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Review

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

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Abstract: This paper provides an overview of the recent advancements in magnetic structured triboelectric nanogenerators (MSTNGs) 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, 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 MSTNGs and their applications in coastal infrastructure. Specifically, it covers magnetic spherical triboelectric nanogenerator networks, magnet-assisted triboelectric nanogenerators, MSTNGs for bridges, and magnetic multilayer structures based on triboelectric nanogenerators. The advantages and limitations of each type of MSTNG 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 MSTNGs. These include the need for improved durability and sustainability of MSTNGs 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 MSTNG performance.

Key words: Energy Harvesting; Intelligent Coastal Infrastructure; Triboelectric nanogenerators (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., 2017b; Zhao et al., 2019a; Jiao et al., 2020; Rashidi et al., 2021). One promising solution that addresses both of these needs is magnetic structured triboelectric nanogenerators (MSTNGs), which harvest energy from mechanical motion and can provide sustainable energy and real-time monitoring for coastal infrastructure applications (Xu et al., 2017; Jiao, et al., 2020; Egbe et al., 2021a; Liu et al., 2021a; Matin Nazar et al., 2021a; Nazar et al., 2021a; Ayegba et al., 2022; Egbe et al., 2022a; Jiao et al., 2022a; Jiao et al., 2022c; Jiao, 2022; Matin Nazar et al., 2022a; Matin Nazar et al., 2022b; Rahimi Sardo et al., 2022; Matin Nazar et al., 2023; Rayegani et al., 2023a; Rayegani et al., 2023b). MSTNGs integrate magnetic structures with TENGs to generate electricity from mechanical motion (Lee et al., 2018; Egbe et al., 2022b; Nazar et al., 2022). 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; Cui et al., 2015; Liang et al., 2015; Chen et al., 2016; Liang et al., 2016; Ahmed et al., 2017; Feng et al., 2017; Ren et al., 2018; An et al., 2019; Lin et al., 2019; Ren et al., 2019). Furthermore, MSTNGs can be integrated with sensors to provide real-time

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monitoring for coastal infrastructure or other applications in structures (Lai et al., 2019; Rayegani and Nouri, 2022b,2022a). This paper provides a comprehensive review of the recent advances in MSTNGs, covering the fundamental physics modes of triboelectric nanogenerators, triboelectric series (Yang et al., 2013b), and factors affecting TENG power generation and transmission (Fan et al., 2015; Gu et al., 2015; Khan and Kim, 2016; Chen et al., 2019; Cheng et al., 2019; Liu et al., 2019a; Mariello et al., 2019; Zou et al., 2019). The paper also provides an overview of MSTNGs in coastal infrastructure, and presents four different types of MSTNGs that have shown great potential in energy harvesting (Wang et al., 2012; Zhu et al., 2012; Wang et al., 2013; Zhu et al., 2013; Zhu et al., 2015; Wang, 2017; Liu et al., 2018; Yang et al., 2019a; Qin et al., 2020; Yang 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, magnetic structured TENGs for bridges, and magnetic multilayer structures based on triboelectric nanogenerators.

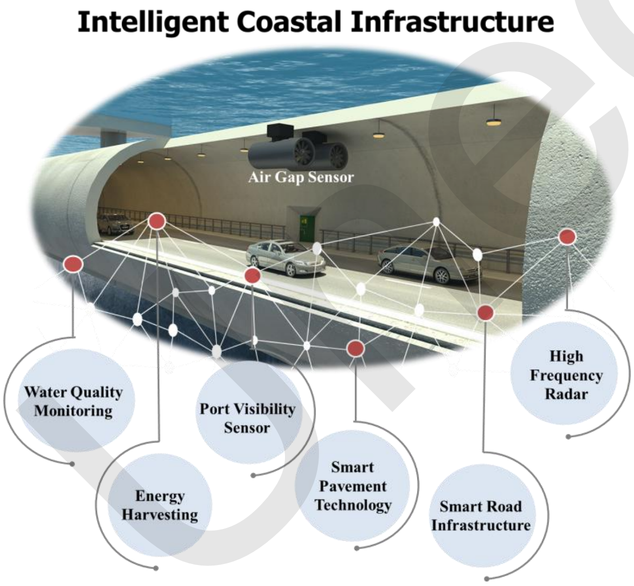

Fig. 1 Intelligent coastal infrastructure

Furthermore, the paper highlights the progress and challenges in MSTNG 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; Lee et al., 2019; Liu et al., 2019c; Nie et al., 2019; Qian et al., 2019; Zhou et al., 2019). Although current MSTNG 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 MSTNGs in coastal infrastructure provide a strong incentive for further research and development (Kanik et al., 2015). Figure 1 shows the intelligent coastal infrastructure (energy harvesting, water-quality monitoring, a port visibility sensor, smart pavement technology, smart road infrastructure, and high-frequency radar) (Horowitz and Sheplak, 2013; Lee et al., 2017; Lei et al., 2019; Zhong et al., 2019; Egbe et al., 2021b; Nazar et al., 2021b; Varmaghani et al., 2021; Matin Nazar, et al., 2022a). In summary, this paper reviews recent advancements in MSTNGs, addressing key aspects such as the fundamental physics underlying the technology, the various types of MSTNGs 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; Hu and Wang, 2015; Guillou et al., 2019; Wu et al., 2019; Matin Nazar et al., 2021b).

