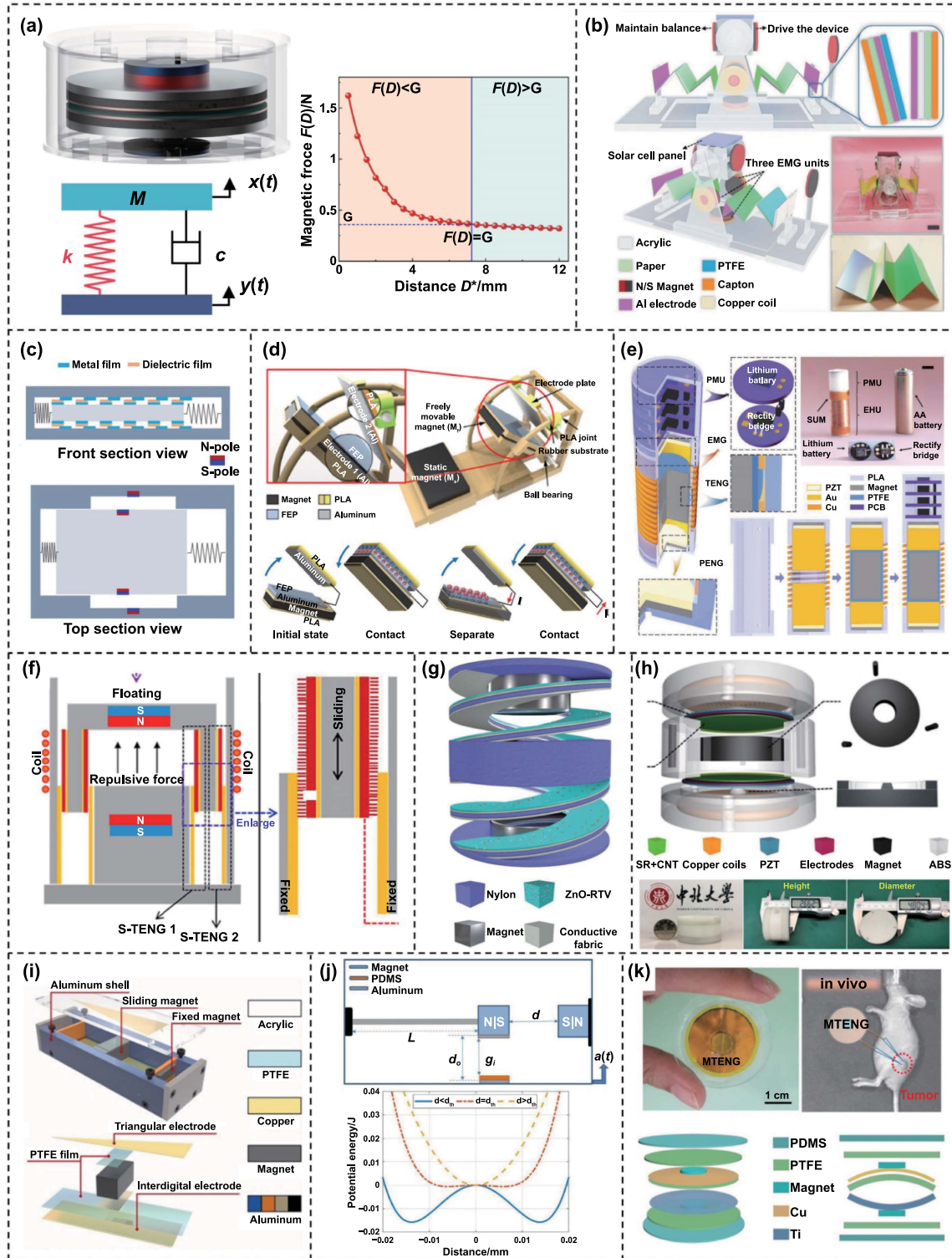


Figure 2. Magnets act as the system stiffness in TENGs. (a) Quasi-zero stiffness structure. Reproduced from [71]. CC BY 4.0. (b) Magnetic force as a nonlinearity caused the system to oscillate [109]. John Wiley & Sons.© 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Non-contact system stiffness in the vertical direction to reduce the frictional resistance. Reproduced from [110]. CC BY 4.0. (d) System stiffness on an inclined plane to get bi-axially sensitivity and a superior response [111]. John Wiley & Sons.© 2021 John Wiley & Sons Ltd. (e) Suspension magnet in a battery-like SUM [112]. John Wiley & Sons.© 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (f) Magnetic force acts as the source of the system stiffness. Reprinted with permission from [89]. Copyright (2014) American Chemical Society. (g) Magnetic levitation double helix TENG [113]. John Wiley & Sons.© 2021 WILEY-VCH Verlag GmbH. (h) Magnetic levitation structure. Reprinted from [114],© 2017 Elsevier Ltd. All rights reserved. (i) MASA sensor for real-time monitoring of vehicle operation and collision based on TENG. Reprinted from [115],© 2022 Elsevier Ltd. All rights reserved. (j) Magnetic bistable broadband vibro-impact TENG. Reproduced from [116]. CC BY 4.0. (k) Vivo cancer therapy by an implantable magnetic TENG [117]. John Wiley & Sons.© 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

movable-magnet rational mechanism [49]. The design illustrated in figure 3(a) automatically adjusts power consumption and mechanically limits the total amount of mechanical energy a given system receives, ensuring efficient operation regardless of wind speed. Under certain wind conditions, this structure is approximately 60 times more efficient than solid mechanical structures. This research paves the way for further advancements in wind energy harvesting technology, offering promising prospects for a wind and more sustainable energy future. Additionally, Zhang *et al* proposed a strategy for low-speed flow energy harvesting realized by an alternating-magnetic-field-enhanced TENG (figure 3(b)) and demonstrated the practicality of utilizing the ampere force to drive TENG operation [118]. This strategy employed wind energy as the power input and achieved a cut-in wind speed of 1 m s^{-1} , the results significantly extend the feasible harvest range of rotational TENG for the low-velocity machinery. This research not only expands the potential applications of rotational TENGs but also contributes to the broader goal of achieving sustainable energy solutions for a wide range of environmental conditions.

Owing to its lightweight, low cost, and high efficiency at low frequencies, TENG presents distinct advantages in blue energy harvesting [127]. To address the irregular and ultralow frequency of blue energy, Xie *et al* presented a non-resonant HETG employing a flexible inverted pendulum structure, successfully realizing all-directional vibration energy acquisition, as depicted in figure 3(c) [119]. The system achieved a conversion efficiency of 48.48%, representing a notable improvement of approximately 2.96 times, which was attributed to the elastic buffering effect of the TENG with a double-helix structure. Zhang *et al* integrated a bifilar-pendulum-coupled hybrid PENG-TENG-EMG nanogenerator module into a vessel-like platform for blue energy harvesting by incorporating an EMG, two PENGs, and two multilayer-structured TENGs (figure 3(d)) [120]. Due to precise geometric design and efficient space utilization, the system achieved a high peak power density of 358.5 W m^{-3} . However, traditional cylindrical pendulum TENGs are effective only within a narrow frequency bandwidth. To address the limitation, Cao *et al* introduced a TENG with a swing-rotation conversion structure coupled with a gravitational potential energy storage/release design [121]. This TENG converts various swing and vibration energy into electric energy, which offers consistent output in intermittent continuous rotation modes (figure 3(e)). The coupling mechanism allows efficient harvesting of low-frequency mechanical energy ranging from 0.3 Hz to 5 Hz. Moving beyond the pendulum structure, a spherical design also proves effective for blue energy harvesting. Zhu *et al* proposed a highly integrated HETG capable of efficiently broadband wave energy harvesting, realized by a self-powered ocean buoy [122]. In figure 3(f), the innovative structure features a permanent-magnetic polytetrafluoroethylene (PTFE) ball, ensuring high integration between the permanent-magnet emerging the EMG and the tribo-material emerging the TENG. As the results show that the magnetic increases the voltage of TENG output, it verified the positive function of the magnetic assistant in TENG. This research

paves the way for the development of more efficient and sustainable solutions for harnessing renewable energy from the vast resources of the ocean.

As regards dispersed raindrop energy harvesting, Zhang *et al* developed a flexible droplet-based HETG incorporating a droplet-based EMG and droplet-based TENG for efficient raindrop energy harvesting [123]. As portrayed by figure 3(g), a flexible magnetically responsive hydrophobic film functions as a ‘spring-like’ design based on the contact and separation (CS) mode in the droplet-based TENG part and as an excitation mechanism for moving the coil to change the magnetic flux through the coil in the droplet-based EMG part. When a water droplet excites the HETG, the vibration of the elastic hydrophobic film induces the CS of the two electrodes in the droplet-based TENG. Simultaneously, the coils cut the magnetic wire in the droplet-based EMG, thereby generating a dual electrical output. This research holds promise for addressing energy needs in regions with abundant rainfall and contributes to the ongoing efforts towards a greener and more sustainable future.

Rana *et al* employed a Halbach magnet array to optimize the additional magnetic flux distribution in the coil, significantly enhancing the EMG output performance, whereas the PTFE nanofibers (NFs) boosted the TENG output [72]. By implementing a classical spring-mass model (figure 3(h)) and rationally integrating the HETG, they achieved an outstanding output power of 1.02 W. Pongampai *et al* designed and optimized a Miura-origami-inspired structure for a hybrid PENG-EMG-TENG (figure 3(c)) [124]. The unique hexagonal multilayer design used in the device design increased the contact surface area and improved the electrical output signal of the TENG. Additionally, Zhang *et al* proposed a self-powered intelligent damper (SID)-integrated HETG unit for in situ vibration monitoring of stay cables [125]. Illustrated in figure 3(j), the SID consisting of ball screws, an arched membrane TENG, a three-phase EMG, and an MR damper is able to operate in both rotational and linear motions. However, the energy utilization efficiency of an EMG is inferior to that of a TENG at low frequencies, limiting the overall efficacy of the HETG [128]. To address this issue, Chen *et al* proposed a layered HETG comprising a rotating disk TENG, a magnetic multiplier, and a coil panel [126]. As depicted in figure 3(k), configuring the number of magnets and coils to achieve n times the rotational speed of the EMG relative to the TENG resulted in an effective energy utilization efficiency of the HETG. The results show that the configuration can improve more than double the energy conversion efficiency. This work discussed the efficient operation of the EMG and TENG tuning in different input frequencies to utilize their respective advantages.

