

## Review

<https://doi.org/10.1631/jzus.A2300231>



# Coastal bridge infrastructure: energy-harvesting and sensing capabilities through magnetic structured triboelectric nanogenerators

Ali MATIN NAZAR<sup>1</sup>✉, Arash RAYEGANI<sup>2</sup>, Maria RASHIDI<sup>2</sup>, Fatemeh RAHIMI SARDO<sup>3</sup>

<sup>1</sup>Zhejiang University-University of Illinois at Urbana-Champaign Institute, Zhejiang University, Jiaxing 314400, China

<sup>2</sup>Centre for Infrastructure Engineering, Western Sydney University, Kingswood 2747, NSW, Australia

<sup>3</sup>Department of Mining Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

**Abstract:** This paper provides an overview of the recent advancements in magnetic structured triboelectric nanogenerators (MSTENGs) and their potential for energy harvesting and sensing in coastal bridge infrastructure. This paper begins with a brief discussion on the fundamental physics modes of triboelectric nanogenerators (TENGs), triboelectric series, and factors affecting TENG power generation and transmission, providing a foundation for the subsequent sections. The review focuses on the different types of MSTENGs and their applications in coastal infrastructure. Specifically, it covers magnetic spherical TENG networks, magnet-assisted TENGs, MSTENGs for bridges, and magnetic multilayer structures based on TENGs. The advantages and limitations of each type of MSTENG are discussed in detail, highlighting their respective suitability for different coastal bridge infrastructure applications. In addition, the paper addresses the challenges and provides insights into the future of MSTENGs. These include the need for improved durability and sustainability of MSTENGs in harsh coastal environments, increasing their power-output levels to fulfill high energy needs, and the requirement for collaborative efforts between academia, industry, and government institutions to optimize MSTENG performance.


**Key words:** Energy harvesting; Intelligent coastal infrastructure; Triboelectric nanogenerator (TENG); Magnetic structured

## 1 Introduction

As the global population continues to grow, so too does the demand for sustainable and reliable energy sources (Javadi et al., 2018). At the same time, coastal infrastructure, such as bridges and offshore platforms, requires reliable and accurate monitoring to ensure safety and structural integrity (Feng and Narins, 2008; Lin et al., 2013; Gandomi et al., 2014; Xi et al., 2017a; Jiao et al., 2020; Rashidi et al., 2021). One promising solution that addresses both of these needs is magnetic structured triboelectric nanogenerators (MSTENGs), which harvest energy from mechanical motion and can

provide sustainable energy and real-time monitoring for coastal infrastructure applications (Jiao et al., 2020, 2022b, 2022c, 2022d; Egbe et al., 2021, 2022b; Liu HQ et al., 2021; Matin Nazar et al., 2021a, 2021b, 2022a, 2022c, 2023; Ayegba et al., 2022; Rahimi Sardo et al., 2022; Rayegani et al., 2023). MSTENGs integrate magnetic structures with triboelectric nanogenerators (TENGs) to generate electricity from mechanical motion (Lee et al., 2018; Egbe et al., 2022a; Matin Nazar et al., 2022b). As such, they offer several advantages over other energy-harvesting technologies, for example, their compatibility with a wide range of mechanical motions, high power-output levels, and cost-effectiveness (Chen et al., 2015, 2016; Liang et al., 2015; Feng et al., 2017; Ren XH et al., 2018; An et al., 2019; Lin et al., 2019; Ren ZW et al., 2019). Furthermore, MSTENGs can be integrated with sensors to provide real-time monitoring for coastal infrastructure or other applications in structures (Lai et al., 2019; Rayegani and Nouri, 2022a, 2022b). This paper

✉ Ali MATIN NAZAR, [matin.22@intl.zju.edu.cn](mailto:matin.22@intl.zju.edu.cn)

 Arash RAYEGANI, <https://orcid.org/0000-0001-7932-7038>

Maria RASHIDI, <https://orcid.org/0000-0003-2847-3806>

Fatemeh RAHIMI SARDO, <https://orcid.org/0000-0002-4331-6879>

Received Apr. 30, 2023; Revision accepted Nov. 3, 2023;  
Crosschecked May 14, 2024; Online first June 28, 2024

© Zhejiang University Press 2024

provides a comprehensive review of the recent advances in MSTENGs, covering the fundamental physics modes of TENGs, triboelectric series (Yang et al., 2013a), and factors affecting TENG power generation and transmission (Fan et al., 2015; Gu et al., 2015; Khan and Kim, 2016; Cheng et al., 2019; Liu WB et al., 2019; Zou et al., 2019). The paper also provides an overview of MSTENGs in coastal infrastructure, and presents four different types of MSTENGs that have shown great potential in energy harvesting (Wang et al., 2012, 2013; Zhu et al., 2012, 2013; Wang, 2017; Liu et al., 2018; Yang HM et al., 2019; Qin et al., 2020; Yang F et al., 2020) and sensing (Chen et al., 2018) in this application (Choi et al., 2017). These include magnetic spherical TENG networks, magnet-assisted TENGs, MSTENGs for bridges, and magnetic multi-layer structures based on TENGs.

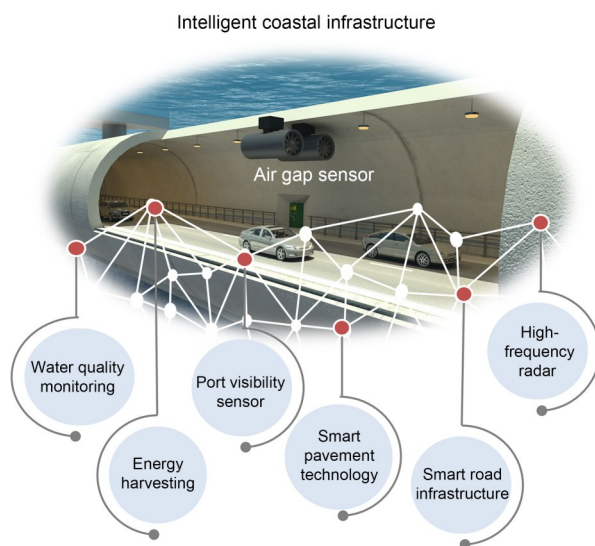
Furthermore, the paper highlights the progress and challenges in MSTENG technology, providing valuable insights into the development of sustainable and real-time monitoring solutions for coastal infrastructure (Lin et al., 2014; Kwak et al., 2016; Xiong et al., 2017; Liu YP et al., 2019; Nie et al., 2019; Qian et al., 2019). Although current MSTENG prototypes face challenges such as limited power-output levels and the need for improved durability in harsh coastal environments (Que et al., 2012), the promising applications of MSTENGs in coastal infrastructure provide a strong incentive for further research and development (Kanik et al., 2015). Fig. 1 shows the intelligent coastal infrastructure (energy harvesting, water-quality

monitoring, port visibility sensor, smart pavement technology, smart road infrastructure, and high-frequency radar) (Horowitz and Sheplak, 2013; Lei et al., 2019; Zhong et al., 2019; Egbe et al., 2021; Matin Nazar et al., 2021b, 2022a; Varmaghani et al., 2021). In summary, this paper reviews recent advancements in MSTENGs, addressing key aspects such as the fundamental physics underlying the technology, the various types of MSTENGs capable of energy harvesting and sensing in coastal infrastructure applications, and the challenges, perspectives, and insights that will drive future advancements in this field (Su et al., 2014; Guillou et al., 2019; Wu et al., 2019; Matin Nazar et al., 2021c). Our goal is to promote further research and development for this innovative and promising energy-harvesting technology (Jiang et al., 2020).

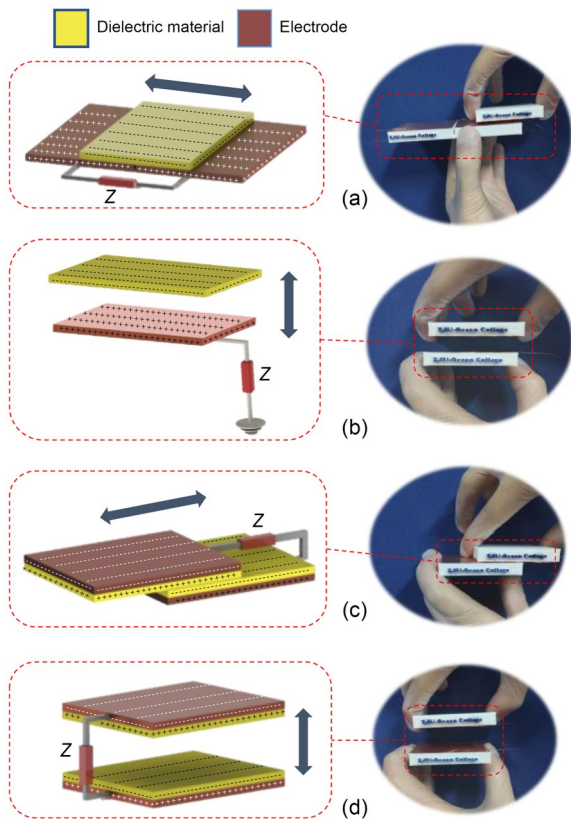
## 2 Fundamental physics modes of TENGs

Fig. 2 displays the four different modes of operation of TENGs: the freestanding triboelectric-layer mode, single-electrode mode, lateral sliding mode, and contact-separation mode (Rahimi Sardo et al., 2022).

Fig. 2a offers a comprehensive view of the freestanding phase of TENGs, an intriguing scenario in which the TENG layer moves independently of the electrode, executing a graceful glide across the electrode surfaces. This movement is instrumental in generating a potential difference, a fundamental phenomenon documented in prior research (Yang et al., 2013b). This phase demonstrates the essence of TENGs, in which the triboelectric effect takes center stage, inducing the redistribution of surface charges during frictional contact and separation. Fig. 2b introduces the single-electrode mode, a fascinating configuration in which a solitary electrode is strategically connected to an external load. In this setup, the TENG layer showcases its remarkable capability to generate an electrical response, driven by mechanical oscillations. The interaction between the TENG layer and the single electrode leads to the accumulation of electrical charge and the creation of a potential difference, a pivotal process in energy-harvesting applications. Fig. 2c introduces the intriguing lateral sliding mode, a variation that parallels the contact-separation mode but features two electrodes thoughtfully positioned beneath the TENG layers. This strategic placement leads to the emergence of a non-electrostatic



**Fig. 1** Intelligent coastal infrastructure



**Fig. 2** Four modes of triboelectric-nanogenerators: (a) freestanding triboelectric-layer mode; (b) single-electrode mode; (c) lateral sliding mode; (d) contact-separation mode (Rahimi Sardo et al., 2022).  $Z$  represents the impedance of the system, which is a quantity that combines resistance and reactance and describes how the system resists the flow of alternating current (AC) electricity

condition as the TENG layers move in relation to each other. This non-electrostatic condition is a crucial aspect of TENG operation, as it fosters the generation of a substantial potential difference, a phenomenon with extensive implications for energy harvesting (Iglesias and Carballo, 2014). To capture the output of this mode, a voltmeter, strategically connected to these electrodes, takes center stage, ready to measure the voltage produced by this potential difference. Fig. 2d showcases the contact-separation mode, a mode that employs two electrodes located at the rear of the TENG layers.