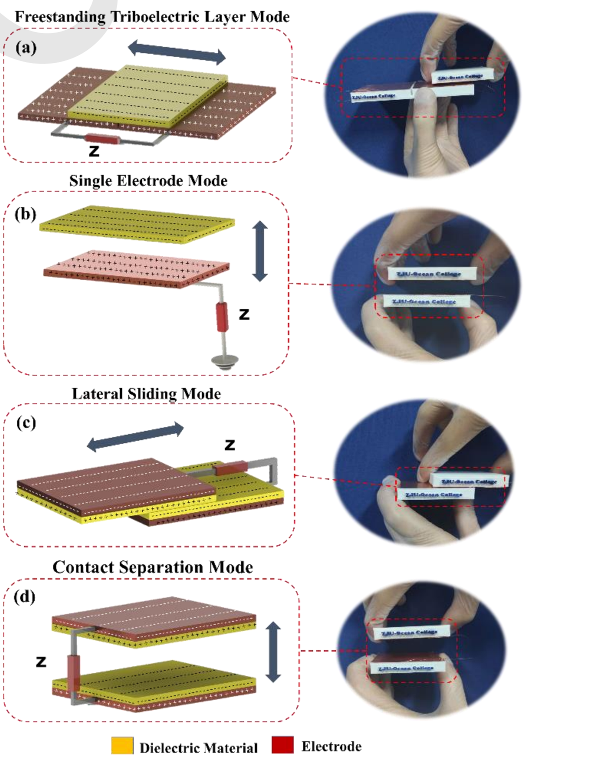

Fig.2. Four modes of triboelectric-nanogenerators: vertical contact-separation mode, sliding mode, single-electrode mode, and freestanding triboelectric-layer mode (Rahimi Sardo, et al., 2022)

Our goal is to promote further research and development for this innovative and promising energy-harvesting technology (Jiang et al., 2019).

2. Fundamental physics modes of triboelectric nanogenerators

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

Figure 2(a) offers a comprehensive view of the Free-Standing 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., 2013a). 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. Figure 2(b) 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. Figure 2(c) 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 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. Figure 2(d) showcases the contact-separation mode, a mode that employs two electrodes located at the rear of the TENG layers.

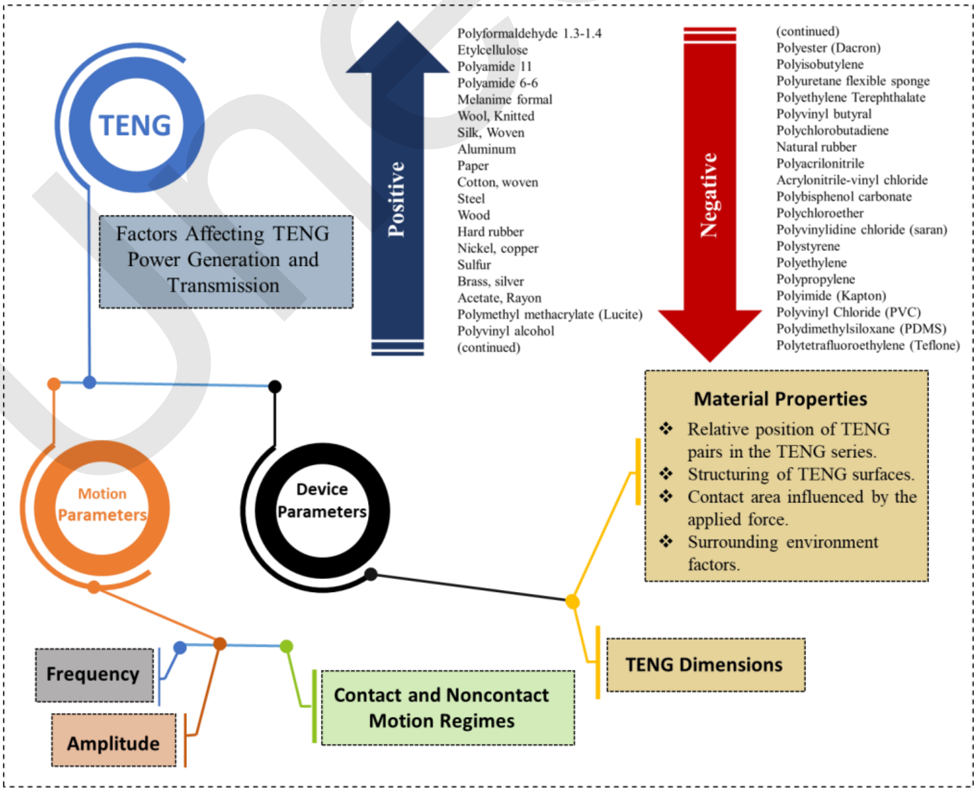

Fig.3. Triboelectric series and factors affecting TENG power generation and transmission (Jiao et al., 2022b)

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 Figure 3. The figure also presents the triboelectric series of commonly utilized materials (Calisal, 1983; Aydoğan et al., 2013; Xi et al., 2017a; Zhao et al., 2018; Liu et al., 2019b; Yang et al., 2019b; 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., 2019b; Nie et al., 2020). Furthermore, Figure 3 lists the various factors that influence the production and transmission of TENG power (Jiao, et al., 2022b).

