Progress in Natural Science: Materials International 34 (2024) 1109–1131

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Progress in Natural Science: Materials International

journal homepage: www.elsevier.com/locate/pnsmi

Progress on wave energy harvesting by adaptively designed triboelectric nanogenerators for marine science

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ARTICLE INFO

Keywords:
Triboelectric nanogenerator
Wave energy
Adaptive structure design
Environmental adaptability
Energy management circuit

ABSTRACT

Wave energy, as a rich renewable resource, is essential to advancing the green transformation of energy structures and sustainable development. However, the complexity and variability of real wave environments pose significant challenges to the effective harvesting of energy, especially in the case of low-frequency energy. Therefore, conducting research on adaptive technologies becomes key to ensuring the efficient and stable operation of wave energy conversion devices in varying conditions. This review methodically outlines the recent research progress on the adaptive structure design, environmental adaptability, and energy management circuit of wave energy triboelectric nanogenerator (TENG). It explores the challenges present in actual marine environments and their resolution strategies, emphasizing the importance of adaptive research in advancing the development and application of wave energy technologies. This review aims to offer foundational theoretical knowledge and actionable guidance to advance future studies and the practical deployment of wave energy harvesting.

1. Introduction

Wave energy, as a rich and renewable marine resource, is a vital component of the green transformation of energy infrastructure and the advancement of sustainable development [1,2]. Firstly, wave energy is abundant and widely distributed, especially in coastal areas, offering a significant potential energy source to address energy shortages [3,4]. Secondly, the conversion and utilization of wave energy do not produce greenhouse gas emissions, contributing to the alleviation of environmental pressures and climate change issues associated with the combustion of fossil fuels [5,6]. However, harvesting low-frequency wave energy presents significant technical challenges. Low-frequency waves are characterized by long periods and relatively low energy density, necessitating wave energy harvesting devices to possess efficient energy conversion mechanisms and sufficient adaptability to achieve stable energy output under low energy input conditions [7–9]. Therefore, the development of harvesting technologies suitable to low-frequency wave that are dependable and efficient is essential to the widespread use of wave energy.

In 2012, Professor Zhong Lin Wang's innovative research achievement, triboelectric nanogenerator (TENG, also known as Wang generator), based on the coupling of triboelectrification and electrostatic induction, pioneered a new realm in energy conversion technology [10–18]. Unlike traditional electromagnetic generators, TENG generates displacement current by establishing an electric field to drive electron movement, showcasing unique advantages in harvesting low-frequency environmental energy [19,20]. This feature makes TENG exceptionally suitable for energy harvesting in certain marine areas with low frequency [21,22], thereby efficiently tackling the issue of energizing low-power sensors in oceanic contexts and offering innovative strategies for energy reliability in areas like marine hydrological observation and the maritime Internet of Things [23–26]. However, applying TENG in real marine environments faces significant challenges. The complexity of the marine environment is primarily manifested in the disorderliness of wave energy-the uncertainty of amplitude and direction, as well as corrosion and output inhibition issues caused by high humidity, varying pH values,

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https://doi.org/10.1016/j.pnsc.2024.09.007
Received 8 July 2024; Received in revised form 4 September 2024; Accepted 28 September 2024
Available online 26 November 2024

and high salinity [27–29]. These factors collectively pose a test to the stable operation and long-term durability of TENG [30–33]. Therefore, to maximize the capabilities of TENG for harvesting marine energy, further optimization of its materials, design, and structure is required to enhance its adaptability to changes in the marine environment and corrosion resistance, ensuring efficient and stable energy conversion performance in the face of severe marine environmental challenges [34–36].