2.3. Transmission for TENGs

Magnetic interactions play a pivotal role in enabling contactless transmission, thereby mitigating the wear issues associated with TENGs. On this basis, Chen *et al* proposed a chaotic pendulum-designed HETG utilizing power transmission through the interactive forces between magnetic spheres

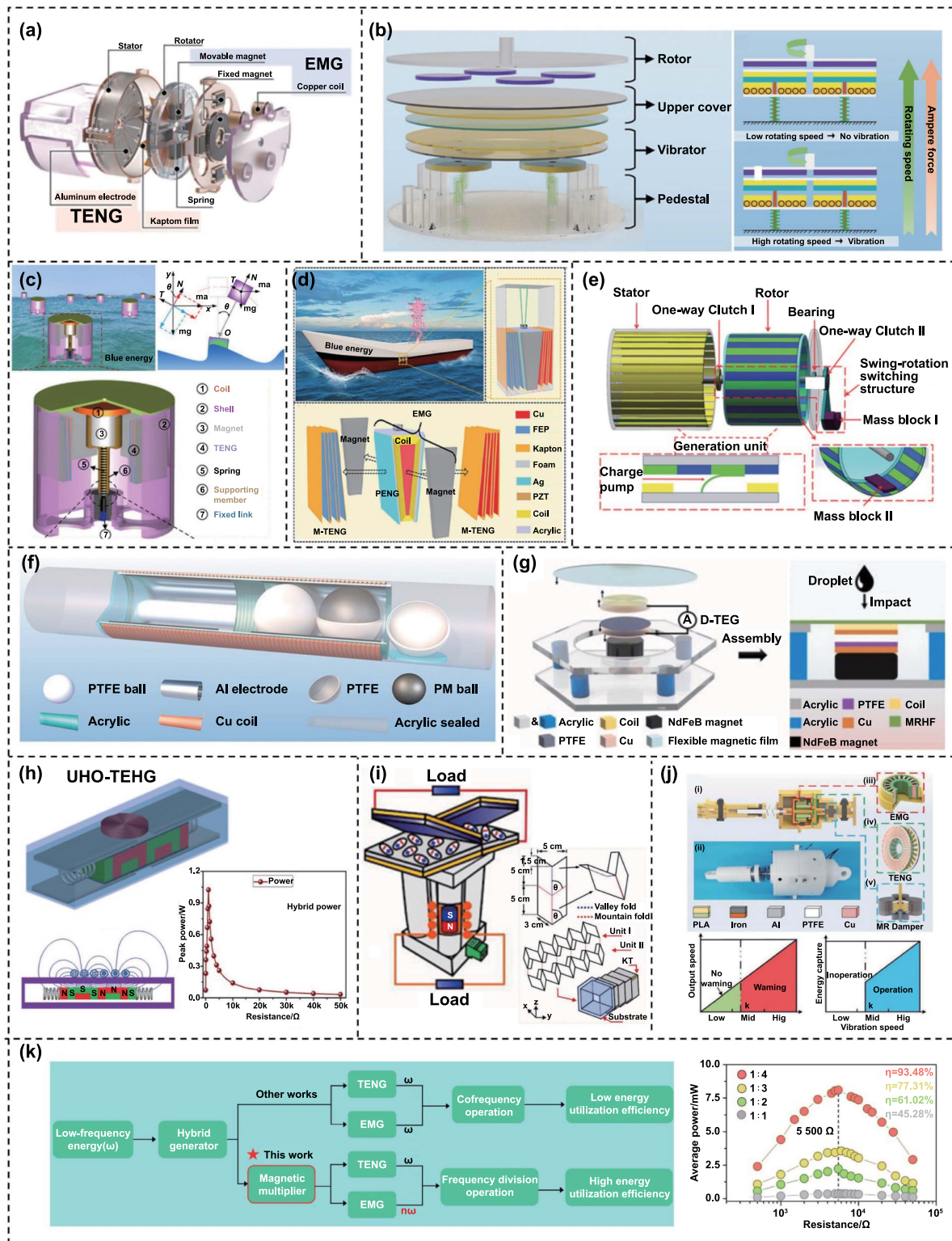


Figure 3. Magnets act as the key component of HETGs. (a) Self-adaptive mechanical HETG for wind energy harvesting. Reprinted from [49], © 2022 Elsevier Ltd. All rights reserved. (b) Alternating magnetic field-enhanced HETG [118]. John Wiley & Sons. © 2023 Wiley-VCH GmbH. (c) Non-resonant inverted pendulum structure HETG. Reproduced from [119]. CC BY 4.0. (d) High space efficiency hybrid nanogenerators [120]. John Wiley & Sons. © 2022 Wiley-VCH GmbH. (e) Swing-rotation switching design with a gravitational potential energy storage/release strategy [121]. John Wiley & Sons. © 2022 Wiley-VCH GmbH. (f) Highly integrated HETG for wind energy harvesting [122]. John Wiley & Sons. © 2023 Wiley-VCH GmbH. (g) Flexible droplet-based HETG. Reprinted from [123], © 2024 Elsevier Ltd. All rights reserved. (h) Halbach magnet array enhanced HETG [72]. John Wiley & Sons. © 2022 Wiley-VCH GmbH. (i) Miura-origami-inspired structure for self-charging HETGs. Reprinted from [124], © 2023 Vietnam National University, Hanoi. Published by Elsevier B.V. (j) Damper-integrated HETG unit [125]. John Wiley & Sons. © 2023 Wiley-VCH GmbH. (k) Magnetic-multiplier-enabled HETG. Reproduced from [126]. CC BY 4.0.

(figure 4(a)) [129]. The physical design of the harvester capitalized on the benefits of a low working frequency and high electromechanical conversion efficiency of the chaotic pendulum. Additionally, Zhu *et al* engineered an autonomous self-powered flow sensor with shaftless turbine intake, incorporating a ball-bearing TENG and an EMG base on a magnetic field modulation-type magnetic gear (figure 4(b)) [76]. The magnetic gear transmission realized a shaftless turbine design, thereby simplifying the design of energy capture mechanisms and reducing obstruction to the turbine blades. This enhancement results in an improved TENG signal broadband and EMG electrical output performance. Kim *et al* introduced a cam-based TENG assembled with magnets to augment power output and sustainability by leveraging non-contact repulsive magnetic forces for power transfer (figure 4(c)) [130]. They also innovatively designed and demonstrated a TENG-based windmill system that was effective in harvesting low-speed wind energy (approximately 4 m s^{-1}) and generating low torque. As a result, this TENG system, devoid of friction, is anticipated to offer a sustainable remedy for effectively capturing various forms of underutilized mechanical energy. This innovative approach not only enhances energy generation efficiency but also minimizes wear and tear, thus extending the lifespan of the system.

Zhong *et al* reported on an easily assembled HETG driven by magnetic coupling (figure 4(d)) [131]. The introduction of magnetic coupling ensures a stable performance irrespective of environmental variations. To ensure the consistent generation of continuous and regular electrical energy beyond the critical speed. Liu *et al* devised a magnetic-switch-structured TENG incorporating transmission gears, energy modulation modules, and a generation unit (figure 4(e)) [132]. The energy modulation modules, designed to store and release energy in response to intermittent wind falling on the wind scoop, rely not on the velocity of the wind but on the magnetic force exerted by the magnets. The results show that this innovative approach facilitates the conversion of wind energy into a continuous and regular electrical supply. The magnetic assistant as a transmission module to tune random energy into regular electrical, the study can reduce the difficulty of circuit management and power load design and provide a good idea for the energy capture mechanism in the subsequent disordered energy input scenario. Recognizing magnetic energy's abundance and enduring presence across diverse sources, Yuan *et al* introduced a HETG system featuring a modified pendulum unit, which interacts mechanically with two multilayered TENGs and remotely with copper coils (figure 4(f)) [133]. The magnets within respond to an alternating magnetic field, facilitating the TENG's operation. This research introduces a fresh approach to harvesting magnetic energy from transmission lines.

2.4. Interaction force for TENGs

For future endeavors involving the large-scale harvesting of blue energy from the ocean using TENGs, the deployment of networks comprising TENGs is envisioned as a feasible

approach to achieving this ambitious objective [134]. Yang *et al* were the pioneers in proposing a macroscopic self-assembled network of encapsulated TENGs for blue energy harvesting purposes [77]. They employed self-adaptive magnetic joints designed with careful consideration, facilitating self-assembly, self-healing, and easy reconfiguration of the network (figure 5(a)). The innovative network significantly enhances system autonomy and robustness. This adaptability not only ensures continuous energy harvesting but also enhances the system's resilience against external disturbances, such as harsh weather or turbulent seas.

Zou *et al* presented a self-regulation approach for a TENG aimed at creating a self-powered wind speed sensor [135]. Through the rational design of centrifugal and nonlinear magnetic forces, the separation and contact levels of the TENG's functional materials were automatically adjusted to suit varying wind speeds (figure 5(b)). Ren *et al* introduced an innovative non-contact high-efficiency HETG driven by magnetic force, designed to scavenge biomechanical energy for the sustainable powering of portable electronics (figure 5(c)) [136]. In this setup, a magnet serves as the trigger for the non-contact drive CS-mode TENG, exploiting the magnetic responsiveness of the triboelectric materials. Additionally, the EMG is derived by simultaneously coupling the magnet with copper coils.

To study the effect of prestress on Lateral sliding triboelectric nanogenerators (LS-TENGs), Zhang *et al* first proposed a pioneering strategy involving the incorporation of flexible magnet layers into the LS-TENG, aimed at investigating the electrification and coupling effects induced by magnetic prestress, referred to as magnetically stressed TENG, both theoretically and experimentally (figure 5(d)) [137]. It can be observed the TENG exhibits high voltage signals as the magnetic field strength increases. This study offers a theoretical framework for understanding the impact of external prestress on enhancing the performance of LS-TENGs, which may provide novel solutions for enhancing the performance of the TENG. In efforts to augment sliding energy scavenging efficiency and bolster device durability, Tang *et al* proposed a flexible Halbach magnetic-array-assisted sliding-mode TENG (figure 5(e)) [138]. Leveraging this operational mode, the output energy and peak power during a single sliding motion were found to be 2.7 times and over 10 times greater, respectively, compared to those of the FS mode TENG. This work provides a potential strategy to overcome the difficulties of efficiency and durability existing in sliding mode TENGs in practical applications.