The orchestration of these electrodes sets the stage for a fascinating performance in which the TENG layers come into contact and part ways, generating electricity and revealing a harmony of motion and electricity. In this mode, a voltmeter is attached between these rear electrodes, primed to measure the output voltage, thus

capturing the essence of the transformative potential of TENGs.

## 2.1 Triboelectric series and factors affecting TENG power generation and transmission

The triboelectric series and the variables that impact power generation and the gearbox in a TENG are depicted in Fig. 3. The figure also presents the triboelectric series of commonly utilized materials (Calisal, 1983; Aydođan et al., 2013; Xi et al., 2017b; Liu XL et al., 2019; Yang XD et al., 2019; Yoo et al., 2019). The wide accessibility of materials for constructing TENGs is attributed to the fact that any of these materials can be utilized (Thorpe, 1999). The ability of a material to undergo electron transfer is determined by its polarity. Specifically, the material's capacity to either gain or lose electrons is influenced by its inherent polarity. It has been observed that the selection of materials possessing a broader energy gap is likely to yield increased output voltage (Pelc and Fujita, 2002; Suzuki and Tanaka, 2003; Leijon et al., 2005; McCormick and Ertekin, 2009; Chatzigiannakou et al., 2017; Deane et al., 2018; Olsen et al., 2019; Prieto et al., 2019; Zhao et al., 2019; Nie et al., 2020). Furthermore, Fig. 3 lists the various factors that influence the production and transmission of TENG power (Jiao et al., 2022a).

Motion parameters and device parameters are only a few examples of these types of variables (Roscow et al., 2017). Motion frequency (Yousry et al., 2018), amplitude, and contact and noncontact motions are some of the parameters to consider (Jbaily and Yeung, 2015). As the frequency of TENG-layer movement rises, the power output increases proportionally (Uchino, 2008; Gu et al., 2017; Marino et al., 2017; Gao et al., 2018). Muralt et al. (2009) discovered that increasing the amplitude ( $H$ ) of the sinusoidal movement has an influence on the output power of the TENG, with the peak power increasing at a decreasing rate as  $H$  is raised. The dimensions and material qualities of TENGs are among the device parameters. The size of a TENG is directly related to its output power (Niu et al., 2014; Niu and Wang, 2015; Dai et al., 2017; Martínez-Ayuso et al., 2017; Shao et al., 2020). For example, the relative location of TENG pairs in the TENG series, the structure of TENG surfaces, the contact area impacted by the applied force, and variables in the surrounding environment, are all examples of the impact of material characteristics (Shao et al., 2019).

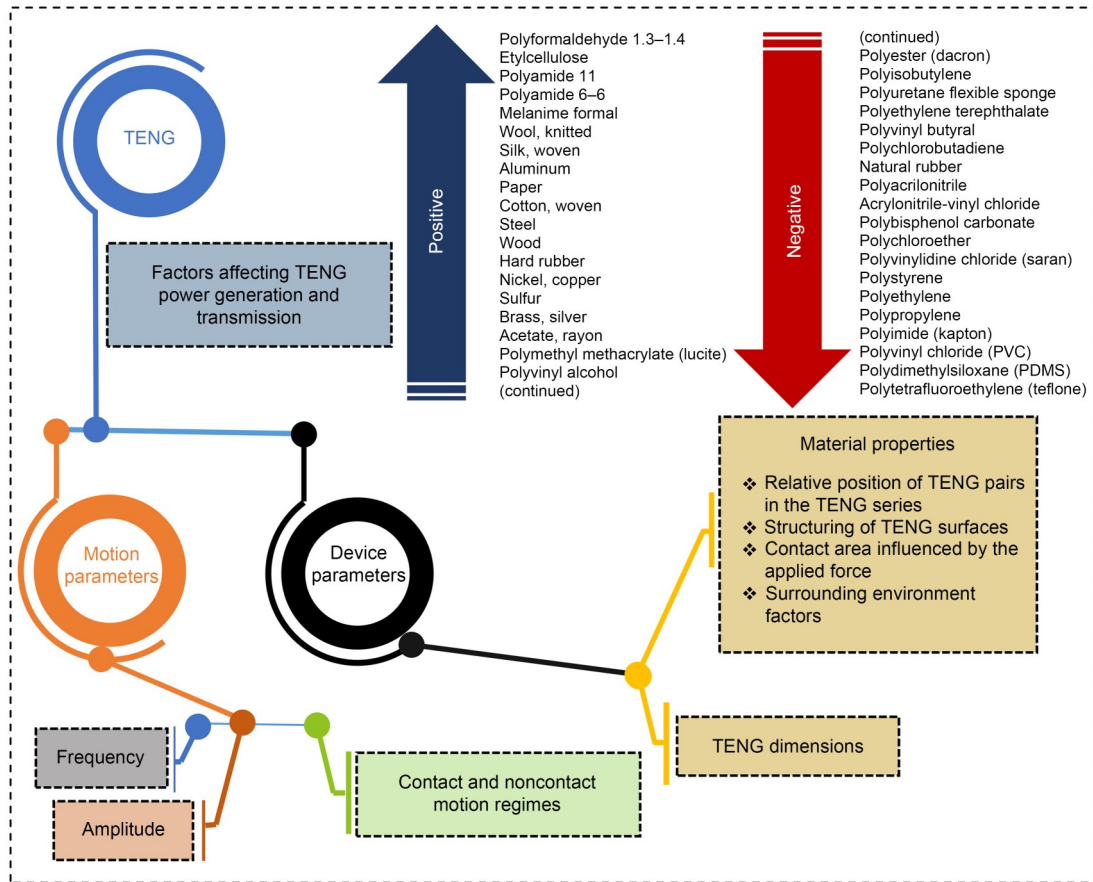


Fig. 3 Triboelectric series and factors affecting TENG power generation and transmission (Jiao et al., 2022a)

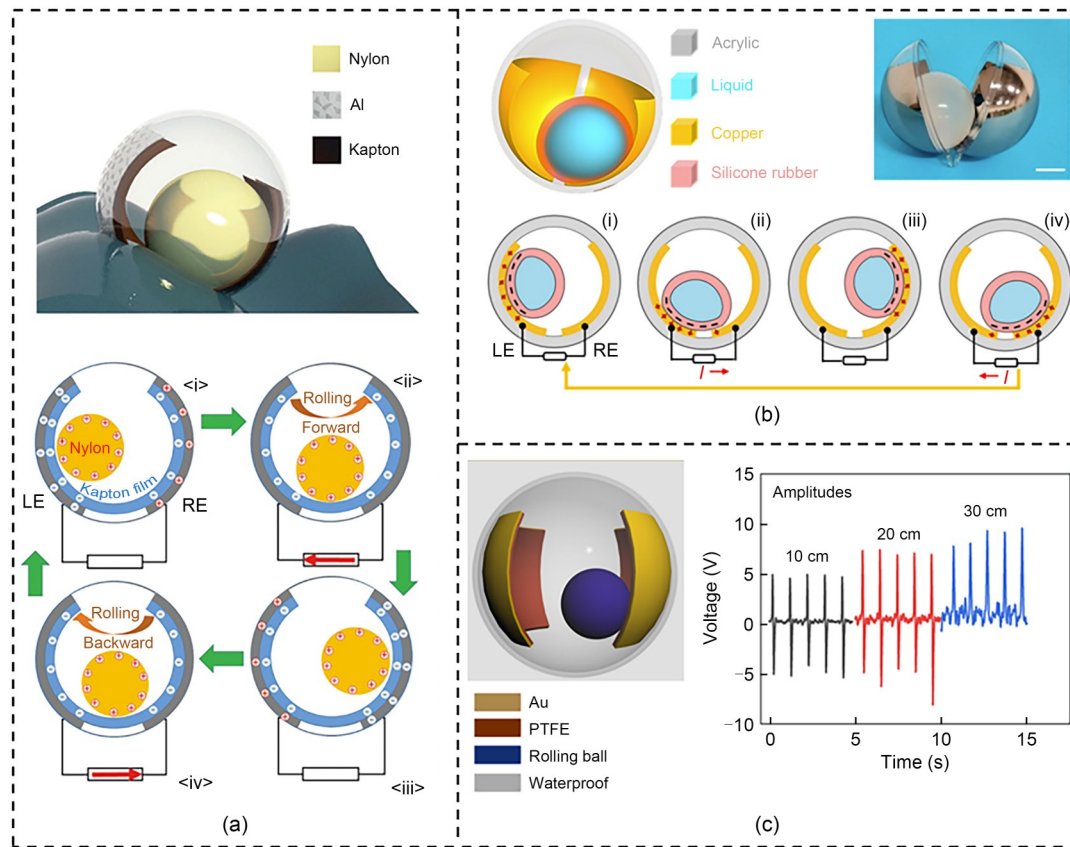
### 3 Overview of MSTENGs in coastal infrastructure

Figs. 4–8 give an overview of MSTENGs in coastal infrastructure, including magnetic spherical TENG networks, magnet-assisted TENGs, MSTENGs for bridges, and magnetic multilayer structures based on TENGs.

#### 3.1 Magnetic spherical TENG networks

The magnetic spherical TENG networks depicted in Figs. 4 and 5 are utilized for the purpose of energy harvesting and sensing in diverse settings. The schematic representation shown in Fig. 4a illustrates the configuration and underlying concepts of a rolling spherical triboelectric nanogenerator (RF-TENG) designed to capture low-frequency kinetic energy from water waves. The proposed design entails a completely enclosed, self-supporting TENG that encompasses a movable sphere within an oscillating spherical casing.

The rolling-structured TENG possesses a low weight and uncomplicated design, enabling it to oscillate on or within aqueous environments for the purpose of wave-energy harvesting. This design embodies a novel and efficacious technique for the collection of blue energy on a grand scale from marine and freshwater sources (Shao et al., 2019). Fig. 4b presents an approach that effectively boosts the output power of spherical TENGs through the optimization of both materials and structural design. A soft-contact spherical triboelectric nanogenerator (SS-TENG) with a hollow acrylic sphere shell and a rolling, flexible liquid or silicon core is shown. The SS-TENG exhibits a maximum output charge that is up to ten times greater than that of traditional polytetrafluoroethylene (PTFE)-based hard-contact designs, due to the considerably enlarged contact area. Cheng et al. (2019) proposed an optimization approach for TENGs, which enhances their potential for extracting significant amounts of blue energy from oceanic water waves, as well as wind energy. The use of