In the field of electromagnetic generation technology, facing the unstable and variable marine energy source of wave energy, power generation technology is gradually evolving towards higher adaptability, aiming to utilize wave energy more efficiently. To achieve this goal, technological innovations include the optimization design of floating structures [37], the integration of intelligent control systems [38], and the construction of hybrid energy systems [39,40] et al. Among these technologies, the adoption of electronic control systems for the adaptive adjustment of power generation devices has become a mainstream strategy, especially widely applied in large-scale blade wind turbines. However, considering that the TENG is a small device focused on harvesting high-entropy energy, the use of active control systems may not be entirely suitable [41]. Therefore, exploring passive adaptive mechanisms is particularly important for TENG. The design of passive adaptive devices such as self-regulating mechanical structures [42–47], multi-directional energy harvesting devices [48–52], damping frequency enhancement mechanisms [53–57], and motion transformation mechanisms [58–63] can not only improve the energy harvesting efficiency of TENG in complex marine environments but also enhance its stability and reliability under variable conditions. The exploration of such passive adaptive mechanisms provides new insights for deploying TENG in the field of marine energy, potentially fostering the optimized harnessing of wave energy and catalyzing the continued evolution of TENG. Finite element simulation analysis, as an efficient tool for design optimization and evaluation, is essential to the design of floating structures and biomimetic research for power generation devices. Through precise simulation of the complex marine environment and its impact on floating structures [64–66], this technology ensures that the designed structures not only have good stability but also meet performance requirements in dynamic response. Simultaneously, in the field of biomimetics, finite element simulation analysis deepens the understanding of the structural features of organisms in nature, providing scientific guidance for innovative designs based on the principle of drag reduction and efficiency enhancement [67–70]. Particularly, the intrinsic adaptability of TENG paves the way for innovative research avenues in crafting versatile energy-generating devices tailored for aquatic settings. Such flexible devices can fully utilize their bendable and stretchable structural features to flexibly adapt to the dynamic changes of waves and the complexity of the marine environment. Furthermore, the effective working capability of flexible TENG under different wave energy levels makes it an ideal choice for harvesting low-frequency wave energy efficiently [71–74]. Therefore, combining finite element simulation analysis for in-depth structural design and performance enhancement of flexible TENG will greatly promote the efficient harnessing of marine energy and sustainable development.

Furthermore, the output performance of TENG is vulnerable to variations in environmental temperature and humidity, with high salinity conditions further posing a risk of substantial corrosion to both the power generation units and their enclosures. These factors collectively present a formidable challenge to the consistent performance of TENG. Therefore, the selection of materials capable of effectively mitigating corrosion issues or adopting corresponding chemical treatment methods becomes particularly crucial [75]. Thanks to the capacitive characteristics of TENGs, the application of charge pump technology not only can effectively enhance their performance but researchers have also discovered that this technology can effectively counteract the negative impact of humidity on TENG [76–78]. Given the potential energy output fluctuations caused by environmental instability, implementing a power management circuit to convert disordered energy into constant output becomes a key strategy for enhancing system stability. The power management circuit [79–83], by integrating energy collection, storage, and regulation functions, not only ensures the stability of the electrical output but also improves the overall efficiency and reliability of the system, effectively mitigating the impact of environmental changes on output stability. The research classification for the aforementioned issues is illustrated in Fig. 1.

In this review, acknowledging the intricate and fluctuating nature of the marine environment, the significance of research into the environmental adaptability, adaptive structure design, and output performance of wave energy TENG is underscored as being of paramount importance. These factors directly determine the potential application of TENGs in marine settings. Although extensive research on the adaptability of wave energy TENGs has been conducted in recent years, a systematic summary and generalization of this important topic are still lacking. Therefore, this article comprehensively organizes and categorizes this field from several aspects, including the fundamental working principles of TENG, key characteristics, and the current development state. Initially, the article introduces the working mechanism of TENGs and their five basic modes, followed by a detailed explanation of the key characteristics for achieving adaptability in wave energy TENGs. Subsequently, the article divides the methods of achieving TENG adaptability into four major categories and provides an in-depth analysis and discussion of each category. Through this exhaustive review, the article revisits the latest progress in adaptive structure design, operational condition adaptability, environmental adaptability, and stable output of wave energy TENGs. Ultimately, the article summarizes the existing problems and challenges in achieving adaptability for wave energy TENGs and offers insights and suggestions for future development directions. Drawing on the adaptive research approaches of some electromagnetic power generation devices in harvesting wave energy, combined with the current development status of wave energy TENGs, this review endeavors to furnish both theoretical foundations and pragmatic advice for deploying wave energy TENG, aspiring to enhance their practical implementation and advancement in the realm of wave energy harnessing.

2. Fundamental principle and working mechanism

2.1. The fundamental working mode of TENG

In 2012, TENG was an innovative energy conversion technology proposed by Professor Zhong Lin Wang, which is based on the coupling of triboelectrification and electrostatic induction. Triboelectrification refers to the intriguing phenomenon wherein electrons migrate from materials with a lower propensity for electron attraction to those exhibiting a higher electron affinity upon the occurrence of contact, resulting in surface charge separation and potential difference [87,88]. The relative motion of these charged materials induces a change in the electric field between them, which induces a reconfiguration of charge distribution across the electrodes of the TENG. This internal structure change generates Maxwell's displacement current, thus realizing the conversion of mechanical energy and electrical energy. The process can efficiently harvest minute mechanical energies and stably output electrical energy in ambient environments, demonstrating TENG's high adaptability and potential application value in energy harvesting and conversion.