3. Magnetic-assisted materials in TENGs

As the direct carriers, the tribo-materials are the crucial determinant of the applicability of TENGs [139–142]. Magnetic-assisted materials have emerged as a promising avenue for enhancing the performance and functionality of TENGs. According to the different preparation methods and the shape of the magnetic-assisted materials, existing

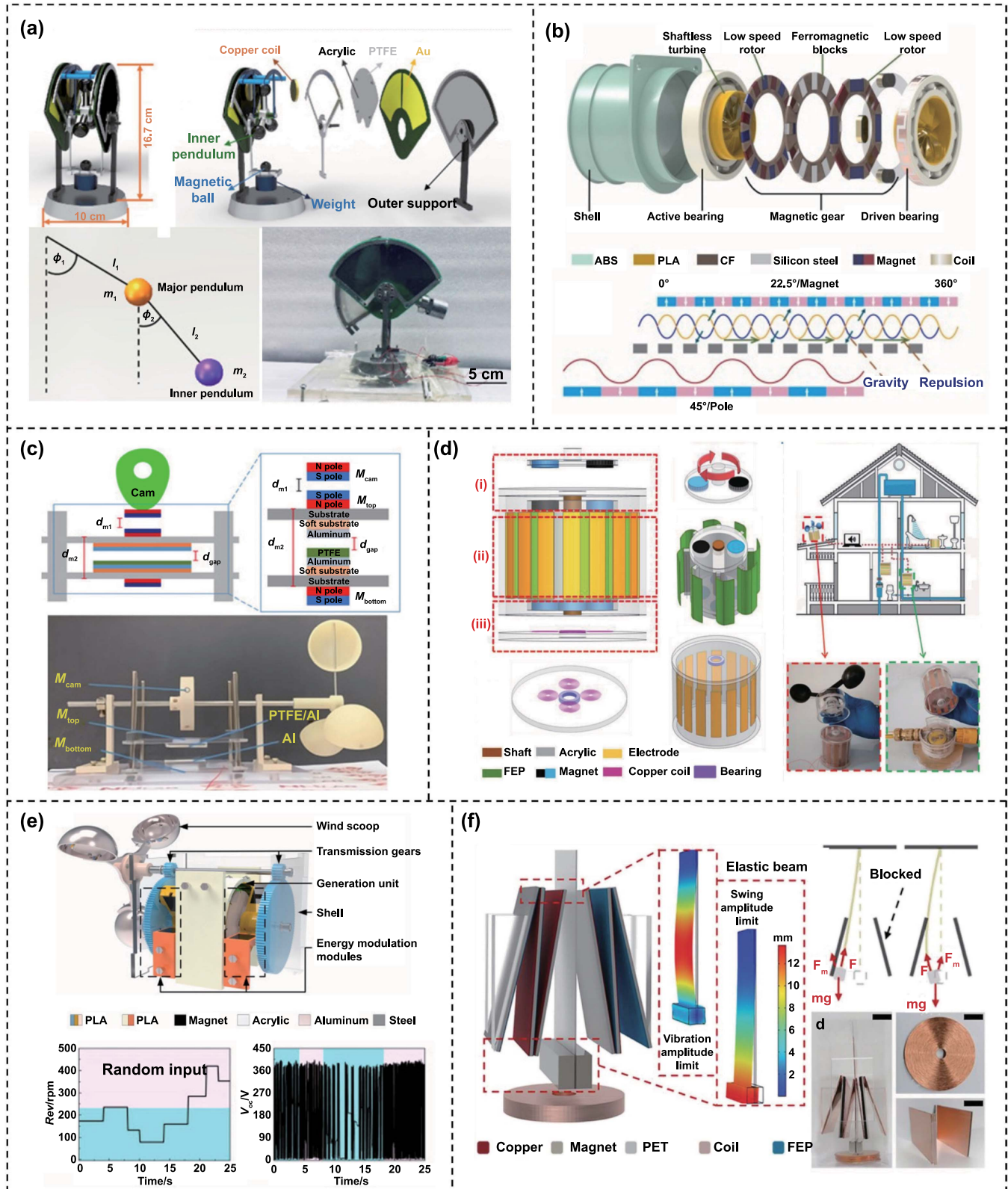


Figure 4. Magnets provide the transmission for TENGs. (a) Chaotic pendulum design constructed by magnetic force. Reprinted from [129], © 2019 Elsevier Ltd. All rights reserved. (b) Variable speed structure of magnetic gear drive. Reprinted from [76], © 2023 Elsevier Ltd. All rights reserved. (c) Vertical magnetic motion transmission from the cam mechanism. Reproduced from [130]. CC BY 4.0. (d) Magnetic coupling drives the HETG [131]. John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) Magnetic switch structured TENG for continuous and regular energy harvesting. Reprinted from [132], © 2021 Elsevier Ltd. All rights reserved. (f) Magnetic transmission in multi-layered TENG [133]. John Wiley & Sons. © 2022 Wiley-VCH GmbH.

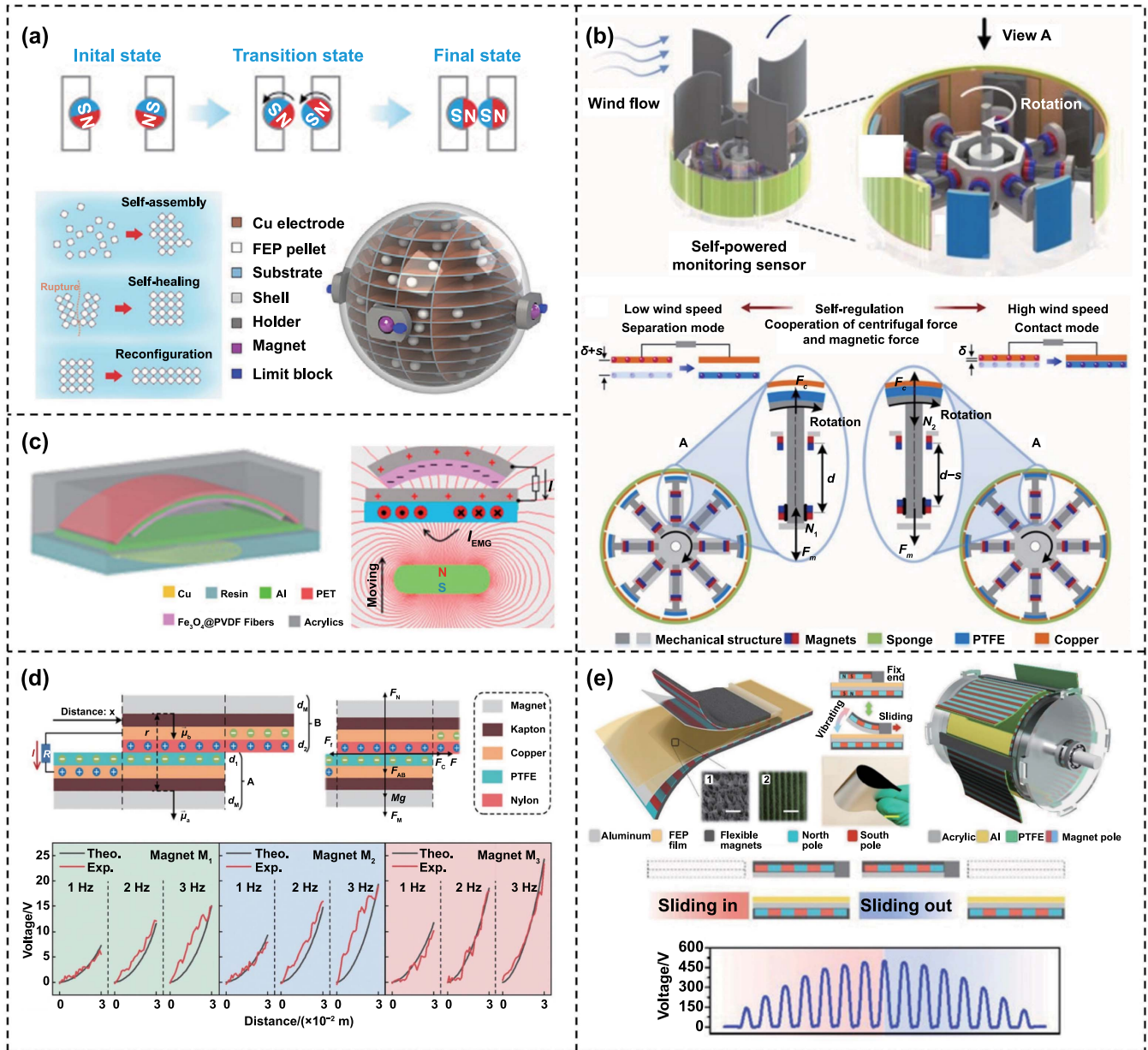


Figure 5. Magnets provide an attractive force for TENGs. (a) Magnetic attraction acts on a macroscopic self-assembly network of encapsulated TENGs. Reprinted from [77], © 2019 Elsevier Ltd. All rights reserved. (b) Self-regulation design of balance between magnetic force and centrifugal force of wind. Reprinted from [135], © 2022 Elsevier Ltd. All rights reserved. (c) Magnetic force-driven noncontact HETG. Reprinted from [136], © 2017 Elsevier Ltd. All rights reserved. (d) Transduction of mechanical energy to triboelectric energy in sliding-mode nanogenerators with magnetic pre-stress [137]. John Wiley & Sons. © 2023 Wiley-VCH GmbH. (e) Alternating magnetic stripe arrays in TENG to promote efficiency and durability. Reprinted from [138], © 2019 Elsevier Ltd. All rights reserved.

studies can be categorized into three main groups: magnetic nano-composites materials, ferrofluid-based TENGs, and magnetically assisted microstructures.

3.1. Enhanced output performance of the TENGs

Magnetic polymeric composites exhibit adjustable capacitance due to the variable arrangement of magnetic particles controlled by a magnetic field, making it crucial to investigate their potential as tribo-materials for TENGs from a microscopic perspective. However, the influence of ferromagnetic

media on the displacement currents of TENG has received limited attention.

Sun *et al* proposed an approach involving the use of a magnetic polymeric composite film as a tribo-material to boost the TENG output performance (figure 6(a)) [143]. The results demonstrated the TENG utilizing the modified film achieved a 4.7-fold enhancement in performance compared to the TENG employing a pure silicone rubber mixture film. This study attempted to enhance TENG output by magnetic nanoparticle doping, providing insights for further improving TENG output performance. Furthermore,

Table 1. Summary of the Magnetic assisted structures in TENGs.