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 motion 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; Mart ńez-Ayuso et al., 2017; Shao et al., 2020; Ma et al., 2021). 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).

3. Overview of Magnetic Structured Triboelectric Nanogenerators in Coastal Infrastructure

Figures 4 to 8 give an overview of magnetic structured triboelectric nanogenerators in coastal infrastructure, including magnetic spherical triboelectric nanogenerator networks, magnet-assisted triboelectric nanogenerators, magnetic structured triboelectric nanogenerators for bridges, and magnetic multilayer structures based on triboelectric nanogenerators.

3.1 Magnetic Spherical Triboelectric Nanogenerator Networks

The magnetic spherical triboelectric nanogenerator networks depicted in Figures 4 and 5 are utilized for the purpose of energy harvesting and sensing in diverse settings. The schematic representation shown in Figure 4(a) 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). Figure 4(b) 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

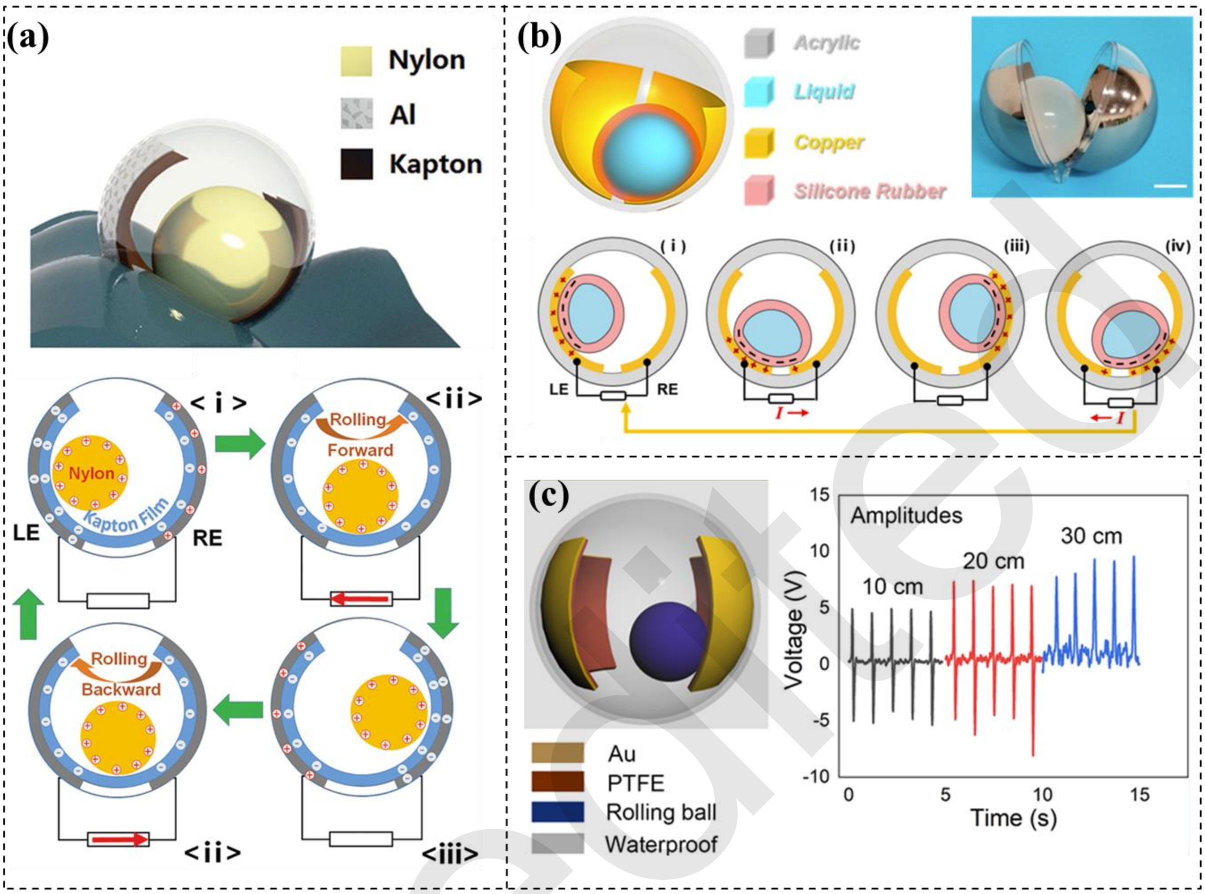

Fig.4. Magnetic Spherical Triboelectric Nanogenerator Networks: (a) Design Structure and basic principle of a RF-TENG (Wang et al., 2015). (b) Structure and working mechanism of a SS-TENG (Cheng, et al., 2019). (c) Illustration of rolling TENGs based on Nano-micro structure for ocean monitoring (Chen, et al., 2021)

up to ten times greater than that of traditional PTFE-based hard-contact designs, due to the considerably enlarged contact area. Cheng, et al. (2019) proposes 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 nano-microstructures in rolling TENGs for ocean monitoring is demonstrated in Figure 4(c). 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).