Through continuous exploration and optimization by researchers, TENG has evolved into five fundamental working modes [89], categorized mainly into normal and tangential movements based on their motion forms, as shown in Fig. 2. Normal movement includes the Contact-Separation Mode [90,91] and the Single-Electrode Mode [92]. In the Contact-Separation Mode, an electric field is formed between two parallel plates with dielectric layers carrying different charges through contact and separation, inducing electron exchange on the electrodes to convert energy. The Single-Electrode Mode simplifies this by generating electricity through the interaction between a single electrode and a dielectric layer. These modes effectively utilize the electric field changes

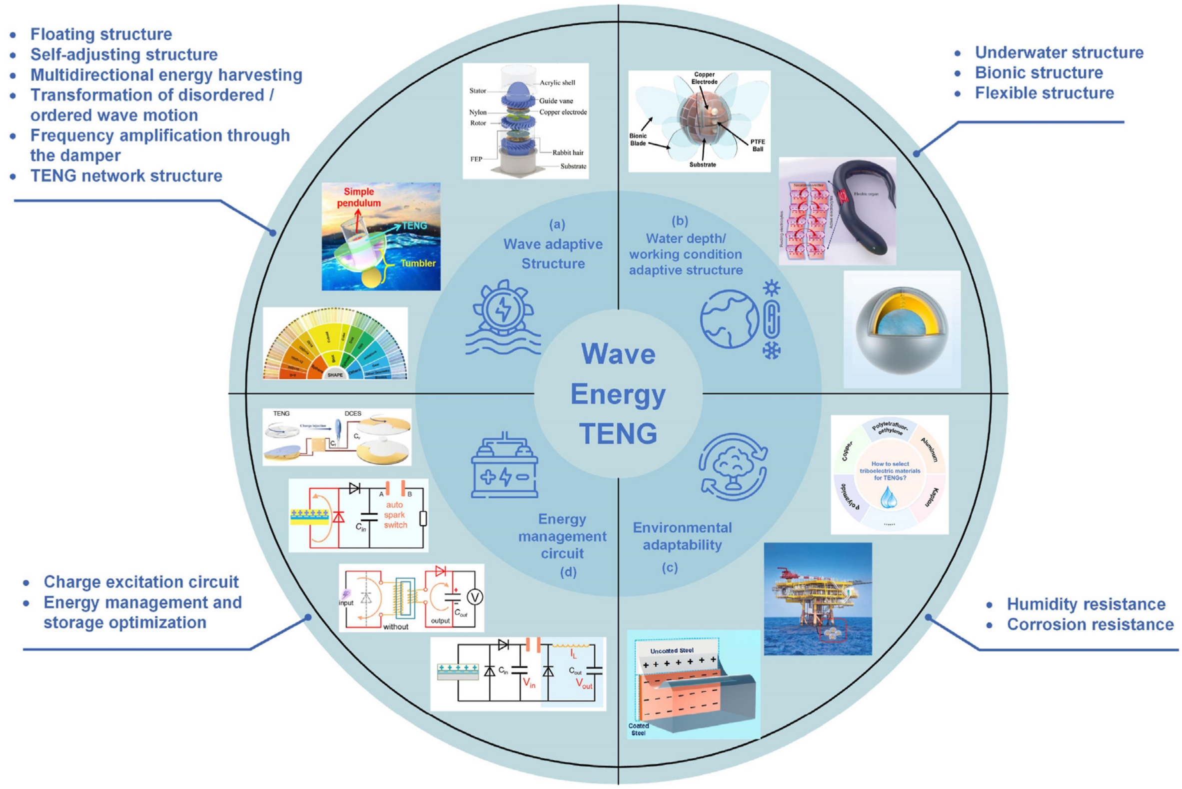

Fig. 1. Classification of adaptive wave energy TENG. (a) Wave adaptive structure [47,63,65]. (b) Water depth/working condition adaptive structure [70,71,84]. (c) Environmental adaptability [75,85,86]. (d) Energy management circuit [78,82,83].