Type	Mode/Materials	Output (OC-V, SC-I)	Power density	Applications	References
System stiffness	CS/PTFE, Cu	207 V, 18.23 μ A	0.157 mW cm ⁻³	Running state and fault type monitoring	[71]
	CS/PTFE, Al	TENG: 491 V, 34 μ A EMG: 1.74 V, 3.5 mA	N/A	Portable practical power source	[109]
	LS//PTFE, Cu	13.5 V	N/A	Vibration energy harvesting	[110]
	CS/FEP–Al	300 V, 18 μ A	N/A	Multidirectional	[111]
	SF/PTFE, Kapton, Al	TENG: 28 V, 0.6 μ A EMG: 5 V, 15 mA Hybrid: 4.8 V, 15 mA	2 mW cm ⁻³	Low-frequency vibrations harvesting	[112]
	LS/Kapton, Cu	TENG: 500 V, 18.9 mA EMG: 1.5 V, 12.5 mA Hybrid: 4.6 V, 2.2 mA (5 k Ω)	N/A	Driving wearable and portable electronics	[89]
	CS/ZnO-RTV, conductive fabric	400 V, 8 μ A	N/A	Vibration isolator and energy harvesting	[113]
	CS/silicone with carbon nanotube-magnet	EMG1: 7 V, 7 mA EMG2: 4 V, 4 mA PENG1: 60 V, 2.8 mA PENG2: 39 V, 1.8 mA TENG: 15 V, 2 μ A	EMG1: 0.786 mW cm ⁻³ EMG2: 0.737 mW cm ⁻³ PENG1: 2.15 mW cm ⁻³ PENG2: 2.498 mW cm ⁻³ TENG: 0.0016 mW cm ⁻³	Vibration energy harvesting	[114]
	LS/PTFE, Cu	Low acc: 0.045 V, 0.1 μ A High acc: 0.025 V, 0.08 μ A	N/A	Measuring the acceleration	[115]
	CS/PDMS, Al	3.2 V ($d = 12$ mm)	N/A	Energy harvesting	[116]
Hybrid type	CS/PTFE, Ti	70 V, 0.55 μ A	N/A	Delivery of drugs for use in cancer therapy	[117]
	CS/PTFE, Cu	179.3 V, 11.3 μ A, 104.1 nC	0.68 mW	Low-speed flow energy harvesting	[118]
	SF/PTFE, Al	TENG: 230.25 V, 1.35 μ A EMG: 2.3 V, 10.43 mA	TENG: 0.014 mW cm ⁻³ EMG: 0.15 mW cm ⁻³	Self-powered marine buoy	[122]
	CS/PTFE, BC/BT-NPs	TENG: 414 V, 48.3 μ A EMG: 2.04 V, 38 mA	N/A	Driving the wireless global positioning system (GPS)	[124]
	CS/FEP, Cu	TENG: 900 V, 0.7 mA EMG: 2.5 V, 7 mA PENG: 17 V, 10.6 mA	0.358 mW cm ⁻³	Wave energy harvesting	[120]
	CS/PTFE, Cu	TENG: 3.01 V EMG: 11.21 mA	TENG: 2.81×10^{-6} mW cm ⁻² EMG: 0.008 mW cm ⁻²	Raindrop energy harvesting	[123]
	SF/Kapton, Al	TENG: 300 V EMG: 15 mA	TENG: 0.013 mW cm ⁻³ EMG: 0.02 mW cm ⁻³	Harvest the wind energy	[49]
	CS/FEP, Cu	TENG: 190 V, 12.4 μ A EMG: 37.42 V, 22.45 mA	TENG: 0.001 mW cm ⁻³ EMG: 1.13 mW cm ⁻³	Obtain the ultralow frequency energy	[119]
	LS/PTFE, PEO	TENG1: 720 V, 80.5 μ A TENG2: 890 V, 115.3 μ A EMG: 46 V, 500.3 mA Total: 1.02 W	N/A	Biomechanical energy harvesting	[72]
	SF/FEP, nylon	385 V, 37.2 μ A	0.01 mW cm ⁻³ (1.8 Hz) 0.015 mW cm ⁻³ (5 Hz)	Ocean energy harvesting	[121]
	SF/PTFE, nylon	TENG: 80 V, 16 μ A EMG: 40 V, 0.3 A Hybrid: 34.3 V, 0.24 A	0.2 mW cm ⁻³	Vibration in situ monitoring of stay cables	[125]
	SF/FEP, rabbit fur	TENG: 2 800 V 250 nC EMG: 40 V, 7.5 mA	N/A	Mechanical energy harvesting	[126]

(Continued.)

Table 1. (Continued.)

Type	Mode/Materials	Output (OC-V, SC-I)	Power density	Applications	References
Transmission	SF/PTFE, Au	TENG: 197.03 V, 3 μ A EMG: 1.08 V, 4 mA	N/A	Scavenging low-frequency marine vibrations	[129]
	SF/POM, glass	TENG: 33 V, 6 μ A EMG: 374 V, 31 mA	N/A	Airflow sensing in large flow pipelines	[76]
	CS/PTFE, Al	93.8 V, 4.79 μ A	N/A	Harvest a broadband of wasted mechanical energies	[130]
	SF/FEP, Cu	EMG: 12 V, 125 mA TENG: 157 V, 11.5 μ A Hybrid: 270 V, 27.7 μ A	N/A	Harvest fluid energy and flow monitoring	[131]
	SF/FEP, PLA	410 V, 18 μ A	1.3 mW cm ⁻³	Wind energy harvesting	[132]
	CS/FEP, Cu	TENG-P: 120 V, 16 μ A TENG-S: 160 V, 8 μ A EMG-S: 2 V, 4 mA EMG-B: 5 V, 9 mA	N/A	Magnetic energy harvesting	[133]
Magnetic attraction	FS/ FEP, Cu	207 V, 18.23 μ A	Average power density of 8.69 W m ⁻³	Water wave energy harvesting	[77]
	FS/ PTFE, Cu	558 V, 2.79 mW (average power)	N/A	Wind speed measurement	[135]
	CS/ Fe ₃ O ₄ @PVDF, Al	EMG: 3.4 mW TENG: 0.23 mW	N/A	Human motion energy harvesting	[136]
	LS/ PTFE, nylon	19.62 V, 5.63 μ W	N/A	N/A	[137]
	LS/ FEP, Al	500 V, 130 μ A	N/A	Efficient and durable TENG	[138]
	CS/ FEP, MRE	16 mV mT ⁻¹	N/A	Magnetic field detection	[184]

Xiang *et al* presented a simple approach for fabricating TENGs with magnetic properties using composite films of carboxylated chitosan (figure 6(b)). Incorporating magnetic nanoparticles not only significantly improved inter-layer friction but also imparted macroscopic magnetism to the composite film [144]. Pabba *et al* fabricated flexible ferromagnetic poly(vinylidene fluoride-co-hexafluoropropylene) (P(VDF-HFP))/nickel ferrite (NiFe₂O₄) fiber composite film-based TENGs [145]. Through the electrospinning technique, highly crystalline NiFe₂O₄ NFs with a high aspect ratio were synthesized, and these fibers were then integrated into a polymeric matrix, leading to a substantial enhancement in TENG performance, as depicted in figure 6(c). Tayyab *et al* developed TENGs utilizing PVDF in NF form, showcasing remarkable crystallinity, as illustrated in figure 6(d). Electrospinning was utilized to fabricate PVDF NFs, with commercially available printer ink (PI) nanofillers incorporated to augment their crystallinity and amplify the output of the PVDF-PI NF-based TENGs [146]. By leveraging electrospinning and nanofiller incorporation techniques, it has unlocked new possibilities for enhancing energy conversion efficiency and expanding the range of applications for TENG technology.

Liu *et al* proposed enhancing Maxwell's displacement current using a ferromagnetic-assisted approach to improve the TENG output, employing a polymer/iron composite film (figure 6(e)). Theoretical exploration of the magnetizing current in a ferromagnetic medium coupled with the displacement current, based on Maxwell's equations, was pursued to enhance the output of the TENG, this proposition was

validated through both simulation and experimentation [78]. This study established a theoretical model for magnetically nanoparticle-doped enhanced TENG based on Maxwell's displacement current, providing an important theoretical foundation for subsequent research.

3.2. Ferrofluid-based TENGs

Ferrofluid-based TENGs represent an innovative and promising approach in the field of energy harvesting technology. By integrating ferrofluids, which are colloidal suspensions of magnetic nanoparticles in a carrier fluid, into the design of TENGs, researchers have unlocked new avenues for efficient energy conversion from mechanical motion. Solid-liquid-based TENGs have garnered considerable attention owing to their diverse forms [147], and magnetic fluids, in particular, stand out as functional materials that combine the fluidity of liquids with the magnetism of solid magnetic materials. Consequently, magnetic fluid plays a pivotal role in the development of hybrid nanogenerators. In this context, Yang *et al* introduced a magnetic-fluid-based TENG operating in the FS mode (figure 7(a)) [82]. In this setup, the magnetic fluid encapsulated as a tribo-material in a PTFE container facilitated TENG tuning. The results revealed a robust linear correlation between the vibration amplitude and the output voltage, alongside an impressive low-frequency vibration response. Furthermore, Yang *et al* proposed a HETG based on a magnetic liquid comprising water, surfactants, and ferromagnetic particles (figure 7(b)). Electrostatic and electromagnetic inductions within the magnetic liquid, polymer sidewalls, and

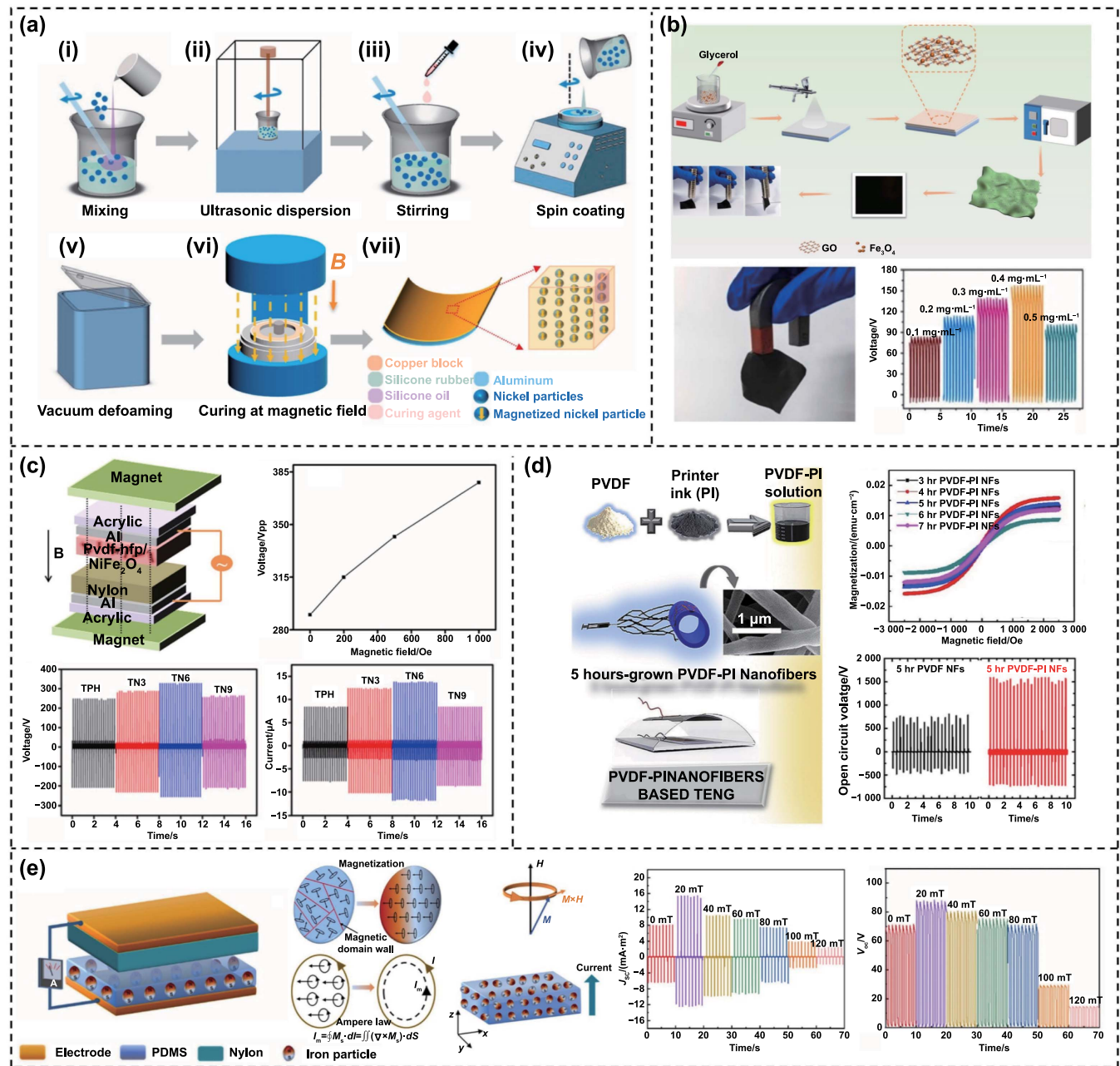


Figure 6. Magnetic nano-composites materials in TENGs. (a) Magnetic polymeric composite TENG. Reprinted from [143], © 2020 Elsevier Ltd. All rights reserved. (b) Flexible and highly sensitive TENG with magnetic nanocomposites. Reprinted from [144], © 2022 Published by Elsevier Ltd. All rights reserved. (c) High-performance TENGs assisted by magnetic fields, utilizing P(VDF-HFP)/NiFe₂O₄ nanofiber composites. Reprinted from [145], © 2023 Elsevier Ltd and Techna Group S.r.l. All rights reserved. (d) Enhanced output in polyvinylidene fluoride nanofibers based TENG using printer ink as nano-fillers. Reprinted from [146], © 2020 Elsevier Ltd. All rights reserved. (e) Maxwell's displacement current enhanced output performance by ferromagnetic properties, utilizing iron/polymer composites. Reprinted from [78], © 2022 Elsevier Ltd. All rights reserved.