Figure 5(a) displays the utilization of coupled triboelectric nanogenerator 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 Figure 5(b) 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 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, Figure 5(c) depicts the gyroscope-structured triboelectric nanogenerator (GS-TENG) proposed for the purpose of harvesting multidirectional ocean-wave energy. The inner and

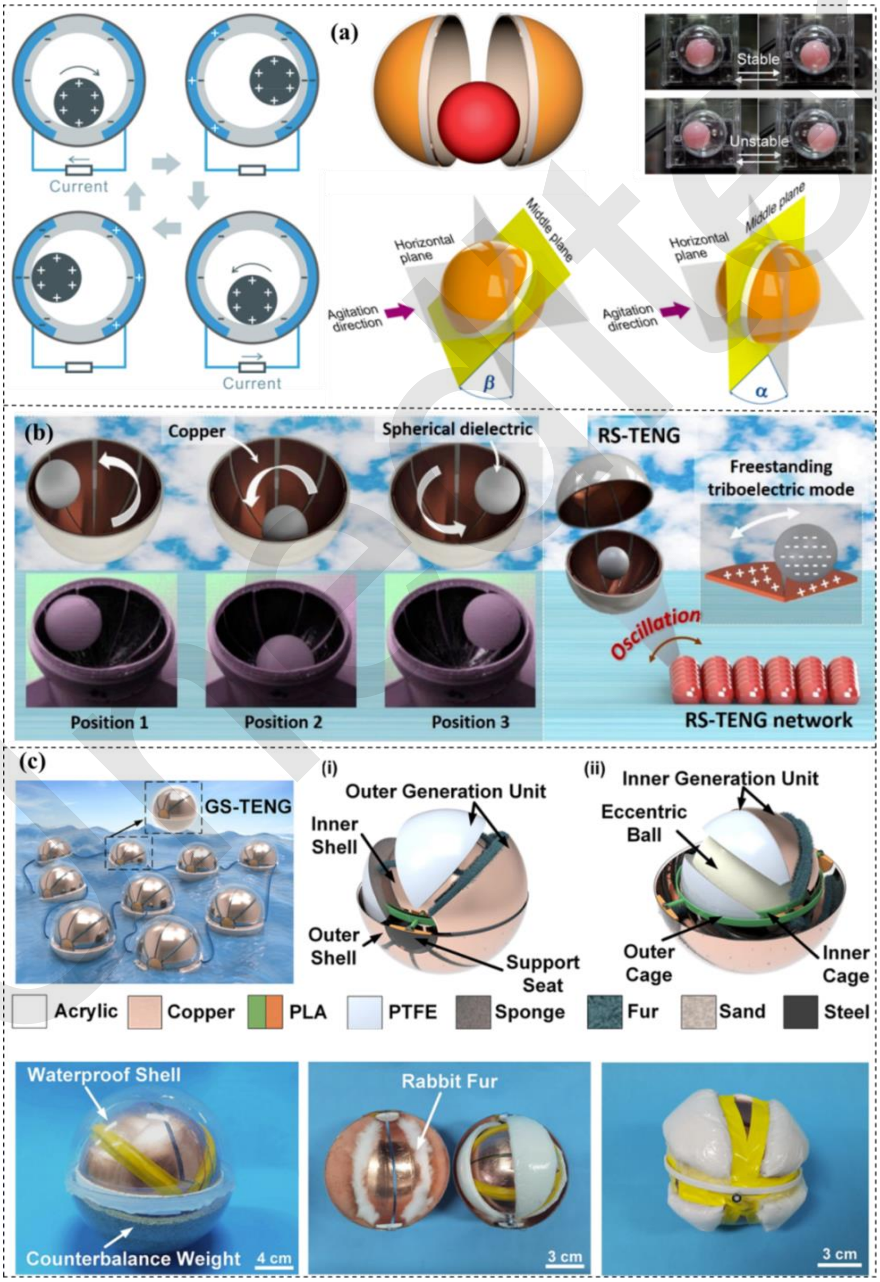

Fig.5. Magnetic Spherical Triboelectric Nanogenerator Networks: (a) Water-wave energy harvesting using coupled triboelectric nanogenerator networks (Xu, et al., 2018). (b) Working principle of a RS-TENG (Wang, et al., 2022). (c) Structural design of a GS-TENG for harvesting multidirectional ocean energy (Gao et al., 2022)

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 Triboelectric Nanogenerator