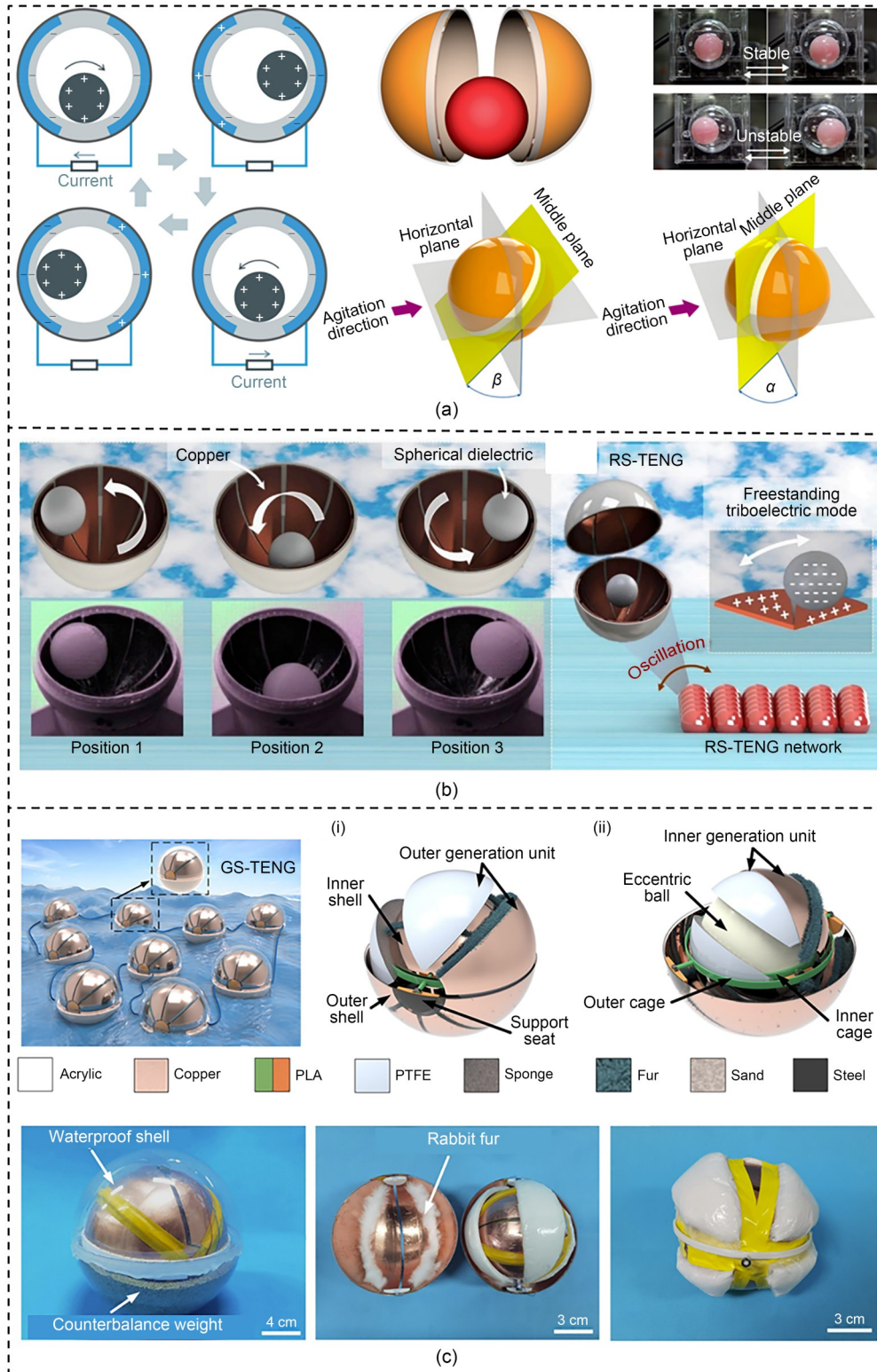
**Fig. 4** Magnetic spherical TENG networks: (a) design structure and basic principle of an RF-TENG (reprinted from (Wang et al., 2015), Copyright 2015, with permission from John Wiley and Sons); (b) structure and working mechanism of an SS-TENG (reprinted from (Cheng et al., 2019), Copyright 2019, with permission from Elsevier); (c) illustration of rolling TENGs based on nano-micro structure for ocean monitoring (Chen et al., 2021). LE and RE represent the left-hand and right-hand electrodes, respectively. References to color refer to the online version of this figure

nano-microstructures in rolling TENGs for ocean monitoring is demonstrated in Fig. 4c. The present study introduced a rolling TENG design capable of enhancing performance. It was based on nano-micro-structured PTFE films. The enhancement of output performance can be achieved through an increase in the effective contact area and improvement of the triboelectric effect, which is facilitated by the nano-microstructure present on the surface of PTFE. Moreover, this TENG indicates efficient water-wave energy-harvesting capabilities across a range of amplitudes and frequencies, thereby exhibiting promising potential for the utilization of ocean energy in the context of environmental monitoring (Chen et al., 2021).

Fig. 5a displays the utilization of coupled TENG networks to harvest energy from water waves. The present study employed a coupling strategy within TENG networks in order to accomplish the aforementioned objective. The output of the rationally linked

units exhibits an increase of over tenfold in comparison to the output without any linkage. TENG networks employing diverse connecting methodologies have been synthesized and exhibit superior efficacy in the case of those featuring pliable connections (Xu et al., 2018).

The rolling spherical triboelectric nanogenerators (RS-TENGs) depicted in Fig. 5b were specifically engineered to harness energy from low-frequency ocean waves. The design entails the fabrication of a spherical framework utilizing copper and aluminum materials, which function as the electrodes. In addition, a range of spherical dielectrics denoted as SD1, SD2, SD3, and SD4, were fabricated to assess the impact of dielectric properties on output performance. The design incorporates multiple electrodes situated on both sides of the spherical configuration, facilitating the movement of dielectric layers with minimal oscillation and the consequent production of electrical energy. Wang et al. (2022) conducted an experimental



**Fig. 5** Magnetic spherical TENG networks: (a) water-wave energy harvesting using coupled TENG networks (reprinted from (Xu et al., 2018), Copyright 2018, with permission from American Chemical Society); (b) working principle of an RS-TENG (Wang et al., 2022); (c) structural design of a GS-TENG for harvesting multidirectional ocean energy (reprinted from (Gao et al., 2022), Copyright 2022, with permission from American Chemical Society). PLA is the polylactic acid. References to color refer to the online version of this figure

investigation on the performance of the RS-TENG. The findings demonstrate that energy-harvesting performance is significantly influenced by the spherical dielectrics, whereas the triboelectric materials have a comparatively lesser impact (Wang et al., 2022).

Additionally, Fig. 5c depicts the gyroscope-structured triboelectric nanogenerator (GS-TENG) proposed for the purpose of harvesting multidirectional ocean-wave energy. The inner and outer generation units of the system are capable of operating autonomously in diverse directions, and they all use the surface-contact friction mode. This design successfully accomplishes multidirectional energy harvesting without interference, while simultaneously augmenting the power-generation surface area (Gao et al., 2022).

### 3.2 Magnet-assisted TENG

Fig. 6 illustrates the use of magnetic-assisted TENGs for energy harvesting and sensing in coastal infrastructure. Fig. 6a demonstrates the magnetic-assisted TENG design, which employs magnetic force to generate electricity.

This section sheds light on magnetic-assisted TENGs, which present a promising avenue for energy harvesting and sensing in coastal infrastructure. The use of magnetic-assisted TENGs is illustrated in Fig. 6a for the development of a self-sustaining omnidirectional tilt sensor capable of quantifying both the degree and orientation of the tilt angle. By means of theoretical computations and empirical evaluations, it has been observed that a direct correlation exists between the tilt angle and output voltage at significant angles. This discovery has opened up the possibility of developing a sensing system that is portable, user-friendly, and self-sustaining.

The implementation of this system in visualizing data greatly streamlines the process of measurement and facilitates the advancement of self-sustaining systems (Han et al., 2014). The illustration shown in Fig. 6b showcases a TENG that is structured with a magnetic switch (MS). The TENG comprises transmission gears, energy modulation modules, and a generation unit that is designed to effectively harness wind energy. The energy-modulation modules are capable of storing and releasing energy without being influenced by wind speed. This is due to the force of the magnets, which facilitates the conversion of wind energy into a consistent and uninterrupted flow of electric energy (Liu SM

et al., 2021). In addition, Fig. 6c shows an innovative approach to harvesting wind and blue energy utilizing magnetic-assisted noncontact TENGs.

The present study proposes a design that integrates a magnetic responsive composite with a TENG to convert wind and water forces into contact-separation action between Al/Ni electrodes and polydimethylsiloxane (PDMS) film. The performance of the produced TENGs was analyzed in a methodical manner, taking into account pertinent factors such as frequency of contact and separation, wind velocity, and humidity level. The findings indicate that magnetic-assisted noncontact TENGs have significant potential for harvesting wind and blue energy (Huang et al., 2016).

### 3.3 MSTENGs for bridges

MSTENGs, which have been specifically developed for use in bridge applications, are presented in Fig. 7. They emphasize the use of magnetic capsule triboelectric nanogenerators (MC-TENGs) as a means of harvesting energy in the presence of unfavorable mechanical stimuli, as depicted in Fig. 7a. Capsulate TENGs have been developed to produce electrical energy by utilizing the concept of freestanding triboelectricity, which is activated by an oscillation-triggered magnetic force within a retaining structure. The electrical performance of an MC-TENG was investigated under cyclic loading in three energy-harvesting modes, through experimental and numerical studies. The results show that the energy-harvesting efficacy of an MC-TENG is considerably influenced by the structural configuration of the encapsulated TENG (Jiao et al., 2022a).

The work also incorporates a novel concept called magnetically circular layer (MCL) (Fig. 7b), which serves the purpose of detecting velocity and identifying damages. The design of the MCL-TENG incorporates magnets that are affixed to the device, thereby generating an attractive force that facilitates movement. The MCL-TENG exhibits a high degree of responsiveness to delicate impacts and can be employed to measure velocity parameters and detect cracks, all without necessitating intricate configurations. The MCL-TENG was used to create a self-sustaining velocity sensor for automobiles and a sensor for detecting cracks, thereby establishing a foundation for the effective implementation of TENGs in the realm of intelligent monitoring (Jiao et al., 2022b). Finally, it can be observed from