water solvent activated the friction and EMG components, respectively. The HETG exhibits a remarkably low threshold amplitude and a wide operating frequency range, offering distinct advantages for capturing subtle and irregular vibrations [96]. To mitigate potential pollution concerns associated with the triboelectric interface and the external environment, Wang and colleagues introduced a novel magnetic field-assisted non-contact liquid-liquid interaction TENG (figure 7(c)). In this configuration, ferrofluid was injected into a sealed PTFE tube

containing Cu electrodes, while a lubricating oil layer was introduced to improve the sliding behavior of the ferrofluid. Consequently, the range of the linear relationship between the TENG output signals and the surface ferrofluid velocity was extended, increasing the maximum measurable velocity of external movement from 0.1 cm s⁻¹–5 cm s⁻¹. This advancement demonstrated the effectiveness of this innovation as a self-powered sensor for liquid levels in water [148]. Chen *et al* introduced a solid ferrofluid TENG designed

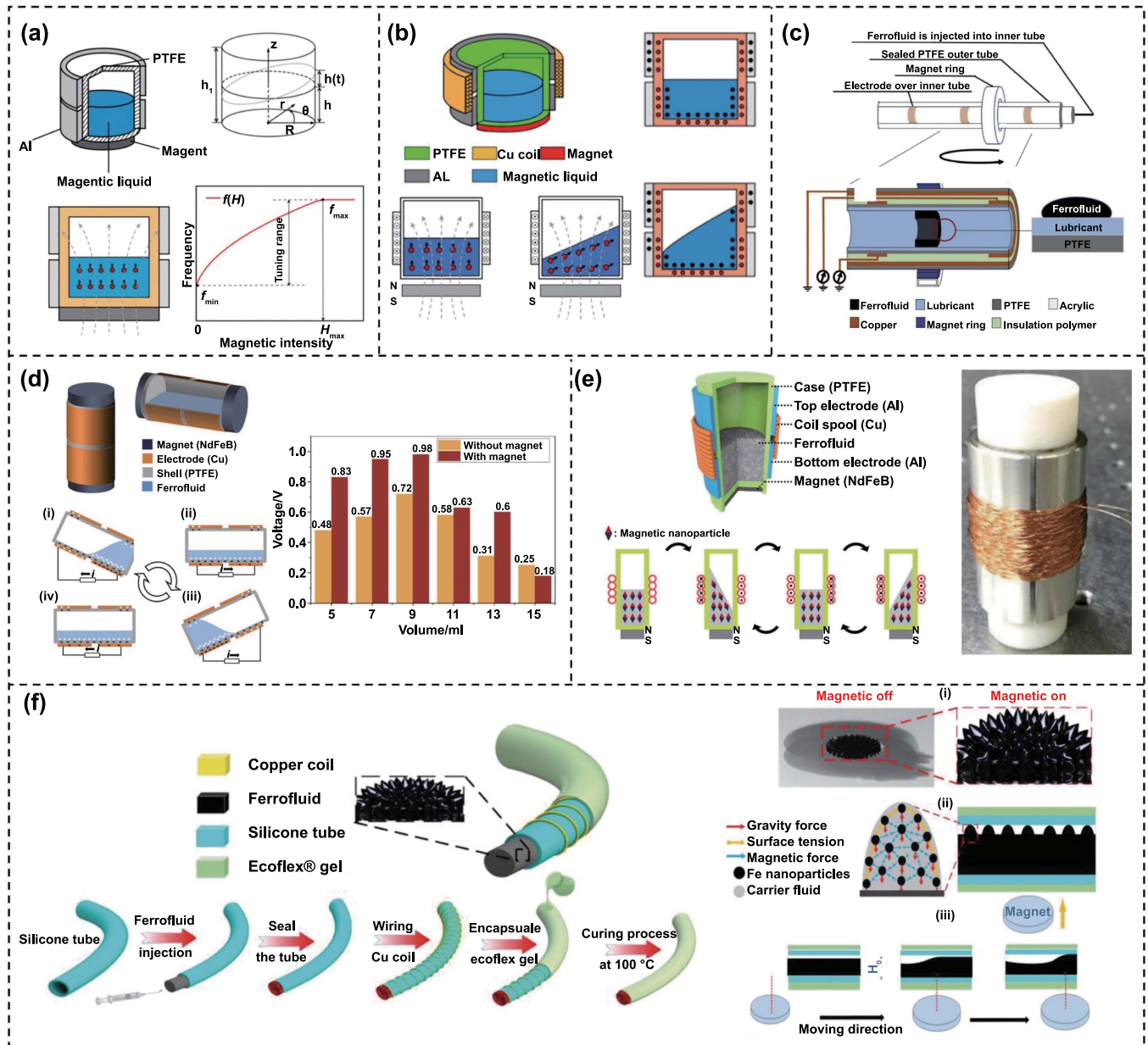


Figure 7. Ferrofluid-based TENGs. (a) A tuned TENG using a magnetic liquid for low-frequency vibration energy harvesting. Reproduced from [82] with permission from the Royal Society of Chemistry. (b) HETG energy harvester based on magnetic liquid. Reprinted with permission from [96]. Copyright (2023) American Chemical Society. (c) Self-powered water/liquid level sensing system based on a non-contact, liquid-liquid interfacing TENG. Reprinted from [148], © 2020 Elsevier Ltd. All rights reserved. (d) Solid-ferrofluid TENG for ultra-low-frequency vibration energy harvesting. Reprinted from [149], © 2023 Elsevier Ltd. All rights reserved. (e) Sensitive and sustainable vibration energy harvesting generator utilizing a ferrofluid-based HETG. Reprinted from [151], © 2016 Elsevier Ltd. All rights reserved. (f) Highly malleable, intelligent sensing platform incorporating a multimodal surface infused with ferrofluid [152]. John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

for ultralow-frequency vibration energy harvesting. Operating on the principle of triboelectric electrification between the PTFE shell and the ferrofluid, the solid-ferrofluid-TENG (SF-TENG) displayed optimal performance under a magnetic field of 56 kA m^{-1} (figure 7(d)) [149]. Sun *et al* introduced a TENG incorporating elastic ink enriched with macroscopic magnetism as the capture point. This entailed applying elastic ink droplets containing magnetic nickel onto the rear surface of the dielectric layer of PTFE and nylon films. The Ni particles

in the magnetic ink act as microelectronic containers, preventing the binding of induced charges on the tribo-layer and its electrode, thus achieving long-term high-output states [150]. In a separate study, Seol *et al* presented a ferromagnetic fluid-based TENG device (figure 7(e)) that encapsulated TENG and EMG components in a single integrated structure [151]. Activated by aqueous solvents and magnetic nanoparticles suspended in water, this device exhibited remarkable operational capabilities under extremely weak vibrations of 1 mm

amplitude, with no critical limit on the input vibration frequency. This characteristic is advantageous for collecting fine and irregular vibrational energies.

In a related study, Ahmed *et al* reported a multimodal ferrofluid-based TENG (FO-TENG) (figure 7(f)) that demonstrated sensing capabilities across various hazardous stimuli, including exposure to a strong magnetic field, high noise levels, and risks of falling or drowning. The FO-TENG design featured a deformable elastomer tube filled with ferrofluid as the tribo-layer, surrounded by a patterned copper wire serving as the electrode. Notably, it exhibited exceptional waterproofing, conformability, and stretchability (up to 300%). Additionally, the FO-TENG displayed remarkable flexibility and maintained its structural integrity and detection capability even under repeated deformation, such as bending and twisting. This innovative technology holds significant promise for applications in hazard-prevention wearable devices and remote medical monitoring [152]. In terms of output performance, ferrofluid-based TENGs currently lag behind existing TENGs, but they demonstrate outstanding performance in mechanical performance and response to weak stimuli.

3.3. Magnetic-assisted microstructures in TENGs

Conventional microstructure fabrication processes often rely on micron-scale molds with fixed orientations. In contrast, magnetofluid-based microstructures can be controlled by modifying the magnetic field. Moreover, magnetic-assisted microstructures offer opportunities for self-assembly and self-regulation, leading to improved stability and reliability of TENG devices. The integration of magnetic elements into TENG microstructures enhances their adaptability to external stimuli and environmental conditions. In a recent study, Liu *et al* reported a method to form ferrofluid-based microstructures (figure 8(a)) [81]. Exploiting the unique properties of ferrofluids, external magnetic fields can induce the rapid formation of diverse peak structures. Real-time dynamic control of sensor sensitivity was achieved by manipulating the position of the magnet.

Additionally, Seo *et al* employed PDMS-carbonyl iron composites to fabricate a SE-mode TENG with ciliary microstructures using a simple and fast magnetic field induction method (figure 8(b)) [153]. The ciliary microstructure, with its high surface-area-to-volume ratio, plays a crucial role in TENG, enhancing the surface charge compared with a regular surface. As the results show that the PDMS-Fe 10 wt% based C-TENG gives the highest open-circuit voltage of 70 V. To tackle the challenge of wear in flexible ciliary structures, Wang *et al* proposed a strategic approach that integrated ferromagnetic friction media (figure 8(c)) [154]. They developed a highly integrated HETG comprising a TENG and a multilayer coil-based rotating FS-mode EMG. By utilizing ferromagnetic cilia and an external magnetic field, the TENG achieved maximum power even with a friction gap of 0 mm. In a separate study, Hajra *et al* developed multi-ferroic materials by integrating the ferroelectric characteristics of BaTiO₃ with the magnetic properties of rare-earth orthofer-

rites (RFeO₃, R: rare-earth) (figure 8(d)) [155]. Furthermore, Li *et al* introduced an innovative flexible HETG based on a magnetized microneedle array (MA) for monitoring human motions (figure 8(e)) [156]. They proposed a cost-effective manufacturing method for HETG-magnetized microneedles by employing a self-assembled magnetic-field-induced atomizer using electromagnetic magnetization technology. The magnetized microneedles in the HETG served as both the friction layer of the TENG and the flexible magnetic pole of the EMG. In another innovative approach, Chen *et al* presented a TENG based on flexible MAs by leveraging the closed-bending friction deformation behavior of additive manufacturing for mechanical energy harvesting (figure 8(f)) [95]. Three-dimensional MA structures were continuously self-assembled from the moving films of a curable magnetorheological fluid using rotating external magnetic fields. When integrated into the insole of the right shoe, the MA-based TENG acted as an accurate pedometer with excellent energy harvesting capabilities. Additionally, Liu *et al* assembled a TENG by integrating a magnetic sponge with a conductive polymer film, enabling both mechanical and magnetic energy harvesting, as well as smart oil-water separation. (figure 8(g)) [157]. Carbonyl iron dispersed in Ecoflex using sacrificial sugar form technology resulted in a sponge with a porous structure. The inherent hydrophobicity and lipophilicity of the sponge enable the use of TENG-based intelligent adsorbents. The magnetic-assisted microstructure demonstrates superior performance in mechanical properties, response time, and other aspects. This technology is poised to shine in the field of sensing.