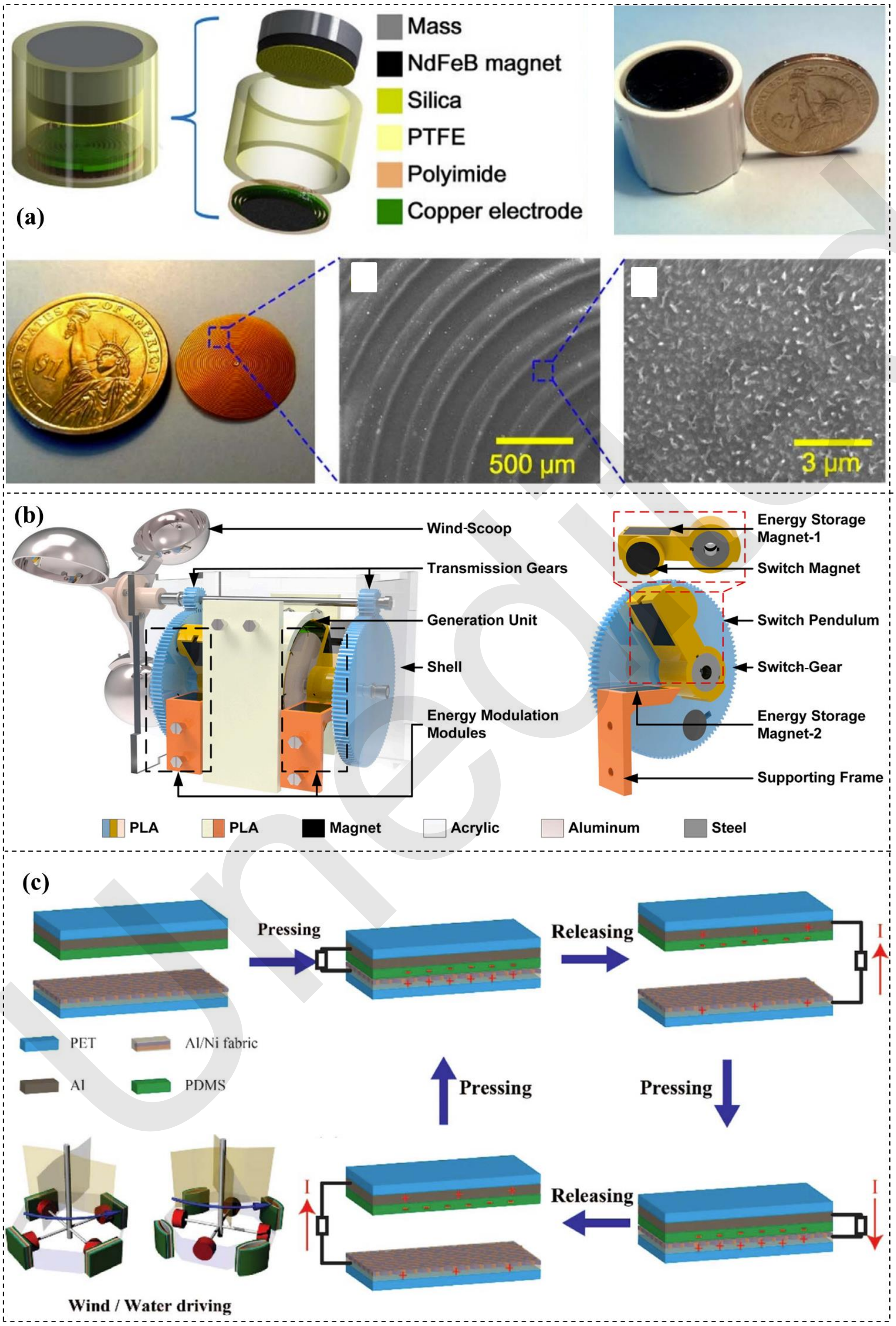

Fig.6. Magnet-Assisted Triboelectric Nanogenerator: (a) Diagram and image of the magnetically assisted TENG as a self-powered sensing system (Han et al., 2014; Zhao et al., 2021). (b) Design principle of a magnetic-switch TENG for energy harvesting (Liu et al., 2021b). (c) Design and fabrication of a magnetic-assisted noncontact TENG (Huang et al., 2016)

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

This section sheds light on magnetic-assisted triboelectric nanogenerators, which present a promising avenue for energy harvesting and sensing in coastal infrastructure. The use of magnetic-assisted TENGs is illustrated in Figure 6(a) 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 Figure 6(b) showcases a TENG that is structured with

Fig.7. Magnetic Structured Triboelectric Nanogenerators for bridges: (a) Working principle of the MC-TENG (Jiao, et al., 2022b). (b) Illustration of application and various scenarios of the MCL-TENG (Jiao, et al., 2022c). (c) Design structure of the ml-TENG as a self-powered sensor (Matin Nazar, et al., 2021a)

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, et al., 2021b). In addition, Figure 6(c) 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 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 Magnetic Structured Triboelectric Nanogenerators for Bridges

Magnetic structured triboelectric nanogenerators, which have been specifically developed for use in bridge applications, are presented in Figure 7. They emphasize the use of magnetic capsulate triboelectric nanogenerators (MC-TENGs) as a means of harvesting energy in the presence of unfavorable mechanical stimuli, as depicted in Figure 7(a). 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 a 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 a MC-TENG is considerably influenced by the structural configuration of the encapsulated TENG (Jiao, et al., 2022b)