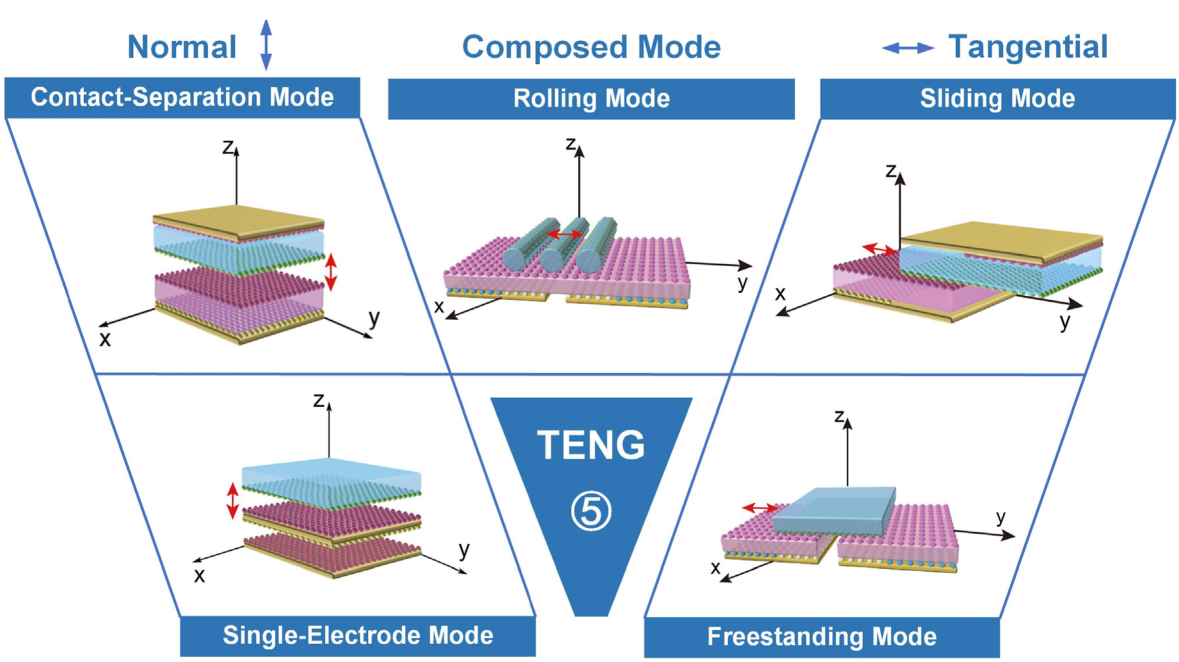

Fig. 2. Four fundamental modes and a composed mode of TENG [89,91,94].

produced by normal movement for energy conversion. In contrast, tangential movement TENGs, including the Sliding Mode [93,94] and the Freestanding Mode [95], feature electric field formation between non-contact parts of dielectric layers to drive electron exchange. The Sliding Mode achieves energy conversion through the relative sliding of two dielectric layers, while the Freestanding Mode generates an electric field through tangential movement between independent dielectric layers. Building on these four modes, researchers have innovatively proposed a composite mode - the Rolling Mode [96]. Its working principle involves electron exchange induced by the movement of a roller over a dielectric film, combining features of both normal and tangential movements to realize the improvement of energy conversion efficiency.

Five modes of TENG significantly contribute to harvesting high-entropy environmental energies, offering new solutions for the efficient use and sustainable development of environmental energy. With ongoing technological advancements and expanding application fields, TENG is anticipated to assume a progressively pivotal role within the domains of energy science and engineering technology.

2.2. The theory of TENG

The Maxwell equations form the foundation of electromagnetic theory, delineating the relationships among electric fields, magnetic fields, charges, and currents. Within the contexts of nanoscale dimensions and triboelectric effects, Professor Zhong Lin Wang has expanded these equations to more accurately depict the charge transfer and electric field variations occurring [17,97–99] during frictional processes. The specifics are as follows in Fig. 3.

Firstly, Gauss's law for electric fields states that the divergence of the electric displacement field equals the charge density:

$$\nabla \cdot \boldsymbol{D}' = \rho_f - \nabla \cdot \boldsymbol{P}_S \tag{1}$$

where $\boldsymbol{D}'$ is the electric displacement field, ρ_f is the charge density, and $\boldsymbol{P}_s$ is the polarization density term in the displacement vector.