4. Applications of magnetic-assisted TENGs

TENGs function as mechanical transducers, leveraging the interplay between triboelectric and electrostatic induction effects. In this context, the electrical output of a device is chiefly influenced by various external mechanical stimuli, encompassing displacement [158–160], speed [161–163], force [164–166], impulse [167, 168], frequency [169, 170], and environmental conditions [171, 172]. This inherent sensitivity to mechanical stimulation, along with its well-defined parameter characteristics, makes the TENG an ideal candidate for deployment as a self-powered mechanical sensor. The distinctive structure of magnetically assisted TENGs facilitates the construction of non-contact or highly sensitive self-powered sensing systems. Here, our focus will be on the application of physical quantity sensing and HMI.

4.1. Physics of self-powered sensing

Wang *et al* developed a multifunctional sensor with a magnetic flap for detecting pneumatic flow and liquid levels [173]. As illustrated in figure 9(a), this self-powered sensor includes an outer magnetic flap, an inner magnetic float, and a conical cavity. Design principles such as the impulse theorem, connector principle, and magnetic coupling principle were employed in the sensor's design to enhance its performance. The magnetic flap not only enhances the abrasion resistance of the device but

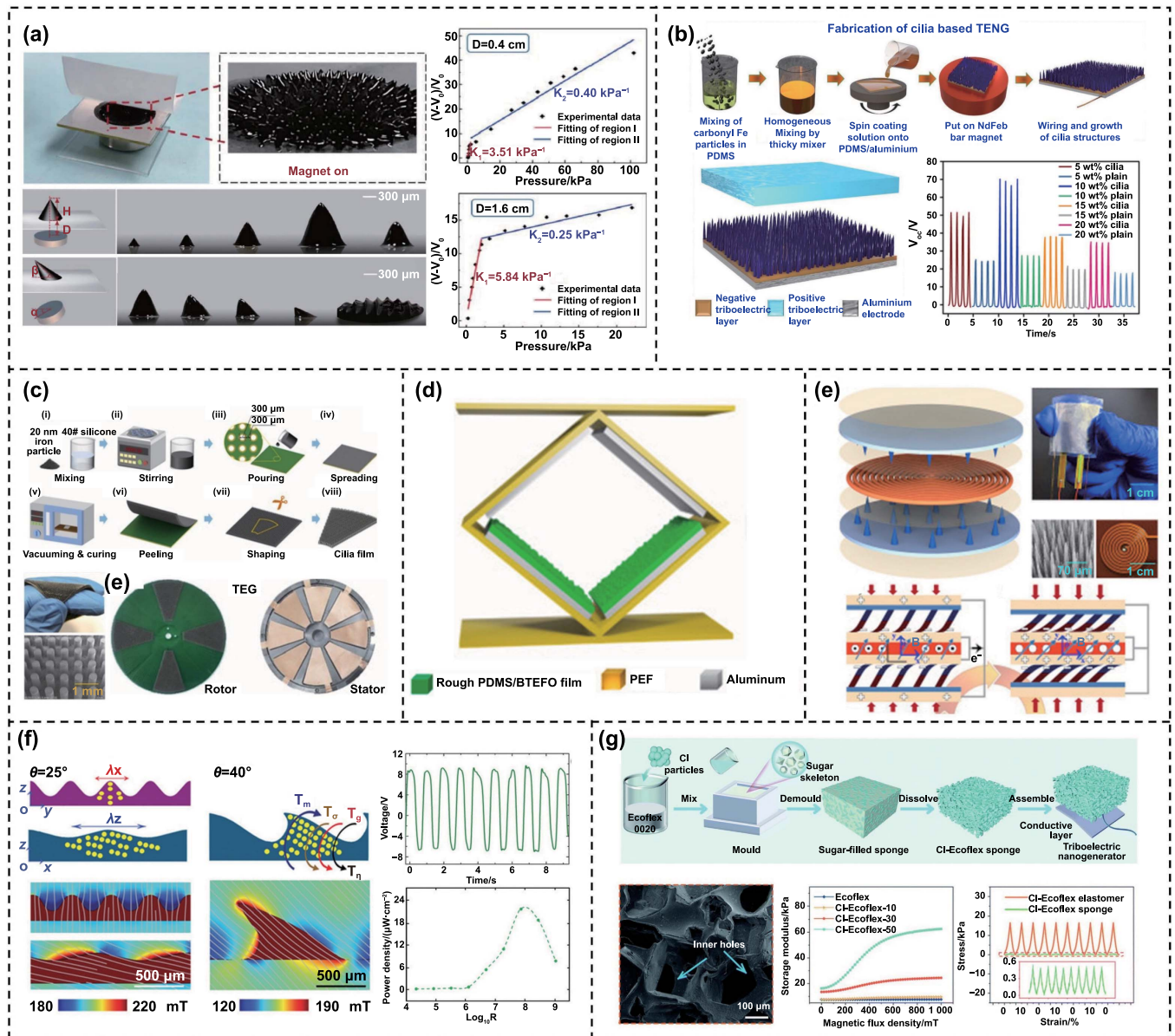


Figure 8. Magnetic-assisted microstructure in TENGs. (a) Ferrofluid-based TENG with immediately formed spike-shaped microstructure. Reproduced from [81]. CC BY 4.0. (b) Impact of cilia microstructure and ion injection on single-electrode TENG performance. Reprinted from [153], © 2021 Elsevier B.V. All rights reserved. (c) Ferromagnetic tribo-cilia enhanced HETG. Reprinted from [154], © 2023 Elsevier Ltd. All rights reserved. (d) Leveraging multiferroic materials for energy harvesting and self-powered magnetic field detection. Reprinted from [155], © 2021 Elsevier Ltd. All rights reserved. (e) Magnetized microneedle-array-based flexible HETG. Reprinted from [156], © 2019 Elsevier Ltd. All rights reserved. (f) Self-assembling bendable microneedle arrays for TENGs induced by magnetization [95]. John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) Fabricating multi-hole films by combining a magnetic sponge with a conductive polymer film. Reproduced from [157] with permission from the Royal Society of Chemistry.

also introduces a novel concept for vector motion detection. The results show that the self-powered sensor detects pneumatic flows from 10 to 200 l min $^{-1}$ with a flow resolution of 2 l min $^{-1}$. This study paves the way for exploring new avenues in the development of multifunctional triboelectric sensors.

In a related innovation, Chen *et al* introduced a pump-switched TENG customized for real-time wireless sensing (figure 9(b)) [174]. By integrating an inductor magnetic sensor coil with the TENG, they established an LC resonant circuit that transformed the pulsed TENG output into a resonant sig-

nal containing sensing data. This signal was further amplified using an integrated microswitch and charge pump before being wirelessly transmitted via a laser diode, reaching distances of up to 2 m. It can be observed that the sensor exhibits good sensitivity and stability, which has a height recognition sensitivity of 11.7 kHz mm $^{-1}$ and a horizontal position recognition sensitivity of 5.6 kHz mm $^{-1}$ with the largest error of 8.5 kHz. This research underscores the significant potential of real-time self-powered wireless sensing systems, particularly in production-line management applications.

Table 2. Summary of the Magnetic assisted materials in TENGs.

Type	Mode/ materials	Fabrication	Output/sensitivity	Power density	Application	References
Magnetic nano-composites materials	SE/ PDMS, ferromagnetic Ni	In-situ electrodeposition	80 V 4 $\mu\text{A cm}^{-2}$	N/A	Energy harvesting	[185]
	CS/PDMS/MXene, $\text{Fe}_3\text{O}_4/\text{COF}$	Drying	146 V, 32 μA	N/A	Energy harvesting	[186]
	CS/ magnetic polymeric, Al	Drying	233.4 V, 32.6 μA	0.058 mW cm^{-2} (4.7 times)	Target-scoring system	[143]
	CS/FEP, MGC	Drying	168.2 V, 7.6 μA	10.7 mW cm^{-2}	Human motion monitoring and cultural relics protecting	[144]
	CS/ P(VDF-HFP)/ niFe_2O_4 , nylon	Electrospinning	584 V, 25 μA , 1.6 kV	N/A	N/A	[145]
	CS/ PVDF-PI NFs, PET	Electrospinning		2.2 mW cm^{-2}	Biomechanical energy harvesting	[146]
	CS/ P1CF, nylon	Drying	27 mA m^{-2}	0.2 mW cm^{-2} (800% and 8 200%)	Self-powered humidity-temperature sensing system	[78]
	SE/ CFO/PVDF	Drying	17.2 V, 2.27 μA	0.09 mW cm^{-2} (2.4 times)	N/A	[187]
	CS/ ANF/CNT@Ni, FEP	Magnetic alignment, supercritical drying	N/A	75 $\mu\text{C m}^{-2}$ at 300 $^\circ\text{C}$	Tactile perception	[75]
Ferrofluid	FS/ magnetic liquid, PTFE	N/A	5.40 nW	N/A	N/A	[82]
	LS/ magnetic liquid, PTFE	N/A	26 mV	N/A	N/A	[96]
	FS/ ferrofluid, PTFE, Cu	N/A	0.178 nA at 0.137 cm s^{-1}	N/A	Water level sensor	[148]
	LS/ ferrofluid, PTFE	N/A	0.98 V, 1.05 nA	42.6 $\mu\text{W m}^{-3}$	N/A	[149]
	CS/ magnetic dot/ PTFE, Cu	Dring	259 V	167 mW m^{-2}	Human motion monitoring	[150]
	LS-EMG/ ferrofluid, PTFE,	N/A	TENG: 0.3 V, EMG: 1.8 μA	N/A	N/A	[151]
	CS/ferrofluid, silicone,	N/A	18 V	N/A	Healthcare monitoring	[152]
Surface microstructure	SE/ PTFE, ferrofluid, Al	N/A	21.48 kPa^{-1}	N/A	Novel password lock	[81]
	SE/ PDMS-Fe,	Drying	70 V, 0.3 μA ,	2.75 $\mu\text{W cm}^{-2}$	Biomechanical energy	[153]
	FS-EMG/ ferromagnetic cilia, nylon	String	TENG: 442.5 μW , EMG: 3 W	TENG: 0.04 mW cm^{-2} EMG: 17.5 mW cm^{-3}	Agricultural environment monitoring	[154]
	CS/ PDMS/BTEFO, Al	Curing	320 V, 12 μA	0.025 mW cm^{-2}	Magnetic field detecting	[155]
	CS-EMG/ MA, Al	Magnetic-field-induced spray	TENG: 10 V, EMG: 80 μA	TENG: 16.19 $\mu\text{W m}^{-2}$, EMG: 9.09 $\mu\text{W m}^{-2}$	Healthcare monitoring	[156]
	SE/ CI-ecoflex, contact substance	Sugar sacrificial templating technique	495 mV at 540 mT,	71.0 mW m^{-2}	Multi-mode sensors and oil-leakage treatment systems	[157]
	CS/ microneedles, Al	Magnetization-induced self-assembled method	1.37 $\mu\text{A cm}^{-2}$	22 $\mu\text{W cm}^{-2}$	Step meter	[95]