.The work also incorporates a novel concept called magnetically circular layers (see Figure 7(b)), 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., 2022c). Finally, it can be observed from Figure 7(c) 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 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 Triboelectric Nanogenerators

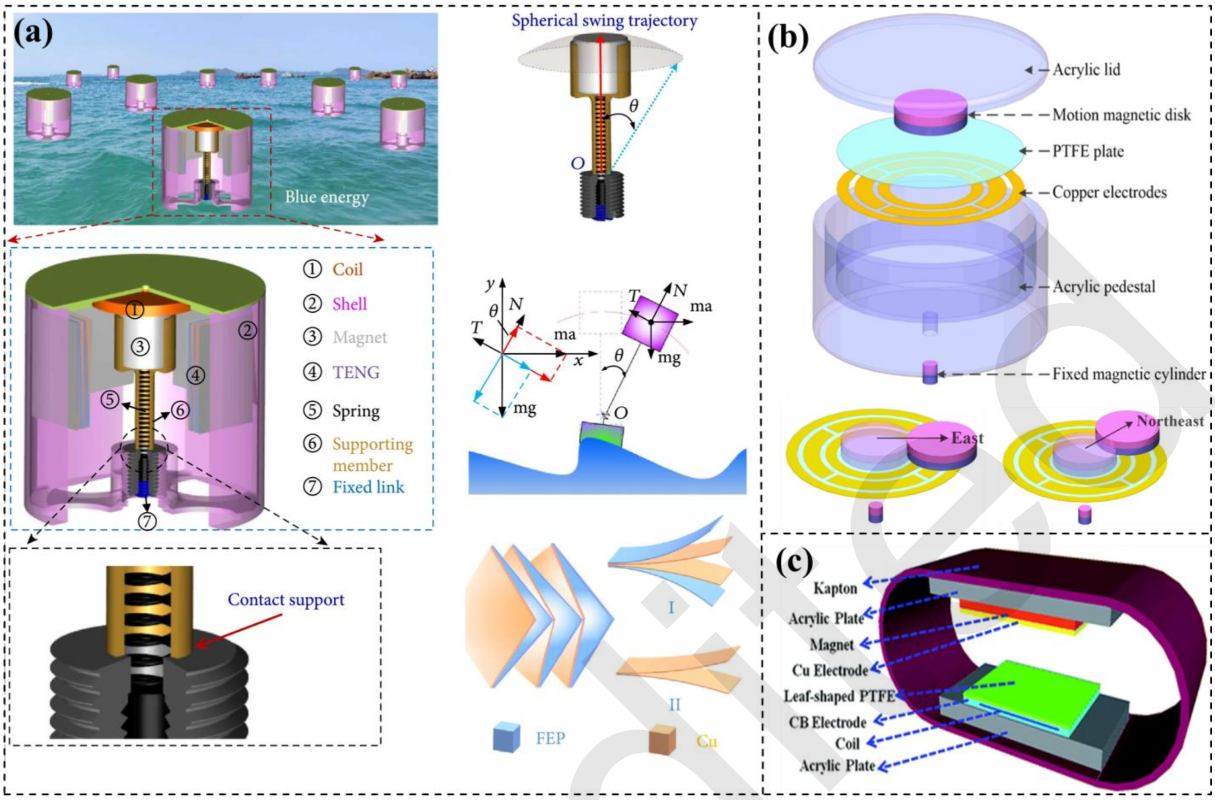

Fig.8. Magnetic Multilayer structure based on Triboelectric Nanogenerators: (a) The working principle of the magnetic triboelectric nanogenerator design (Xie et al., 2021). (b) Structural design of a magnetic self-powered multifunctional motion sensor (Wu et al., 2018). (c) Schematic view of a TENG arc-shaped brace structure for energy harvesting (Huang and Zhu, 2017)

The deployment of magnetic multilayer structured TENGs is shown in Figure 8. Figure 8(a) illustrates a nonresonant hybridized electromagnetic-triboelectric nanogenerator 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 Figure 8(b) 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 (MFMS) 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 (MFMS) 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 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. Figure 8(c) demonstrates a combination of an electromagnetic generator (EMG) and a leaf-shaped TENG made of polytetrafluoroethylene (PTFE). This hybrid system is designed to harvest mechanical energy and is supported by an arc-shaped brace structure. The electromagnetic generator (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 Magnetic Structured TENGs in Comparison to Conventional TENGs

Figure 9 shows a comparative analysis of magnetic structured TENGs and conventional TENGs. Magnetic structured TENGs 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. Magnetic structured TENGs may also exhibit reduced