Secondly, Gauss's law for magnetism asserts the nonexistence of magnetic monopoles, indicating that magnetic field lines are closed.

$$\nabla \cdot \boldsymbol{B} = 0 \tag{2}$$

where $\boldsymbol{B}$ is the magnetic flux density.

Next, Faraday's law of electromagnetic induction describes how a time-varying magnetic field produces an electric field:

$$\nabla \times \boldsymbol{E} = -\left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla\right)\boldsymbol{B} \tag{3}$$

where $\boldsymbol{E}$ is the electric field induced by the time-varying magnetic field, and $\boldsymbol{v}$ is the velocity.

Lastly, Ampère's law, inclusive of Maxwell's correction, describes how electric currents and changing electric fields together generate a magnetic field.

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}_f + \left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla\right)(\boldsymbol{P}_S + \boldsymbol{D}') \tag{4}$$

where $\boldsymbol{H}$ is magnetic field intensity, and $\boldsymbol{J}_f$ is the local free electric current density.

When two materials of opposite polarities contact and subsequently separate, their interface generates equal but opposite surface charges during the separation process. This interaction forms a substantial amount of electric dipoles at the material interface, leading to significant polarization intensity. As the substrates of the two materials move relative to each other, this polarization intensity varies over time. Such variations can induce the generation and conduction of electric currents. This phenomenon is crucial for the dynamic response and energy conversion processes in electronic devices and is especially pivotal for the understanding and design of sensors and energy harvesters based on contact-electrification effects.

2.3. Energy conversion mechanism of wave energy TENG

The operation of a TENG in harnessing wave energy and further transforming it into electrical energy is indeed a complex and multifaceted process, primarily unfolding through the following critical phases, as illustrated in Fig. 4.

(1) Primary Energy Conversion

In this stage, wave energy is initially transformed into mechanical energy. This process is achieved by transforming the kinetic energy in the wave setting into the mechanical energy of moving body, such as buoys or pendulums. For example, a buoy oscillates vertically in sync with the wave motion, converting the cyclic kinetic energy of waves into mechanical motion energy. This step facilitates the primary conversion of wave energy to mechanical energy, laying the foundation for subsequent energy conversion.

(2) Power Take-Off (PTO)

Commonly, a direct drive of the TENG is employed to improve energy conversion efficiency. This approach is favored for its simplicity and high reliability. However, in the face of irregular wave conditions, the direct output of electrical energy often appears unstable and chaotic. To overcome this challenge, researchers have introduced PTO devices, which indirectly drive the generator through mechanical transmission systems or turbines. PTO not only effectively regulates the output signal to adapt to the fluctuations of wave energy but also enhances the adaptability to wave energy and the overall energy conversion efficiency.

(3) Energy Output and Management

Ultimately, the electrical energy harvested by the TENG must undergo meticulous regulation through an energy management circuit to ensure it aligns with the specific demands of electrical energy requirements. The batteries or capacitors are employed to store the regulated energy and then, supply power to low-power consumption sensors. The utilization of the energy management circuit is crucial as it not only ensures the stability and availability of energy output but also optimizes the efficiency of energy storage and distribution, thereby maximizing the overall performance generated by wave energy TENG.

In conclusion, the working mechanism of the wave energy TENG encompasses the entire process from the primary conversion of wave energy to mechanical energy, to the efficient transformation and management of electrical energy. The real marine environment, influenced

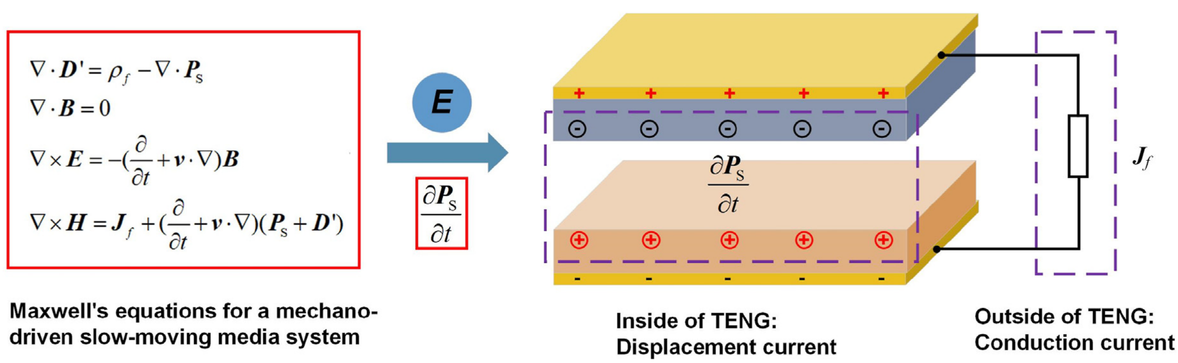

Fig. 3. The expanded Maxwell's equations and its application on TENG modeling [17,98].