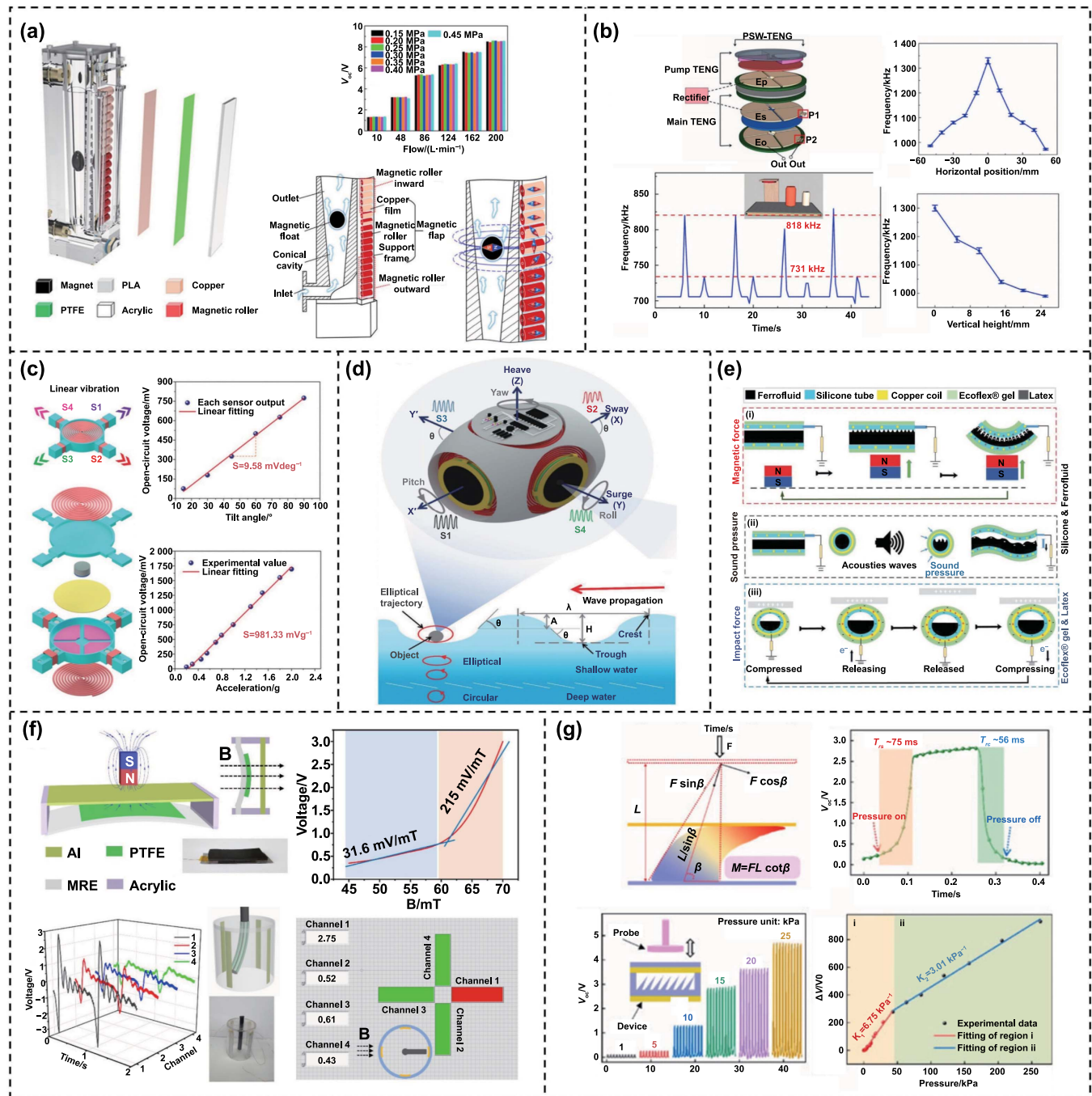


Figure 9. Application of magnetically assisted TENGs in physic quantity sensing. (a) Magnetic flap-type difunctional sensor for detecting pneumatic flow and liquid level. Reprinted with permission from [173]. Copyright (2020) American Chemical Society. (b) Self-powered pumping switched TENG enabled real-time wireless metal tin height and position recognition and counting. Reprinted from [174], © 2021 Elsevier Ltd. All rights reserved. (c) Arbitrary motion sensing system using magnetic repulsion-based self-powered motion sensors [73]. John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (d) Hybrid self-powered arbitrary wave motion sensing system for real-time wireless marine environment monitoring application [74]. John Wiley & Sons. © 2021 Wiley-VCH GmbH. (e) the multimodal ferrofluid-based TENG as magnetic, acoustic, and impact force sensors [152]. John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (f) Magnetorheological elastomer-based self-powered triboelectric sensor for monitoring magnetic field. Reproduced from [175]. CC BY 4.0. (g) Surface-microengineering triboelectric tactile sensor via dynamically assembled ferrofluid template. Reprinted from [176], © 2021 Elsevier Ltd. All rights reserved.

Additionally, Bhatta *et al* integrated a magnetic-repulsion-assisted self-powered motion sensor with a HETG to develop a battery-free arbitrary motion sensing system (figure 9(c)) [73]. This self-powered sensor effectively detects motion

parameters in any arbitrary direction while simultaneously converting low-frequency vibrations ($<5 \text{ Hz}$) into usable electricity. The motion sensor holds a high sensitivity of 981.33 mV g^{-1} under linear motion excitation and has a

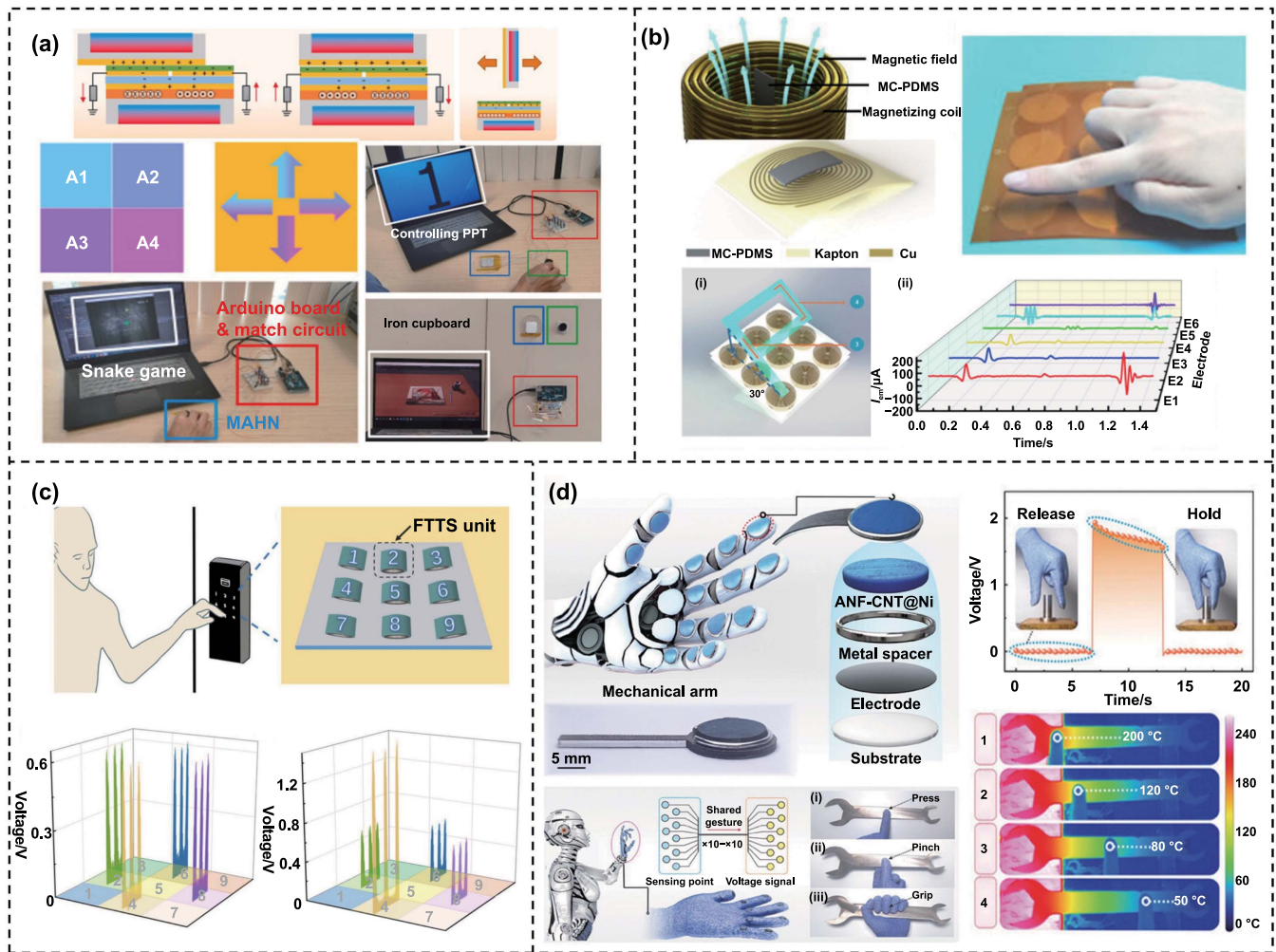


Figure 10. Applications of Magnetic assisted TENGs in HMI. (a) Magnetic-interaction assisted HETG. Reprinted from [79], © 2021 Elsevier Ltd. All rights reserved. (b) Flexible HETG for 3D trajectory sensing. Reprinted from [177], © 2020 Elsevier Ltd. All rights reserved. (c) Triboelectric tactile sensor utilizing a liquid-solid interface. Reproduced from [81], CC BY 4.0. (d) Magnetic-tunable anisotropic triboelectric aerogel for wearable self-powered tactile perception [75]. John Wiley & Sons. © 2023 Wiley-VCH GmbH.

tilting angle sensitivity of 9.83 mV deg^{-1} . Furthermore, this innovative approach obviates the need for batteries in arbitrary motion sensing systems, thus opening up possibilities for future autonomous control applications.

In parallel, for achieving all-day and real-time monitoring of ocean wind and wave information, Bhatta *et al* proposed a HETG consisting of six coils arranged in all directions. This configuration allows the harvesting of energy from arbitrary motion waves, and the wireless transmission of wave information, all accomplished with complete self-power (figure 9(d)) [74]. The results show that the sensor exhibits good linearity for the frequencies, accelerations, and tilt angles, and it can deliver a peak power of 106 mW and 44.8 mW (at 3 Hz) along with major and minor axis motion directions. Hence, this device realizes self-sustaining wireless ocean environment monitoring, presenting potential applications for next-generation intelligent all-day and real-time ocean monitoring.