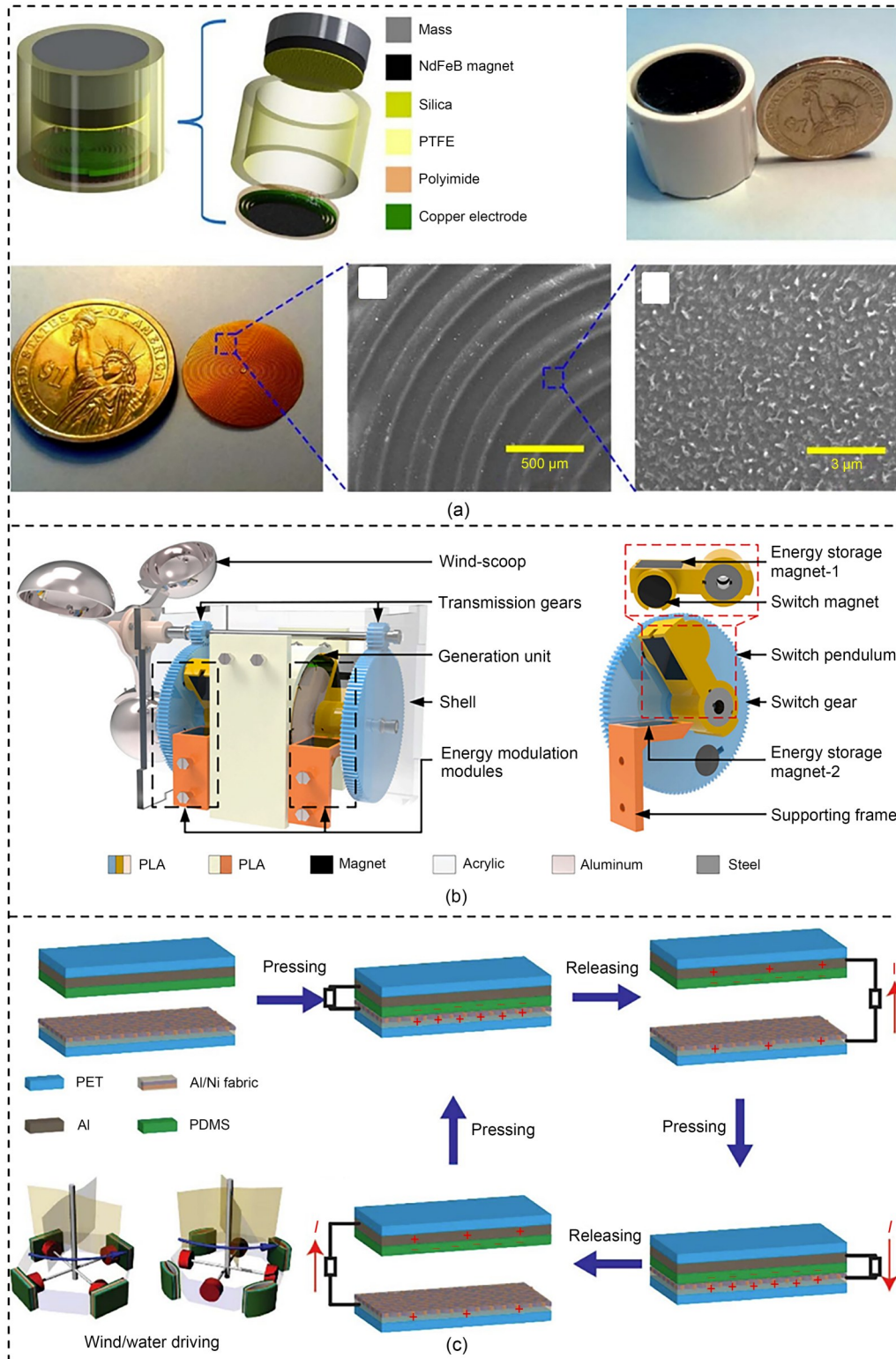


Fig. 6 Magnet-assisted TENG: (a) diagram and image of the magnetically assisted TENG as a self-powered sensing system (Han et al., 2014); (b) design principle of a magnetic-switch TENG for energy harvesting (reprinted from (Liu SM et al., 2021), Copyright 2021, with permission from Elsevier); (c) design and fabrication of a magnetic-assisted noncontact TENG (reprinted from (Huang et al., 2016), Copyright 2016, with permission from Elsevier). PET is the polyethylene terephthalate. References to color refer to the online version of this figure

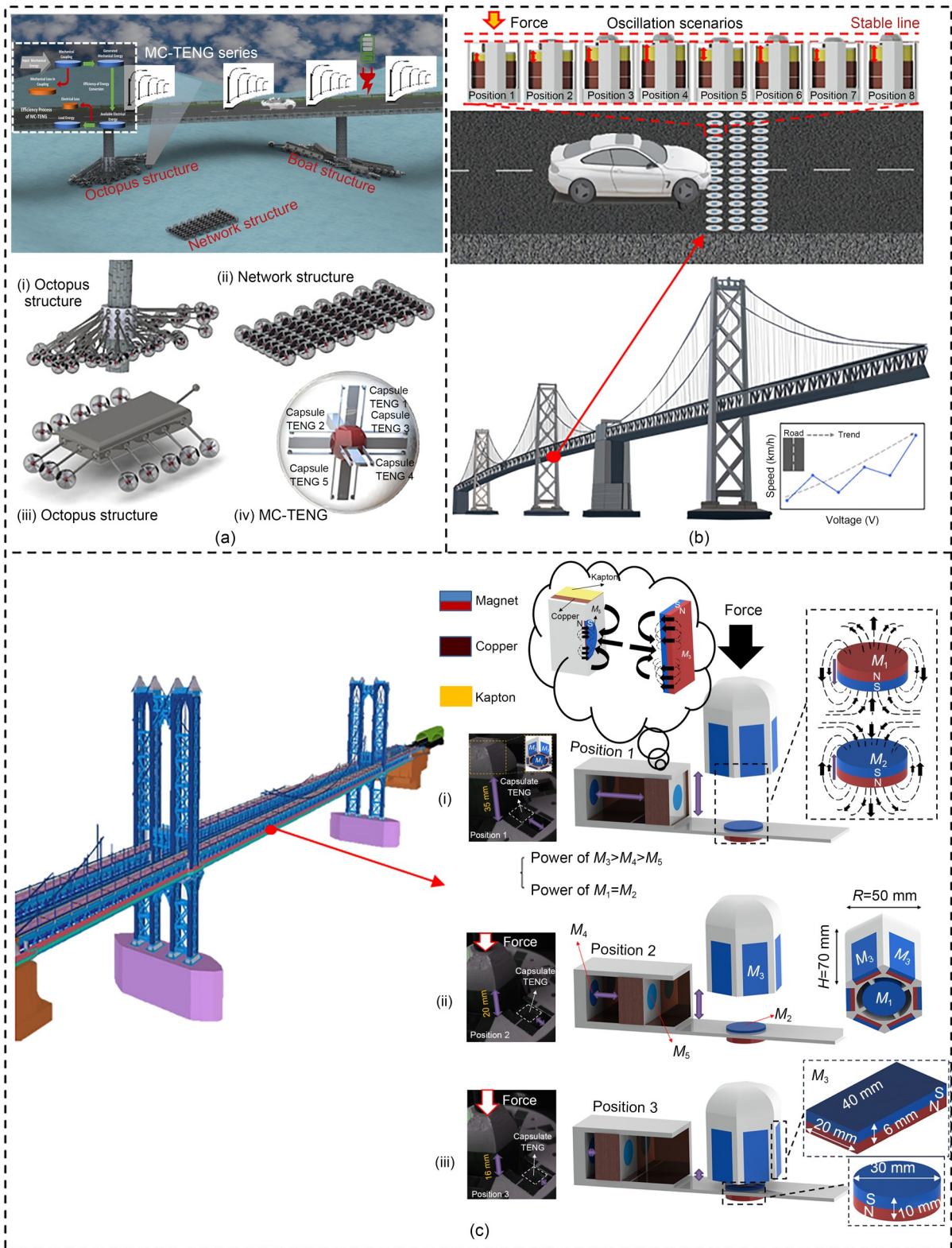


Fig. 7 MSTENGs for bridges: (a) working principle of the MC-TENG (Jiao et al., 2022a); (b) illustration of application and various scenarios of the MCL-TENG (reprinted from (Jiao et al., 2022b), Copyright 2022, with permission from Elsevier); (c) design structure of the ml-TENG as a self-powered sensor (Matin Nazar et al., 2021a). References to color refer to the online version of this figure

Fig. 7c that magnetic lifting triboelectric nanogenerators (ml-TENGs) are suitable for energy harvesting and active sensing in the presence of cyclic loads, such as traffic. The design employs magnetic force to induce a repulsive force, thereby initiating relative displacement between the electrode and dielectric layers in the lateral sliding mode. The development of a self-powered active sensing system for velocity utilizing the ml-TENG has yielded a potent instrument for the creation of active sensing systems intended for practical applications, such as the detection of velocity (Matin Nazar et al., 2021a).

### 3.4 Magnetic multilayer structure based on TENGs

The deployment of magnetic multilayer structured TENGs is shown in Fig. 8. Fig. 8a illustrates a nonresonant hybridized electromagnetic-TENG that has been designed to effectively acquire ultralow-frequency energy. The present study proposes a novel design that includes a flexible pendulum structure to achieve efficient acquisition of all-directional vibration energy. The design integrates the principles of electromagnetism

and triboelectricity, resulting in a precise and effective system. This methodology exhibits potential as a viable option for the extraction of irregular and extremely low-frequency blue energy in significant quantities (Xie et al., 2021). The self-powered multifunctional motion sensor (MFMS) shown in Fig. 8b is capable of detecting various motion parameters, including direction, speed, and acceleration of both linear and rotary motions, in a simultaneous manner. The multifunctional magnetic field sensor is composed of three main components: a module based on TENG technology, a module for magnetic regulation, and an outer shell made of acrylic material. The displacement of the magnetic flux-modulation system results in the motion of a self-supporting magnetic disc (MD) positioned on a PTFE substrate equipped with six copper electrodes, which generates an electrical potential difference (Wu et al., 2018).

The copper electrodes, comprising an inner circle electrode, an outer circle electrode, and four arc electrodes positioned between them, are meticulously crafted to differentiate between eight distinct directions of motion with acceleration, and to ascertain both

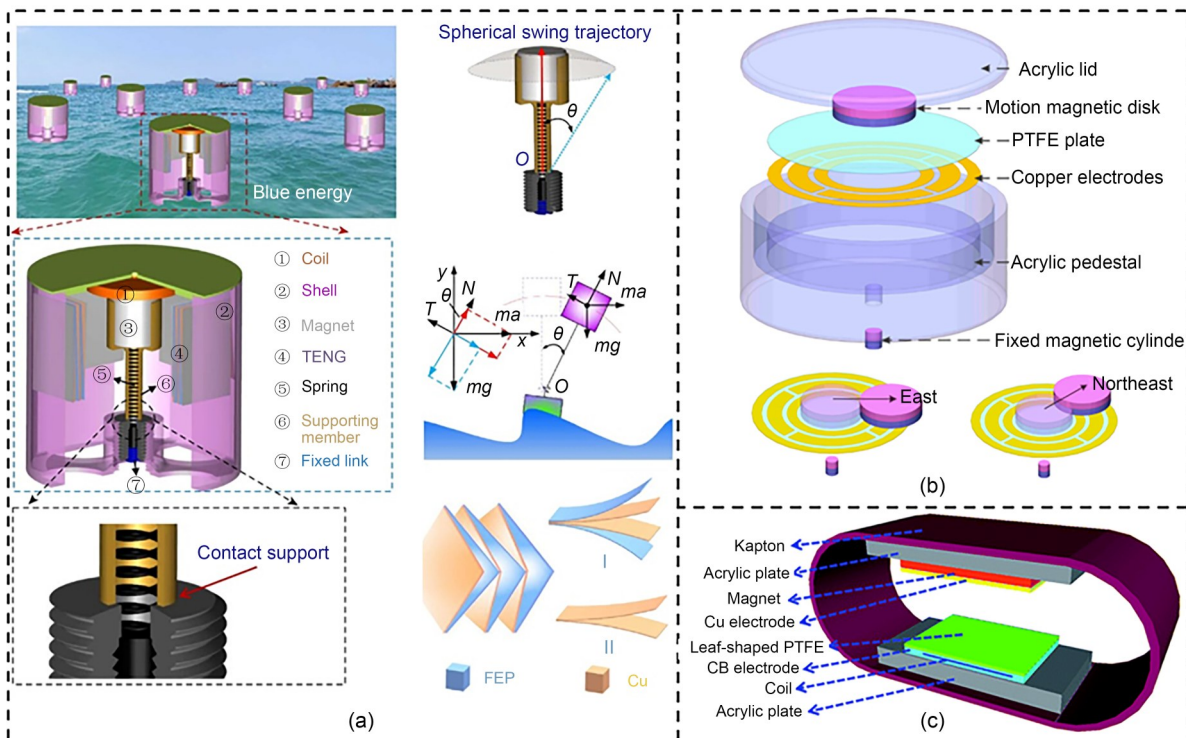


Fig. 8 Magnetic multilayer structure based on TENGs: (a) working principle of the magnetic TENG design (Xie et al., 2021); (b) structural design of a magnetic self-powered multifunctional motion sensor (reprinted from (Wu et al., 2018), Copyright 2018, with permission from American Chemical Society); (c) schematic view of a TENG arc-shaped brace structure for energy harvesting (Huang and Zhu, 2017). FEP is the fluorinated ethylene propylene. References to color refer to the online version of this figure