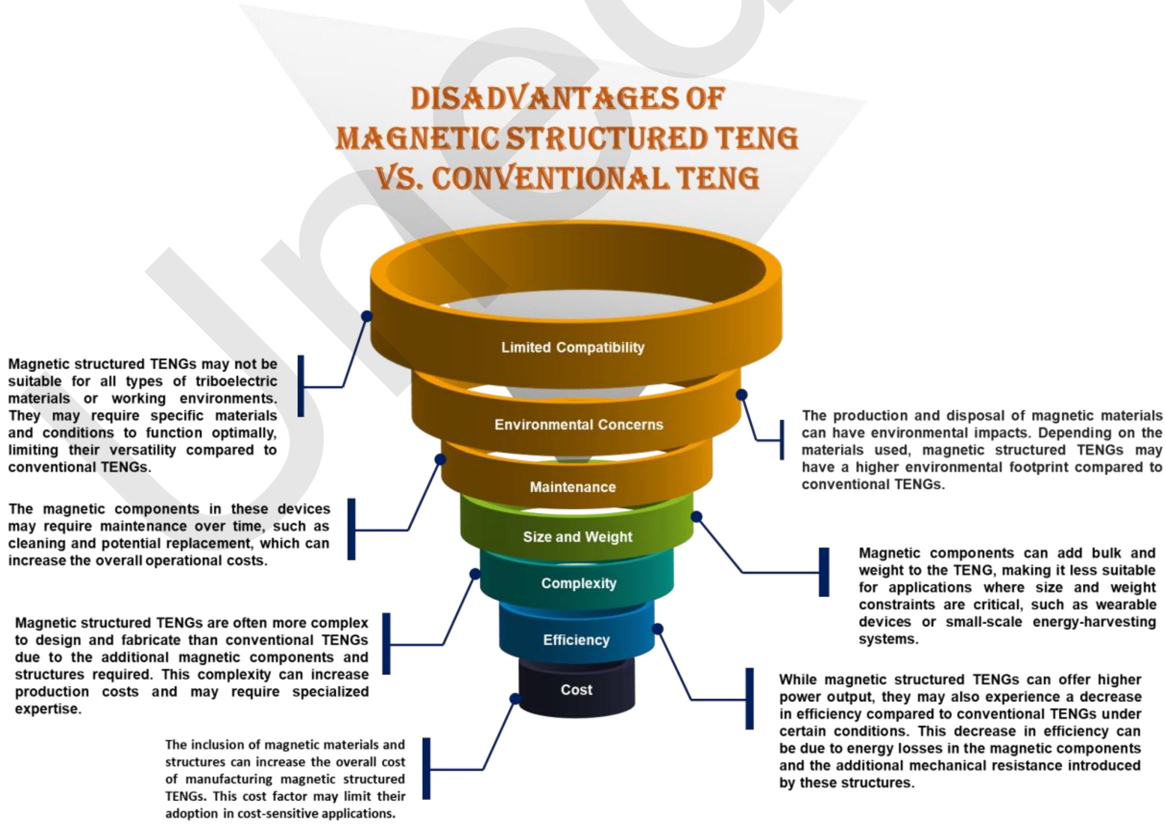

Fig.9. Assessing Magnetic Structured TENGs in Comparison to Conventional TENGs

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, magnetic structured TENGs 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 lead to a higher environmental footprint for magnetic structured TENGs compared to conventional TENGs, adding consideration in their selection. Ultimately, the choice between magnetic structured TENGs and conventional TENGs hinges on the specific application and its requirements. Magnetic structured TENGs 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 magnetic structured TENGs for energy harvesting and sensing in coastal bridge infrastructure

Figure 10 presents a comprehensive view of the challenges, perspectives, and insights surrounding magnetic structured TENGs 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