Furthermore, Ahmed *et al* utilized a multimodal ferrofluid to design a self-powered sensor (figure 9(e)) capable of sensing various hazardous stimuli, including exposure to a

strong magnetic field, high noise levels, and risks of falling or drowning [152]. Wan *et al* developed a self-powered magnetic sensor utilizing a refined TENG integrated with a magnetorheological elastomer (figure 9(f)) [175]. This sensor operates by harnessing triboelectrification and electrostatic induction to produce electrical signals in reaction to the deformation of the magnetorheological elastomer induced by a variable magnetic field. Based on this, the fabricated magnetic sensor exhibits a desirable sensitivity of 31.6 mV mT^{-1} in a magnetic field range of 35–60 mT. Moreover, the work provides a new route for monitoring dynamic magnetic fields and paves a way for self-powered electric-magnetic coupled applications.

Zhang *et al* designed an exceptionally sensitive triboelectric tactile sensor employing a two-step reversal method utilizing a dynamic ferrofluid template (figure 9(g)) [176]. By leveraging the mechanical properties of the ferrofluid, the sensor enables precise control over the shape, including the inclination angle and height, of the ferrofluid spikes grown on the surface. Subsequently, this structure was transferred to a silicon rubber, serving as the triboelectric layer. When the inclination

Table 3. Summary of the Magnetic assisted TENG-based self-powered sensing and system.

Detect type	Mode/materials	Sensitivity	Resolution	Detection range	Linearity	Response time	References
Flow and liquid level	SE/PTFE, Cu	0.04 V/L min ⁻¹	2 l min ⁻¹	10 l min ⁻¹ ~ 200 l min ⁻¹ (flow), 30 mm to 130 mm (height)	Linear	N/A	[173]
Height and position recognition	FS/PTFE, PA6; Kapton, Cu	11.7 kHz mm ⁻¹ (height), 5.6 kHz mm ⁻¹ (horizon)	8.5 kHz	50 mm (height), 50 mm (horizon)	Non-linear	13 ms	[174]
Motion sensors	FS/PTFE, Cu	0.98 V g ⁻¹ (linear motion), 9.83 mV deg ⁻¹ (angle)	N/A	N/A	Linear	N/A	[73]
Arbitrary wave sensing	CS/PVDF/MXene, nylon	39.97 V g ⁻¹	N/A	2 g (acceleration) 15 deg ~ 90 deg (angle)	Linear	N/A	[74]
Magnetic field sensing	CS/PTFE, Al	31.6 mV mT ⁻¹	N/A	35 mT ~ 60 mT	Two consecutive linear regions	80 ms	[175]
Tactile sensor	CS/Silicon, Cu	6.75 kPa ⁻¹	N/A	250 kPa	Two consecutive linear regions	75 ms, 56 ms	[176]
Tactile sensor	SE/ferrofluid, PTFE	21.48 kPa ⁻¹	1.25 Pa	390 kPa	Two consecutive linear regions	90 ms	[81]
Vibration sensing	CS/PTFE, Cu	0.32 V g ⁻¹ –134.9 V g ⁻¹	0.1 g	2.5 Hz to 4000 Hz	Linear	N/A	[71]

angle of the microstructure is 30°, the sensitivity delivers 6.75 kPa⁻¹ with pressure lower than 44 kPa and keeps excellent linearity with the sensitivity of 3.01 kPa⁻¹ even when the detection pressure reaches 250 kPa. Simultaneously, the tactile sensor has a fast response/ recovery time of 75 ms and 56 ms, respectively. This work shows the excellent research prospect of ferrofluid-based triboelectric tactile sensing.

4.2. HMI

Liu *et al* introduced a magnetic-interaction-assisted HETG, optimized with two attraction magnets and a silicone-based cushion featuring microstructures (figure 10(a)) [79]. Equipped with cross-divided electrodes, the HETG showcased advanced applications in HMI, including orientation control in a snake game, real-time operation of a PowerPoint presentation, and recognition of simple air gestures for contactless control. This research highlights the potential of HETG with magnetic interactions for harvesting distributed mechanical energy, demonstrating significant innovation in HMI.

For flexible devices, Wan *et al* presented a flexible HETG comprised of PDMS, multi-walled carbon nanotubes, and NdFeB microparticles (figure 10(b)) [177]. The single-electrode TENG functioned effectively through the contact between the multi-walled carbon-nanotube-doped PDMS and the kapton-coated flexible printed circuit board

coil. Additionally, it demonstrated utility in self-powered 3D trajectory sensing, involving the detection of height information above the coil array. This device holds promising potential for application in wearable electronics and HMI.

In the field of ferrofluid-based TENG, Liu *et al* introduced a liquid-solid interface ferrofluid-based triboelectric tactile sensor [81]. Illustrated in figure 10(c), leveraging the fluidity and magnetism of the ferrofluid facilitated flexible adjustment of microstructure topography by directly employing the ferrofluid as a triboelectric material and controlling the position of the outward magnet. The results show that this design achieved an ultrahigh sensitivity of 21.48 kPa⁻¹. The demonstration of a personalized password lock with a high-security level underscores its practical potential in smart homes, artificial intelligence, the IoT, and other applications.

Chi *et al* presented a wearable self-powered sensing device constructed using a thermostable anisotropic aramid triboelectric aerogel, enabling tactile perception in high-temperature environments (figure 10(d)) [75]. By leveraging the triboelectric sensing mechanism, these wearable temperature tactile sensors, resistant to high temperatures, are envisioned to be deployed in smart protective clothing for real-time astronaut motion sensing. Such a perfect coordination between self-powered sensing and thermostability innovates multifunctional wearable sensing design at high temperatures, allowing

aramid-based aerogel to be a candidate for advanced sensing materials for applications in the military and aerospace fields.

5. Summary and perspectives

Given the ongoing depletion and saturation of global land natural resources, TENG has witnessed rapid development over the past decade [178–183]. This study provides a comprehensive review of the latest research advances in magnetic-assisted TENGs, which aims to facilitate the subsequent development in related domains, the latest progress in the structures (table 1), materials (table 2), and self-sensing systems (table 3) of magnetic-assisted TENG. The aforementioned progress indicates that magnetic-assisted TENGs can be considerably enhanced through various approaches, thereby enriching their functionalities using structural and material engineering. By leveraging these advances, self-powered sensing, and HMI systems have been successfully implemented. Overall, the magnetic assistant is introduced as a means to improve the dynamic response range of the TENGs and orderly control the performance of the tribo-materials, which enhances the environmental adaptability and output performance. Looking ahead, the potential applications extend to diverse fields such as smart mining, smart oceans, environmental safety, medical health, human-computer interaction, national defense and military, urban transportation, and smart homes. This broad spectrum of potential applications underscores the versatility and importance of magnetically assisted TENGs in terms of addressing contemporary challenges and advancing technology in numerous sectors. However, the related research still needs to be promoted to achieve large-scale application. Hence, we put forward the following suggestions for the future development of the three research directions, respectively (figure 11).

5.1. Manufacture and structure optimization

The key roles of magnetic-assisted structures can be summarized as follows: broadening the response bandwidth, facilitating small excitation initiation, and enhancing the overall output performance. However, future research must address several non-negligible challenges. These challenges include: the magnetic interference to electronic devices, the output of a single TENG device still has a physical limit and does not increase linearly with the increase in volume, and most of the existing manufacturing methods of the TENG devices are manufactured by hand in small batches, thereby hampering consistency in terms of output. In the future, the following three directions can solve the above problems: (i) effective shielding and packaging of magnetic devices to prevent magnetic field interference with external devices, (ii) strategic arraying and networking devices to alter the energy volume and enhance universality, and (iii) ensuring the consistency and stability of triboelectric devices by large-scale production using incorporating techniques such as 3D printing technology.

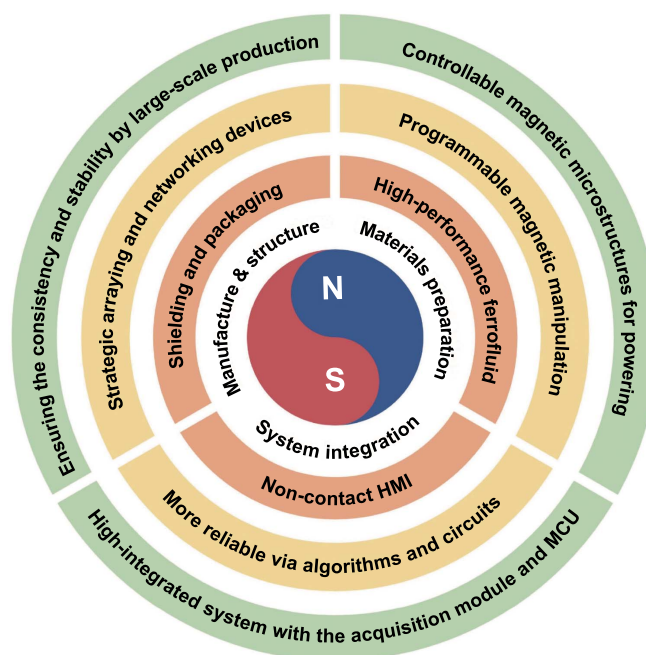


Figure 11. Perspectives of the magnetic-assisted TENG.

5.2. Material preparation

Magnetic nano-composites not only provide a crucial strategy for preparing anisotropic materials externally but also enhance the electric output performance of the TENGs. Despite the low electric output performance reported in existing studies, ferrofluid-based TENGs exhibit remarkable mechanical response characteristics under minimal excitation. Magnetic assistance in microstructure preparation eliminates the need for precision molds (at the micro/nano level), thereby reducing costs. Further, actuated microstructures using a magnetic drive are a seamless process. In the future, magnetic-assisted material TENGs research must prioritize (i) the preparation of complex tribo-material structures using programmable magnetic manipulation, (ii) the development of high-sensitivity, self-powered sensing that leverages the superior mechanical response of ferrofluid-based TENGs, and (iii) the control of magnetic microstructures through external magnetic fields for powering a microscopic actuation such as drug delivery.

5.3. System integration

As a mechanical transducer, the TENG efficiently converts external mechanical stimulation into electrical energy owing to its simple structure, which is different from piezoresistive sensing without an external power supply [188–196]. Furthermore, when cleverly integrated with nano-sensing materials, TENGs extend their capabilities beyond detecting mechanical physical quantities to achieve the self-driven detection of various physical and chemical parameters. Although researchers have explored various applications of magnetic-assisted TENGs, related research still needs to be

promoted to achieve large-scale application. Hence, we propose the following suggestions for the future development of the three research directions, respectively: (i) non-contact HMI applied in dangerous scenarios, (ii) ensuring signal repeatability and stability through deep-learning algorithms or processing circuits, and (iii) achieving the completeness of entire self-powered systems through the integration of acquisition and central microcontroller units.

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