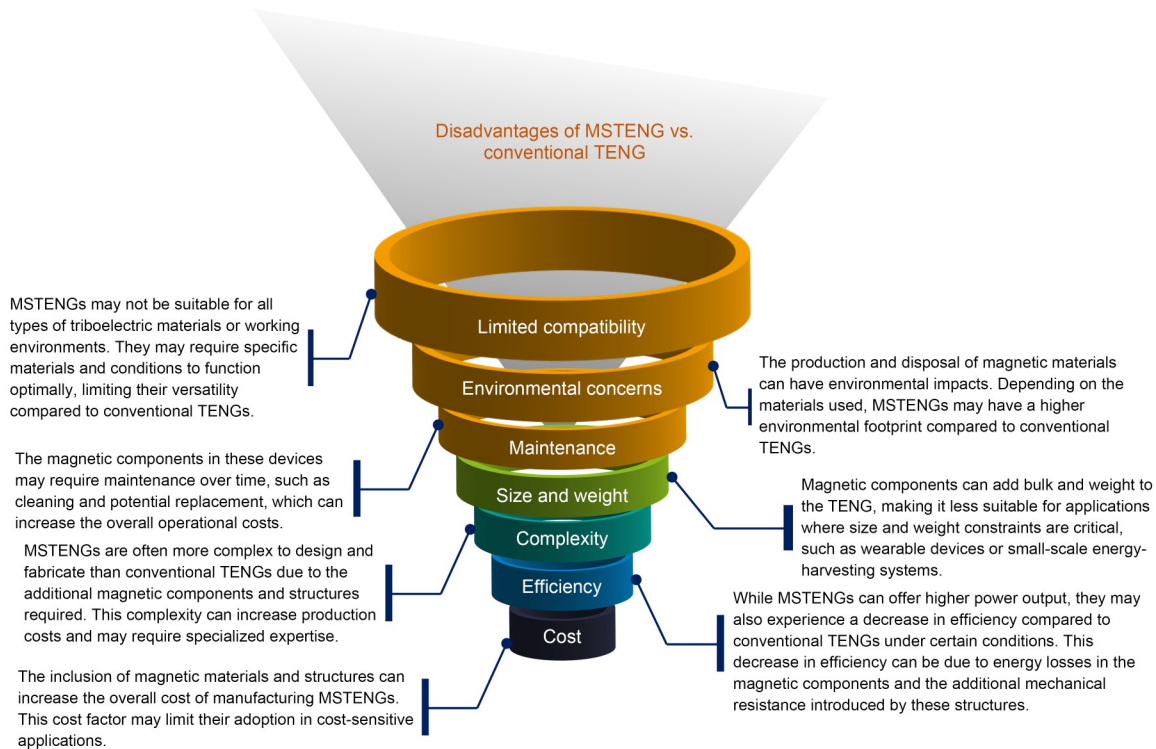
the rotational velocity and direction. As a component of the magnetic regulation module, a magnetic cylinder (MC) is affixed within the shell at the center of the PTFE plate. This type of sensor offers high practical applicability as a result of the magnetic attraction exerted by the MC, which causes the MD to return to the center automatically in preparation for subsequent detection rounds. Fig. 8c demonstrates a combination of an electromagnetic generator (EMG) and a leaf-shaped TENG made of PTFE. This hybrid system is designed to harvest mechanical energy and is supported by an arc-shaped brace structure. The EMG is comprised of a carbon black (CB) and silicone rubber composite film situated at the base of the separation component, which also functions as the pickup coil. The TENG is carefully engineered to incorporate a pair of arc-shaped braces that are oriented in opposite directions to facilitate both contact and separation (Huang and Zhu, 2017).

### 3.5 Assessing MSTENGs in comparison to conventional TENGs

Fig. 9 shows a comparative analysis of MSTENGs and conventional TENGs. MSTENGs offer benefits like enhanced power generation and increased durability,

but they also present several drawbacks. These drawbacks include increased complexity of design and fabrication due to the added magnetic components, which potentially elevate production costs and require specialized expertise.

Additionally, the incorporation of magnetic materials can lead to bulkier and heavier TENGs, limiting their suitability for applications with strict size and weight constraints, such as wearable devices and small-scale energy-harvesting systems. MSTENGs may also exhibit reduced efficiency compared to their conventional counterparts under specific conditions, due to energy losses in magnetic components and increased mechanical resistance. This increased complexity and the use of magnetic materials can further raise manufacturing costs, potentially limiting their adoption in cost-sensitive applications. Furthermore, MSTENGs may not be universally compatible with all triboelectric materials or working environments, necessitating specific materials and conditions for optimal performance which can restrict versatility. Maintenance requirements, such as cleaning and potential component replacement, can also add to overall operational costs. Lastly, concerns related to the environmental impact of magnetic materials in terms of production and disposal may



**Fig. 9 Assessing MSTENGs in comparison to conventional TENGs**

lead to a higher environmental footprint for MSTENGs compared to conventional TENGs, adding consideration in their selection. Ultimately, the choice between MSTENGs and conventional TENGs hinges on the specific application and its requirements. MSTENGs offer distinct advantages, including increased power output and improved energy-harvesting capabilities, making them valuable in certain scenarios despite these inherent disadvantages.

#### 4 Challenges, perspective, and insight for MSTENGs for energy harvesting and sensing in coastal bridge infrastructure

Fig. 10 presents a comprehensive view of the challenges, perspectives, and insights surrounding MSTENGs in the context of energy harvesting and sensing for coastal infrastructure. They have significant promise as a sustainable and cost-effective solution for these applications. However, they are not without their share of challenges that warrant attention. Notably, the durability and sustainability of MSTENGs

face significant hurdles in harsh coastal environments due to the corrosive nature of seawater and the relentless exposure to adverse weather conditions, which can degrade their performance and reduce efficiency and lifespan. Another challenge pertains to the limited power output of current prototypes, which necessitates substantial improvements to meet the energy demands of coastal infrastructure. On a positive note, magnetic-structured TENGs have the potential to reduce dependence on fossil fuels and provide renewable energy for coastal infrastructure. Additionally, they can play a pivotal role in monitoring structural integrity by delivering real-time data on structural vibrations and stress. These TENGs also find versatile applications in power generation, sensing, and remote monitoring. Valuable insights from the literature highlight the need for collaborative efforts across academia, industry, and government institutions to address these challenges and develop more practical MSTENG devices suited for demanding coastal infrastructure environments. Achieving breakthroughs in energy harvesting and sensing in coastal regions hinges on introducing novel materials and advanced fabrication techniques, making dedicated

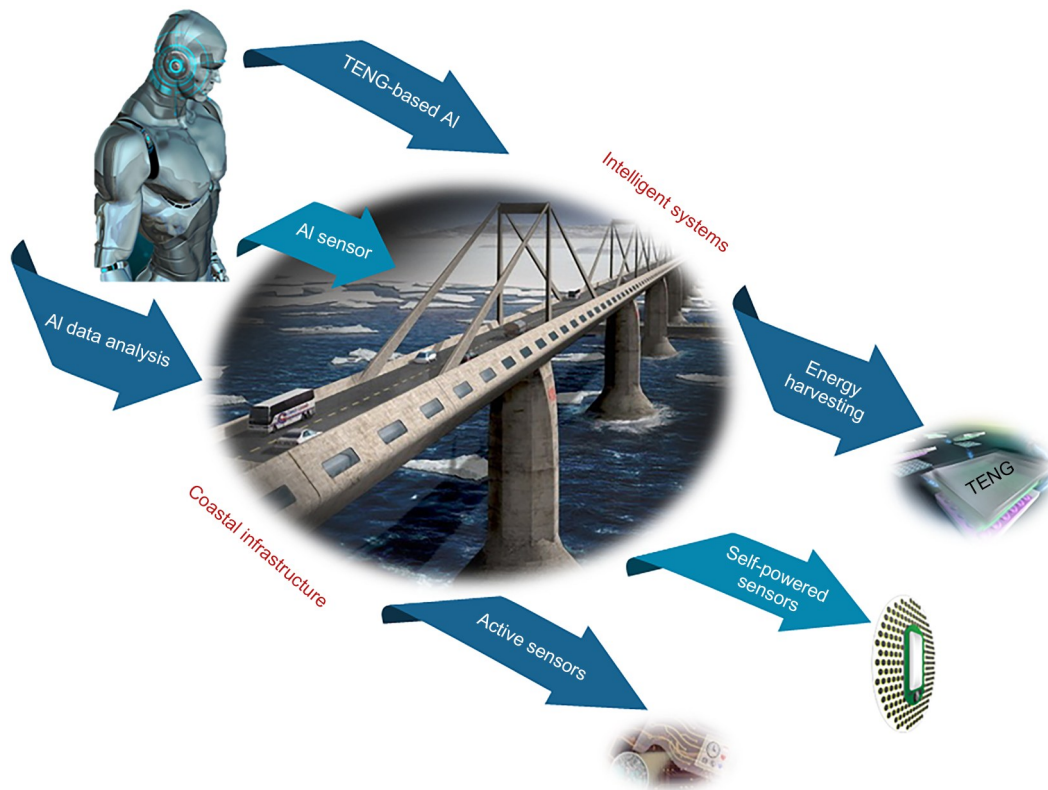


Fig. 10 Challenges, perspective, and insight for MSTENGs for energy harvesting and sensing in coastal infrastructure. AI is the artificial intelligence

optimization efforts, aligning with emerging trends such as integrating intelligent systems, advancing active sensors, exploring self-powered sensor solutions, and improving energy-conversion efficiency through innovative design and material approaches (He and Huang, 2017; He et al., 2023). Table 1 shows a summary of MSTENGs as devices for energy harvesting and sensing in coastal infrastructure. While MSTENGs offer advantages like compact and lightweight designs, their energy efficiency remains a key challenge. They exhibit energy-conversion efficiencies ranging from 10% to 60%, influenced by factors such as material selection, mechanical design, operational conditions, and electrode configuration. Enhancing their energy efficiency requires addressing various issues, notably minimizing energy loss, improving conversion rates, advancing

triboelectric materials, ensuring consistent performance under varying conditions, and scaling up for practical applications. These challenges underline the need for interdisciplinary research to unlock the full potential of MSTENGs in diverse applications, from portable electronics to large-scale energy generation.