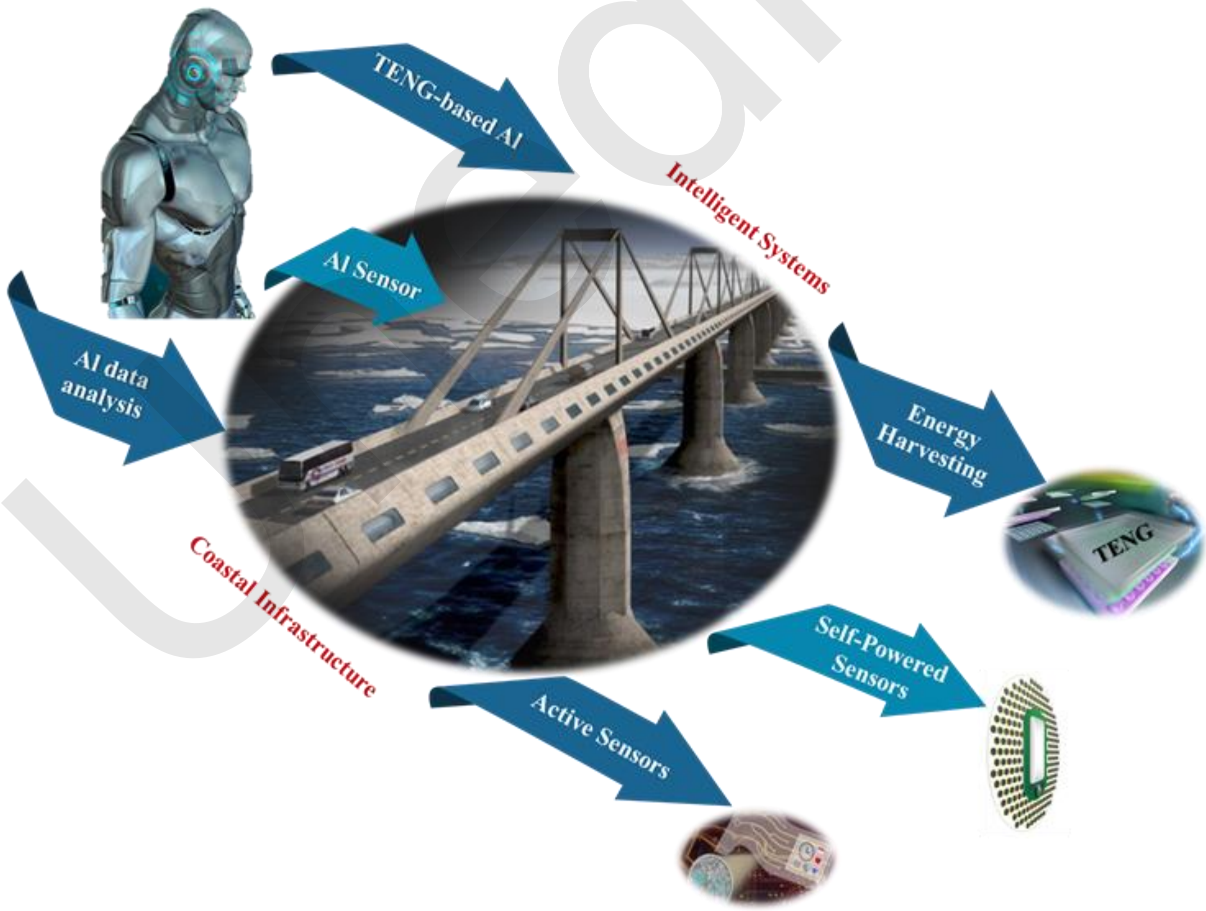

Fig.10. Challenges, perspective, and insight for magnetic structured TENGS for energy harvesting and sensing in coastal infrastructure

challenges that warrant attention. Notably, the durability and sustainability of magnetic structured TENGs 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 magnetic structured TENG 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 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 materials approaches (He and Huang, 2017; Dharmasena et al., 2018; He et al., 2023). Table 1 shows a summary of magnetic structured triboelectric nanogenerators as devices for energy harvesting and sensing in coastal infrastructure. While MSTNGs 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 MSTNGs in diverse applications, from portable electronics to large-scale energy generation.

5. Conclusions

In conclusion, magnetic structured triboelectric nanogenerators (MSTNGs) 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 MSTNGs, from the fundamental physics modes of TENGs to the various types of MSTNGs and their applications in coastal infrastructure. The review of magnetic spherical TENG networks, magnet-assisted TENGs, magnetic structured TENGs for bridges, and magnetic multilayer 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 MSTNGs 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 MSTNGs in the future.

Conflict of interest

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

Table 1. Summary of magnetic structured triboelectric nanogenerators as devices for energy harvesting and sensing in coastal infrastructure.

Structure	Year	Authors	Applications	Max-open circuit voltage (V)	Max-short circuit current	Surface power density	Power density and power
Magnetic Spherical Triboelectric Nanogenerator Networks	2015	Wang, et al. (2015)	Harvesting low-frequency water-wave energy	-	1 μA	10 mW.A	-
	2019	Cheng, et al. (2019)	Harvesting of water-wave energy	1600	5 μA	-	10 mW
	2021	Chen, et al. (2021)	Ocean environmental monitoring	25.1	7.3 μA	-	-
	2018	Xu, et al. (2018)	Efficient water-wave energy harvesting	1780	34.5 μA	-	5.93 mW
	2022	Wang, et al. (2022)	Energy harvesting and ocean monitoring	12,75	-	-	455 nW
	2022	Gao, et al. (2022)	Harvesting multidirectional ocean-wave energy	730	3.2 μA	-	-
Magnet-Assisted Triboelectric Nanogenerator	2014	Han, et al. (2014)	(Wang, et al., 2015)Self-powered visualized omnidirectional tilt-sensing system	90	12.66 mA	441.1 mW/m2	204 μW
	2021	Liu, et al. (2021b)	Harvesting of wind energy	410	18 μA		4.82 mW
	2016	(Huang, et al., 2016)	Wind-energy and blue-energy harvesting	300	30 μA		3 mW
Magnetic Structured TENGs for bridges	2022	Jiao, et al. (2022b)	Harvesting low frequency water-wave energy	4	-	-	400 nW
	2022	Jiao, et al. (2022c)	Velocity sensing and damage detection	5.1	-	-	9 μW
	2021	Matin Nazar, et al. (2021a)	Energy harvesting and active sensing	4	-	-	340 μW
Magnetic Multilayer structure based on Triboelectric Nanogenerators	2021	Xie, et al. (2021)	Irregular and ultralow-frequency blue-energy harvesting	190	12.4 μA	-	470 μW
	2018	(Wu, et al., 2018)	Multifunctional motion sensing	1.5	-	-	-
	2017	(Huang and Zhu, 2017)	Energy harvesting	0.25	-	80 μW/Cm2	-

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