## 5 Conclusions

In conclusion, MSTENGs have emerged as a promising technology for energy harvesting and sensing in coastal bridge infrastructure. This paper provides a comprehensive review of the recent advances in MSTENGs, from the fundamental physics modes of TENGs to the various types of MSTENGs and their

**Table 1 Summary of MSTENGs as devices for energy harvesting and sensing in coastal infrastructure**

Structure	Reference	Application	Max-open circuit voltage (V)	Max-short circuit current	Surface power density	Power
Magnetic spherical TENG network	Wang et al. (2015)	Harvesting low-frequency water-wave energy	–	1 $\mu$ A	10 mW·A	–
	Cheng et al. (2019)	Harvesting of water-wave energy	1600	5 $\mu$ A	–	10 mW
	Chen et al. (2021)	Ocean environmental monitoring	25.1	7.3 $\mu$ A	–	–
	Xu et al. (2018)	Efficient water-wave energy harvesting	1780	34.5 $\mu$ A	–	5.93 mW
	Wang et al. (2022)	Energy harvesting and ocean monitoring	12.75	–	–	455 nW
	Gao et al. (2022)	Harvesting multidirectional ocean-wave energy	730	3.2 $\mu$ A	–	–
Magnet-assisted TENG	Han et al. (2014)	Self-powered visualized omnidirectional tilt-sensing system	90	12.66 mA	441.1 mW/m <sup>2</sup>	204 $\mu$ W
	Liu SM et al. (2021)	Harvesting of wind energy	410	18 $\mu$ A	–	4.82 mW
	Huang et al. (2016)	Wind-energy and blue-energy harvesting	300	30 $\mu$ A	–	3 mW
MSTENG for bridges	Jiao et al. (2022a)	Harvesting low-frequency water-wave energy	4	–	–	400 nW
	Jiao et al. (2022b)	Velocity sensing and damage detection	5.1	–	–	9 $\mu$ W
	Matin Nazar et al. (2021a)	Energy harvesting and active sensing	4	–	–	340 $\mu$ W
Magnetic multilayer structure based on TENGs	Xie et al. (2021)	Irregular and ultralow-frequency blue-energy harvesting	190	12.4 $\mu$ A	–	470 $\mu$ W
	Wu et al. (2018)	Multifunctional motion sensing	1.5	–	–	–
	Huang and Zhu (2017)	Energy harvesting	0.25	–	80 $\mu$ W/cm <sup>2</sup>	–

applications in coastal infrastructure. The review of magnetic spherical TENG networks, magnet-assisted TENGs, MSTENGs for bridges, and magnetic multi-layer structures based on TENGs shows the significant advances that have been made in optimizing the performance of these devices. Nonetheless, there remain challenges, such as the requirement to improve the durability and sustainability of MSTENGs in harsh coastal environments and the need for higher power-output levels. Collaboration between academia, industry, and government institutions to achieve sustainable solutions for coastal infrastructure should lead to significant advancements in the design and application of MSTENGs in the future.

### Author contributions

Conceptualization: Ali MATIN NAZAR and Maria RASHIDI; Methodology: Ali MATIN NAZAR and Arash RAYEGANI; Investigation: Ali MATIN NAZAR, Arash RAYEGANI, and Fatemeh RAHIMI SARDO; Writing—original draft preparation: Ali MATIN NAZAR, Arash RAYEGANI, and Fatemeh RAHIMI SARDO; Writing—review and editing: Ali MATIN NAZAR, Arash RAYEGANI, and Maria RASHIDI; Visualization: Arash RAYEGANI and Ali MATIN NAZAR; Project administration: Ali MATIN NAZAR and Maria RASHIDI. All authors have read and agreed to the published version of the manuscript.

### Conflict of interest

Ali MATIN NAZAR, Arash RAYEGANI, Maria RASHIDI, and Fatemeh RAHIMI SARDO declare that they have no conflict of interest.

### References

- An J, Wang ZM, Jiang T, et al., 2019. Whirling-folded triboelectric nanogenerator with high average power for water wave energy harvesting. *Advanced Functional Materials*, 29(39):1904867. <https://doi.org/10.1002/adfm.201904867>
- Aydoğan B, Ayat B, Yüksel Y, 2013. Black sea wave energy atlas from 13 years hindcasted wave data. *Renewable Energy*, 57:436-447. <https://doi.org/10.1016/j.renene.2013.01.047>
- Ayegba BO, Egbe KJI, Matin Nazar A, et al., 2022. Resource efficiency and thermal comfort of 3D printable concrete building envelopes optimized by performance enhancing insulation: a numerical study. *Energies*, 15(3):1069. <https://doi.org/10.3390/en15031069>
- Calisal SM, 1983. A note on the derivation of potential energy for two-dimensional water waves. *Ocean Engineering*, 10(2):133-138. [https://doi.org/10.1016/0029-8018\(83\)90019-7](https://doi.org/10.1016/0029-8018(83)90019-7)
- Chatzigiannakou MA, Dolguntseva I, Leijon M, 2017. Offshore deployments of wave energy converters by seabased industry AB. *Journal of Marine Science and Engineering*, 5(2): 15. <https://doi.org/10.3390/jmse5020015>
- Chen HM, Wang J, Ning AF, 2021. Optimization of a rolling triboelectric nanogenerator based on the nano–micro structure for ocean environmental monitoring. *ACS Omega*, 6(32):21059-21065. <https://doi.org/10.1021/acsomega.1c02709>
- Chen J, Yang J, Li ZL, et al., 2015. Networks of triboelectric nanogenerators for harvesting water wave energy: a potential approach toward blue energy. *ACS Nano*, 9(3):3324-3331. <https://doi.org/10.1021/acsnano.5b00534>
- Chen J, Huang Y, Zhang NN, et al., 2016. Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. *Nature Energy*, 1(10):16138. <https://doi.org/10.1038/nenergy.2016.138>
- Chen YD, Jie Y, Wang J, et al., 2018. Triboelectrification on natural rose petal for harvesting environmental mechanical energy. *Nano Energy*, 50:441-447. <https://doi.org/10.1016/j.nanoen.2018.05.021>
- Cheng P, Guo HY, Wen Z, et al., 2019. Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by soft contacted structure. *Nano Energy*, 57:432-439. <https://doi.org/10.1016/j.nanoen.2018.12.054>
- Choi D, Kim DW, Yoo D, et al., 2017. Spontaneous occurrence of liquid-solid contact electrification in nature: toward a robust triboelectric nanogenerator inspired by the natural lotus leaf. *Nano Energy*, 36:250-259. <https://doi.org/10.1016/j.nanoen.2017.04.026>
- Dai KR, Wang XF, Niu SM, et al., 2017. Simulation and structure optimization of triboelectric nanogenerators considering the effects of parasitic capacitance. *Nano Research*, 10(1):157-171. <https://doi.org/10.1007/s12274-016-1275-7>
- Deane JHB, Dharmasena RDIG, Gentile G, 2018. Power computation for the triboelectric nanogenerator. *Nano Energy*, 54:39-49. <https://doi.org/10.1016/j.nanoen.2018.09.063>
- Egbe KJI, Matin Nazar A, Jiao PC, et al., 2021. Vibrational turbine piezoelectric nanogenerators for energy harvesting in multiphase flow fields. *Energy Reports*, 7:6384-6393. <https://doi.org/10.1016/j.egyrs.2021.09.085>
- Egbe KJI, Matin Nazar A, Jiao PC, 2022a. Magnet-actuated piezoelectric harvester for energy harvesting from fluids. *Applied Mechanics and Materials*, 909:89-98. <https://doi.org/10.4028/p-0y10s0>
- Egbe KJI, Matin Nazar A, Jiao PC, 2022b. Piezoelectric-triboelectric-electromagnetic hybrid rotational energy harvesters (H-REH). *International Journal of Mechanical Sciences*, 235:107722. <https://doi.org/10.1016/j.ijmecsci.2022.107722>
- Fan X, Chen J, Yang J, et al., 2015. Ultrathin, rollable, paper-based triboelectric nanogenerator for acoustic energy harvesting and self-powered sound recording. *ACS Nano*, 9(4): 4236-4243.

- <https://doi.org/10.1021/acsnano.5b00618>
- Feng AS, Narins PM, 2008. Ultrasonic communication in concave-eared torrent frogs (*Amolops tormotus*). *Journal of Comparative Physiology A*, 194(2):159-167. <https://doi.org/10.1007/s00359-007-0267-1>
- Feng YW, Ling LL, Nie JH, et al., 2017. Self-powered electrostatic filter with enhanced photocatalytic degradation of formaldehyde based on built-in triboelectric nanogenerators. *ACS Nano*, 11(12):12411-12418. <https://doi.org/10.1021/acsnano.7b06451>
- Gandomi AH, Alavi AH, Asghari A, et al., 2014. An innovative approach for modeling of hysteretic energy demand in steel moment resisting frames. *Neural Computing and Applications*, 24(6):1285-1291. <https://doi.org/10.1007/s00521-013-1342-x>
- Gao Q, Xu YH, Yu X, et al., 2022. Gyroscope-structured triboelectric nanogenerator for harvesting multidirectional ocean wave energy. *ACS Nano*, 16(4):6781-6788. <https://doi.org/10.1021/acsnano.2c01594>
- Gao XY, Wu JG, Yu Y, et al., 2018. Giant piezoelectric coefficients in relaxor piezoelectric ceramic PNN-PZT for vibration energy harvesting. *Advanced Functional Materials*, 28(30):1706895. <https://doi.org/10.1002/adfm.201706895>
- Gu GQ, Han CB, Lu CX, et al., 2017. Triboelectric nanogenerator enhanced nanofiber air filters for efficient particulate matter removal. *ACS Nano*, 11(6):6211-6217. <https://doi.org/10.1021/acsnano.7b02321>
- Gu L, Cui NY, Liu JM, et al., 2015. Packaged triboelectric nanogenerator with high durability for severe environments. *Nanoscale*, 7(43):18049-18053. <https://doi.org/10.1039/C5NR05514H>
- Guillou N, Thiébot J, Chapalain G, 2019. Turbines' effects on water renewal within a marine tidal stream energy site. *Energy*, 189:116113. <https://doi.org/10.1016/j.energy.2019.116113>
- Han MD, Zhang XS, Sun XM, et al., 2014. Magnetic-assisted triboelectric nanogenerators as self-powered visualized omnidirectional tilt sensing system. *Scientific Reports*, 4(1):4811. <https://doi.org/10.1038/srep04811>
- He F, Huang ZH, 2017. Characteristics of orifices for modeling nonlinear power take-off in wave-flume tests of oscillating water column devices. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 18(5):329-345. <https://doi.org/10.1631/jzus.A1600769>
- He F, Liu YB, Pan JP, et al., 2023. Advanced ocean wave energy harvesting: current progress and future trends. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 24(2):91-108. <https://doi.org/10.1631/jzus.A2200598>
- Horowitz SB, Sheplak M, 2013. Aeroacoustic applications of acoustic energy harvesting. *The Journal of the Acoustical Society of America*, 134(S5):4155. <https://doi.org/10.1121/1.4831230>
- Huang LB, Xu W, Bai GX, et al., 2016. Wind energy and blue energy harvesting based on magnetic-assisted noncontact triboelectric nanogenerator. *Nano Energy*, 30:36-42. <https://doi.org/10.1016/j.nanoen.2016.09.032>
- Huang R, Zhu JX, 2017. A hybrid electromagnetic and leaf-shaped polytetrafluoroethylene triboelectric with an arc-shaped brace structure for energy harvesting. *RSC Advances*, 7(78):49562-49567. <https://doi.org/10.1039/C7RA08572A>
- Iglesias G, Carballo R, 2014. Wave farm impact: the role of farm-to-coast distance. *Renewable Energy*, 69:375-385. <https://doi.org/10.1016/j.renene.2014.03.059>
- Javadi M, Heidari A, Darbari S, 2018. Realization of enhanced sound-driven CNT-based triboelectric nanogenerator, utilizing sonic array configuration. *Current Applied Physics*, 18(4):361-368. <https://doi.org/10.1016/j.cap.2018.01.018>
- Jbaily A, Yeung RW, 2015. Piezoelectric devices for ocean energy: a brief survey. *Journal of Ocean Engineering and Marine Energy*, 1(1):101-118. <https://doi.org/10.1007/s40722-014-0008-9>
- Jiang DD, Liu GX, Li WJ, et al., 2020. A leaf-shaped triboelectric nanogenerator for multiple ambient mechanical energy harvesting. *IEEE Transactions on Power Electronics*, 35(1):25-32. <https://doi.org/10.1109/TPEL.2019.2921152>
- Jiao PC, Egbe KJI, Xie YW, et al., 2020. Piezoelectric sensing techniques in structural health monitoring: a state-of-the-art review. *Sensors*, 20(13):3730. <https://doi.org/10.3390/s20133730>
- Jiao PC, Matin Nazar A, Egbe KJI, et al., 2022a. Magnetic capsule triboelectric nanogenerators. *Scientific Reports*, 12(1):89. <https://doi.org/10.1038/s41598-021-04100-2>
- Jiao PC, Matin Nazar A, Egbe KJI, et al., 2022b. Magnetically circular layers triboelectric nanogenerators (MCL-TENG) for velocity sensing and damage detection. *Sustainable Energy Technologies and Assessments*, 53:102644. <https://doi.org/10.1016/j.seta.2022.102644>
- Jiao PC, Matin Nazar A, Yang Y, 2022c. Ocean Wave Energy Collector Based on Magnetic Force and Triboelectric Effect. US Patent 20220307458A1.
- Jiao PC, Egbe KJI, Matin Nazar A, et al., 2022d. Oscillatory magnetic piezoelectric nanogenerators under low-frequency and low-amplitude excitations. *Sustainable Energy Technologies and Assessments*, 52:102022. <https://doi.org/10.1016/j.seta.2022.102022>
- Kanik M, Say MG, Daglar B, et al., 2015. A motion- and sound-activated, 3D-printed, chalcogenide-based triboelectric nanogenerator. *Advanced Materials*, 27(14):2367-2376. <https://doi.org/10.1002/adma.201405944>
- Khan U, Kim SW, 2016. Triboelectric nanogenerators for blue energy harvesting. *ACS Nano*, 10(7):6429-6432. <https://doi.org/10.1021/acsnano.6b04213>
- Kwak SS, Lin SS, Lee JH, et al., 2016. Triboelectrification-induced large electric power generation from a single moving droplet on graphene/polytetrafluoroethylene. *ACS Nano*, 10(8):7297-7302. <https://doi.org/10.1021/acsnano.6b03032>
- Lai YC, Hsiao YC, Wu HM, et al., 2019. Waterproof fabric-based

- multifunctional triboelectric nanogenerator for universally harvesting energy from raindrops, wind, and human motions and as self-powered sensors. *Advanced Science*, 6(5):1801883.  
<https://doi.org/10.1002/advs.201801883>
- Lee K, Lee JW, Kim K, et al., 2018. A spherical hybrid triboelectric nanogenerator for enhanced water wave energy harvesting. *Micromachines*, 9(11):598.  
<https://doi.org/10.3390/mi9110598>
- Lei R, Zhai H, Nie JH, et al., 2019. Butterfly-inspired triboelectric nanogenerators with spring-assisted linkage structure for water wave energy harvesting. *Advanced Materials Technologies*, 4(3):1800514.  
<https://doi.org/10.1002/admt.201800514>
- Leijon M, Bernhoff H, Agren O, et al., 2005. Multiphysics simulation of wave energy to electric energy conversion by permanent magnet linear generator. *IEEE Transactions on Energy Conversion*, 20(1):219-224.  
<https://doi.org/10.1109/TEC.2004.827709>
- Liang QJ, Yan XQ, Gu YS, et al., 2015. Highly transparent triboelectric nanogenerator for harvesting water-related energy reinforced by antireflection coating. *Scientific Reports*, 5(1):9080.  
<https://doi.org/10.1038/srep09080>
- Lin ZH, Cheng G, Lin L, et al., 2013. Water–solid surface contact electrification and its use for harvesting liquid-wave energy. *Angewandte Chemie International Edition*, 52(48):12545-12549.  
<https://doi.org/10.1002/anie.201307249>
- Lin ZH, Cheng G, Wu WZ, et al., 2014. Dual-mode triboelectric nanogenerator for harvesting water energy and as a self-powered ethanol nanosensor. *ACS Nano*, 8(6):6440-6448.  
<https://doi.org/10.1021/nn501983s>
- Lin ZM, Zhang BB, Guo HY, et al., 2019. Super-robust and frequency-multiplied triboelectric nanogenerator for efficient harvesting water and wind energy. *Nano Energy*, 64:103908.  
<https://doi.org/10.1016/j.nanoen.2019.103908>
- Liu HQ, Egbe KJI, Wang HP, et al., 2021. A numerical study on 3D printed cementitious composites mixes subjected to axial compression. *Materials*, 14(22):6882.  
<https://doi.org/10.3390/ma14226882>
- Liu SM, Li X, Wang YQ, et al., 2021. Magnetic switch structured triboelectric nanogenerator for continuous and regular harvesting of wind energy. *Nano Energy*, 83:105851.  
<https://doi.org/10.1016/j.nanoen.2021.105851>
- Liu WB, Xu L, Bu TZ, et al., 2019. Torus structured triboelectric nanogenerator array for water wave energy harvesting. *Nano Energy*, 58:499-507.  
<https://doi.org/10.1016/j.nanoen.2019.01.088>
- Liu XL, Cheng K, Cui P, et al., 2019. Hybrid energy harvester with bi-functional nano-wrinkled anti-reflective PDMS film for enhancing energies conversion from sunlight and raindrops. *Nano Energy*, 66:104188.  
<https://doi.org/10.1016/j.nanoen.2019.104188>
- Liu YP, Zheng YB, Li TH, et al., 2019. Water-solid triboelectricity with self-repairable surfaces for water-flow energy harvesting. *Nano Energy*, 61:454-461.  
<https://doi.org/10.1016/j.nanoen.2019.05.007>
- Liu YQ, Sun N, Liu JW, et al., 2018. Integrating a silicon solar cell with a triboelectric nanogenerator via a mutual electrode for harvesting energy from sunlight and raindrops. *ACS Nano*, 12(3):2893-2899.  
<https://doi.org/10.1021/acsnano.8b00416>
- Marino A, Genchi GG, Mattoli V, et al., 2017. Piezoelectric nanotransducers: the future of neural stimulation. *Nano Today*, 14:9-12.  
<https://doi.org/10.1016/j.nantod.2016.12.005>
- Martínez-Ayuso G, Friswell MI, Adhikari S, et al., 2017. Homogenization of porous piezoelectric materials. *International Journal of Solids and Structures*, 113-114:218-229.  
<https://doi.org/10.1016/j.ijsolstr.2017.03.003>
- Matin Nazar A, Egbe KJI, Jiao PC, et al., 2021a. Magnetic lifting triboelectric nanogenerators (ml-TENG) for energy harvesting and active sensing. *APL Materials*, 9(9):091111.  
<https://doi.org/10.1063/5.0064300>
- Matin Nazar A, Jiao PC, Zhang QY, et al., 2021b. A new structural health monitoring approach based on smartphone measurements of magnetic field intensity. *IEEE Instrumentation & Measurement Magazine*, 24(4):49-58.  
<https://doi.org/10.1109/MIM.2021.9448251>
- Matin Nazar A, Egbe KJI, Abdollahi A, et al., 2021c. Triboelectric nanogenerators for energy harvesting in ocean: a review on application and hybridization. *Energies*, 14(18):5600.  
<https://doi.org/10.3390/en14185600>
- Matin Nazar A, Egbe KJI, Jiao PC, 2022a. Hybrid piezoelectric and triboelectric nanogenerators for energy harvesting and walking sensing. *Energy Technology*, 10(6):2200063.  
<https://doi.org/10.1002/ente.202200063>
- Matin Nazar A, Egbe KJ, Jiao PC, 2022b. Magnetic structured triboelectric nanogenerators for energy harvesting. *Applied Mechanics and Materials*, 909:81-88.  
<https://doi.org/10.4028/p-4sj54f>
- Matin Nazar A, Narazaki Y, Rayegani A, et al., 2022c. Recent progress of triboelectric nanogenerators as self-powered sensors in transportation engineering. *Measurement*, 203:112010.  
<https://doi.org/10.1016/j.measurement.2022.112010>
- Matin Nazar A, Mohsenian R, Rayegani A, et al., 2023. Skin-contact triboelectric nanogenerator for energy harvesting and motion sensing: principles, challenges, and perspectives. *Biosensors*, 13(9):872.  
<https://doi.org/10.3390/bios13090872>
- Mccormick ME, Ertekin RC, 2009. Renewable sea power. *Mechanical Engineering*, 131(5):36-39.  
<https://doi.org/10.1115/1.2009-MAY-4>
- Muralt P, Polcawich RG, Trolrier-Mckinstry S, 2009. Piezoelectric thin films for sensors, actuators, and energy harvesting. *MRS Bulletin*, 34(9):658-664.  
<https://doi.org/10.1557/mrs2009.177>
- Nie JH, Wang ZM, Ren ZW, et al., 2019. Power generation from the interaction of a liquid droplet and a liquid membrane. *Nature Communications*, 10(1):2264.  
<https://doi.org/10.1038/s41467-019-10232-x>
- Nie JH, Ren ZW, Xu L, et al., 2020. Probing contact-electrification-induced electron and ion transfers at a

- liquid–solid interface. *Advanced Materials*, 32(2):1905696. <https://doi.org/10.1002/adma.201905696>
- Niu SM, Wang ZL, 2015. Theoretical systems of triboelectric nanogenerators. *Nano Energy*, 14:161-192. <https://doi.org/10.1016/j.nanoen.2014.11.034>
- Niu SM, Zhou YS, Wang SH, et al., 2014. Simulation method for optimizing the performance of an integrated triboelectric nanogenerator energy harvesting system. *Nano Energy*, 8:150-156. <https://doi.org/10.1016/j.nanoen.2014.05.018>
- Olsen M, Zhang RY, Örtengren J, et al., 2019. Frequency and voltage response of a wind-driven fluttering triboelectric nanogenerator. *Scientific Reports*, 9(1):5543. <https://doi.org/10.1038/s41598-019-42128-7>
- Pelc R, Fujita RM, 2002. Renewable energy from the ocean. *Marine Policy*, 26(6):471-479. [https://doi.org/10.1016/S0308-597X\(02\)00045-3](https://doi.org/10.1016/S0308-597X(02)00045-3)
- Prieto LF, Rodríguez GR, Rodríguez JS, 2019. Wave energy to power a desalination plant in the north of Gran Canaria Island: wave resource, socioeconomic and environmental assessment. *Journal of Environmental Management*, 231: 546-551. <https://doi.org/10.1016/j.jenvman.2018.10.071>
- Qian Y, Nie JH, Ma X, et al., 2019. Octopus tentacles inspired triboelectric nanogenerators for harvesting mechanical energy from highly wetted surface. *Nano Energy*, 60: 493-502. <https://doi.org/10.1016/j.nanoen.2019.03.068>
- Qin HF, Gu GQ, Shang WY, et al., 2020. A universal and passive power management circuit with high efficiency for pulsed triboelectric nanogenerator. *Nano Energy*, 68:104372. <https://doi.org/10.1016/j.nanoen.2019.104372>
- Que RH, Shao Q, Li QL, et al., 2012. Flexible nanogenerators based on graphene oxide films for acoustic energy harvesting. *Angewandte Chemie International Edition*, 51(22): 5418-5422. <https://doi.org/10.1002/anie.201200773>
- Rahimi Sardo F, Rayegani A, Matin Nazar A, et al., 2022. Recent progress of triboelectric nanogenerators for biomedical sensors: from design to application. *Biosensors*, 12(9): 697. <https://doi.org/10.3390/bios12090697>
- Rashidi M, Hoshyar AN, Smith L, et al., 2021. A comprehensive taxonomy for structure and material deficiencies, preventions and remedies of timber bridges. *Journal of Building Engineering*, 34:101624. <https://doi.org/10.1016/j.jobe.2020.101624>
- Rayegani A, Nouri G, 2022a. Application of smart dampers for prevention of seismic pounding in isolated structures subjected to near-fault earthquakes. *Journal of Earthquake Engineering*, 26(8):4069-4084. <https://doi.org/10.1080/13632469.2020.1822230>
- Rayegani A, Nouri G, 2022b. Seismic collapse probability and life cycle cost assessment of isolated structures subjected to pounding with smart hybrid isolation system using a modified fuzzy based controller. *Structures*, 44:30-41. <https://doi.org/10.1016/j.istruc.2022.07.085>
- Rayegani A, Matin Nazar A, Rashidi M, 2023. Advancements in triboelectric nanogenerators (TEGs) for intelligent transportation infrastructure: enhancing bridges, highways, and tunnels. *Sensors*, 23(14):6634. <https://doi.org/10.3390/s23146634>
- Ren XH, Fan HQ, Wang C, et al., 2018. Wind energy harvester based on coaxial rotatory freestanding triboelectric nanogenerators for self-powered water splitting. *Nano Energy*, 50:562-570. <https://doi.org/10.1016/j.nanoen.2018.06.002>
- Ren ZW, Ding YF, Nie JH, et al., 2019. Environmental energy harvesting adapting to different weather conditions and self-powered vapor sensor based on humidity-responsive triboelectric nanogenerators. *ACS Applied Materials & Interfaces*, 11(6):6143-6153. <https://doi.org/10.1021/acsami.8b21477>
- Roscow JJ, Lewis RWC, Taylor J, et al., 2017. Modelling and fabrication of porous sandwich layer barium titanate with improved piezoelectric energy harvesting figures of merit. *Acta Materialia*, 128:207-217. <https://doi.org/10.1016/j.actamat.2017.02.029>
- Shao JJ, Willatzen M, Jiang T, et al., 2019. Quantifying the power output and structural figure-of-merits of triboelectric nanogenerators in a charging system starting from the Maxwell's displacement current. *Nano Energy*, 59:380-389. <https://doi.org/10.1016/j.nanoen.2019.02.051>
- Shao JJ, Jiang T, Wang ZL, 2020. Theoretical foundations of triboelectric nanogenerators (TEGs). *Science China Technological Sciences*, 63(7):1087-1109. <https://doi.org/10.1007/s11431-020-1604-9>
- Su YJ, Wen XN, Zhu G, et al., 2014. Hybrid triboelectric nanogenerator for harvesting water wave energy and as a self-powered distress signal emitter. *Nano Energy*, 9:186-195. <https://doi.org/10.1016/j.nanoen.2014.07.006>
- Suzuki RO, Tanaka D, 2003. Mathematical simulation of thermoelectric power generation with the multi-panels. *Journal of Power Sources*, 122(2):201-209. [https://doi.org/10.1016/S0378-7753\(03\)00396-3](https://doi.org/10.1016/S0378-7753(03)00396-3)
- Thorpe TW, 1999. A Brief Review of Wave Energy. Technical Report No. ETSU-R120, Department of Trade and Industry, UK.
- Uchino K, 2008. Piezoelectric actuators 2008: key factors for commercialization. Proceedings of the International Conference on Smart Materials—Smart/Intelligent Materials and Nano Technology, p.1-9.
- Varmaghani A, Matin Nazar A, Ahmadi M, et al., 2021. DMTC: optimize energy consumption in dynamic wireless sensor network based on fog computing and fuzzy multiple attribute decision-making. *Wireless Communications and Mobile Computing*, 2021:9953416. <https://doi.org/10.1155/2021/9953416>
- Wang SH, Lin L, Wang ZL, 2012. Nanoscale triboelectric-effect-enabled energy conversion for sustainably powering portable electronics. *Nano Letters*, 12(12):6339-6346. <https://doi.org/10.1021/nl303573d>
- Wang SH, Lin L, Xie YN, et al., 2013. Sliding-triboelectric nanogenerators based on in-plane charge-separation mechanism.

- Nano Letters*, 13(5):2226-2233.  
<https://doi.org/10.1021/nl400738p>
- Wang XF, Niu SM, Yin YJ, et al., 2015. Triboelectric nanogenerator based on fully enclosed rolling spherical structure for harvesting low-frequency water wave energy. *Advanced Energy Materials*, 5(24):1501467.  
<https://doi.org/10.1002/aenm.201501467>
- Wang YZ, Matin Nazar A, Wang JJ, et al., 2022. Rolling spherical triboelectric nanogenerators (RS-TENG) under low-frequency ocean wave action. *Journal of Marine Science and Engineering*, 10(1):5.  
<https://doi.org/10.3390/jmse10010005>
- Wang ZL, 2017. On Maxwell's displacement current for energy and sensors: the origin of nanogenerators. *Materials Today*, 20(2):74-82.  
<https://doi.org/10.1016/j.mattod.2016.12.001>
- Wu CS, Wang AC, Ding WB, et al., 2019. Triboelectric nanogenerator: a foundation of the energy for the new era. *Advanced Energy Materials*, 9(1):1802906.  
<https://doi.org/10.1002/aenm.201802906>
- Wu ZY, Ding WB, Dai YJ, et al., 2018. Self-powered multifunctional motion sensor enabled by magnetic-regulated triboelectric nanogenerator. *ACS Nano*, 12(6):5726-5733.  
<https://doi.org/10.1021/acsnano.8b01589>
- Xi Y, Wang J, Zi YL, et al., 2017a. High efficient harvesting of underwater ultrasonic wave energy by triboelectric nanogenerator. *Nano Energy*, 38:101-108.  
<https://doi.org/10.1016/j.nanoen.2017.04.053>
- Xi Y, Guo HY, Zi YL, et al., 2017b. Multifunctional TENG for blue energy scavenging and self-powered wind-speed sensor. *Advanced Energy Materials*, 7(12):1602397.  
<https://doi.org/10.1002/aenm.201602397>
- Xie WB, Gao LX, Wu LK, et al., 2021. A nonresonant hybridized electromagnetic-triboelectric nanogenerator for irregular and ultralow frequency blue energy harvesting. *Research*, 2021:5963293.  
<https://doi.org/10.34133/2021/5963293>
- Xiong JQ, Lin MF, Wang JX, et al., 2017. Wearable all-fabric-based triboelectric generator for water energy harvesting. *Advanced Energy Materials*, 7(21):1701243.  
<https://doi.org/10.1002/aenm.201701243>
- Xu L, Jiang T, Lin P, et al., 2018. Coupled triboelectric nanogenerator networks for efficient water wave energy harvesting. *ACS Nano*, 12(2):1849-1858.  
<https://doi.org/10.1021/acsnano.7b08674>
- Yang F, Guo JM, Zhao L, et al., 2020. Tuning oxygen vacancies and improving UV sensing of ZnO nanowire by microplasma powered by a triboelectric nanogenerator. *Nano Energy*, 67:104210.  
<https://doi.org/10.1016/j.nanoen.2019.104210>
- Yang HM, Deng MM, Tang Q, et al., 2019. A nonencapsulative pendulum-like paper-based hybrid nanogenerator for energy harvesting. *Advanced Energy Materials*, 9(33):1901149.  
<https://doi.org/10.1002/aenm.201901149>
- Yang XD, Xu L, Lin P, et al., 2019. Macroscopic self-assembly network of encapsulated high-performance triboelectric nanogenerators for water wave energy harvesting. *Nano Energy*, 60:404-412.  
<https://doi.org/10.1016/j.nanoen.2019.03.054>
- Yang Y, Zhang HL, Liu RY, et al., 2013a. Fully enclosed triboelectric nanogenerators for applications in water and harsh environments. *Advanced Energy Materials*, 3(12):1563-1568.  
<https://doi.org/10.1002/aenm.201300376>
- Yang Y, Zhang HL, Lin ZH, et al., 2013b. A hybrid energy cell for self-powered water splitting. *Energy & Environmental Science*, 6(8):2429-2434.  
<https://doi.org/10.1039/C3EE41485J>
- Yoo D, Park SC, Lee S, et al., 2019. Biomimetic anti-reflective triboelectric nanogenerator for concurrent harvesting of solar and raindrop energies. *Nano Energy*, 57:424-431.  
<https://doi.org/10.1016/j.nanoen.2018.12.035>
- Yousry YM, Yao K, Chen ST, et al., 2018. Mechanisms for enhancing polarization orientation and piezoelectric parameters of PVDF nanofibers. *Advanced Electronic Materials*, 4(6):1700562.  
<https://doi.org/10.1002/aelm.201700562>
- Zhao X, Chen B, Wei GD, et al., 2019. Polyimide/graphene nanocomposite foam-based wind-driven triboelectric nanogenerator for self-powered pressure sensor. *Advanced Materials Technologies*, 4(5):1800723.  
<https://doi.org/10.1002/admt.201800723>
- Zhong W, Xu L, Wang HM, et al., 2019. Stacked pendulum-structured triboelectric nanogenerators for effectively harvesting low-frequency water wave energy. *Nano Energy*, 66:104108.  
<https://doi.org/10.1016/j.nanoen.2019.104108>
- Zhu G, Pan CF, Guo WX, et al., 2012. Triboelectric-generator-driven pulse electrodeposition for micropatterning. *Nano Letters*, 12(9):4960-4965.  
<https://doi.org/10.1021/nl302560k>
- Zhu G, Chen J, Liu Y, et al., 2013. Linear-grating triboelectric generator based on sliding electrification. *Nano Letters*, 13(5):2282-2289.  
<https://doi.org/10.1021/nl4008985>
- Zou Y, Tan PC, Shi BJ, et al., 2019. A bionic stretchable nanogenerator for underwater sensing and energy harvesting. *Nature Communications*, 10(1):2695.  
<https://doi.org/10.1038/s41467-019-10433-4>