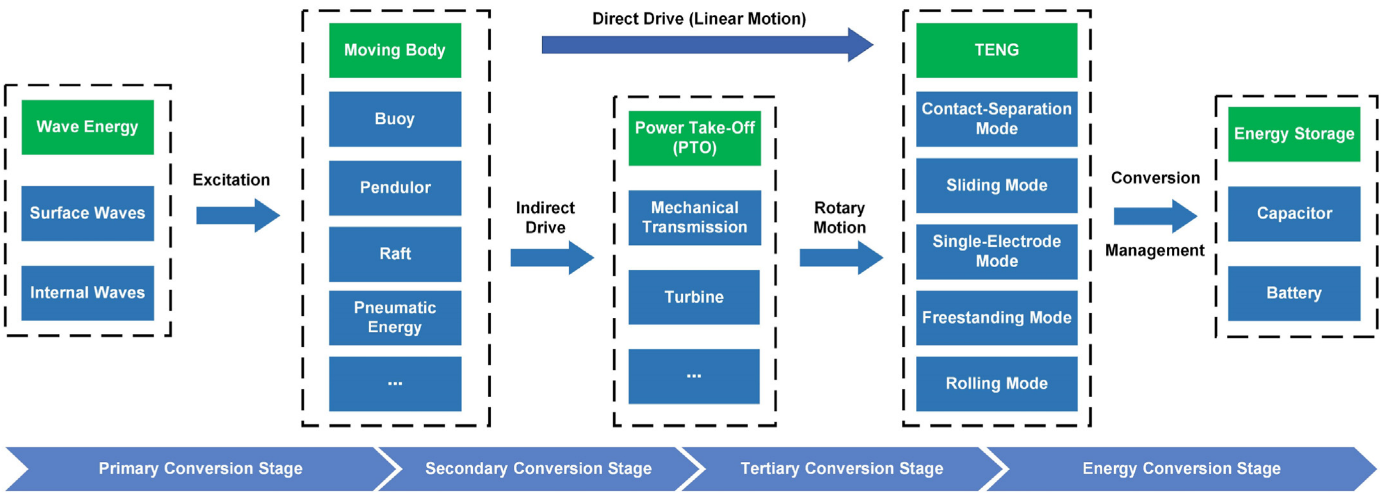

Fig. 4. The working mechanism of wave energy TENG.

by physical, chemical, and meteorological characteristics, exhibits significant instability [100,101]. Physically, the amplitude, frequency, and direction of waves are affected by factors such as wind force, terrain, and tides, leading to highly dynamic changes and unpredictability in wave behavior. Chemically, fluctuations in parameters such as the salinity, dissolved oxygen, and pH value of seawater also impact the wave environment, further increasing its complexity. Moreover, meteorological conditions such as changes in wind speed, air pressure, temperature, and humidity greatly affect the behavior and characteristics of waves. The combined effects of these factors render the wave environment notably unstable.

In such an unstable and constantly changing wave environment, the research on adaptive TENG holds significant importance [102,103]. As analyzed above, adaptive TENGs, through intelligent materials and PTO design, can dynamically adjust their working state to adapt to environmental changes, effectively harvesting energy in the highly fluctuating marine environment. This not only improves the efficiency and stability of energy conversion but also provides a novel pathway for the sustainable development and utilization of wave energy, helping to reduce dependence on traditional energy sources while promoting marine environmental protection and climate change mitigation. Therefore, the research on adaptive TENGs has profound implications for advancing marine energy technology and achieving growth in the blue economy.

2.4. Key features of adaptive design requirements

The key characteristics for meeting the adaptability design requirements of TENG can be summarized from core aspects as follows.

(1) Wave spectrum adaptability

Wave spectrum adaptability refers to the distribution of different wavelengths and frequencies in wave environments. The adaptability of wave energy converters must cover a wide range of wave spectra to effectively harvest energy under varying wavelength and frequency conditions, as seen in flexible generators. For devices with poor spectrum adaptability, effective energy generation is only possible under specific wave conditions.

(2) Response mechanism

TENG is capable of automatically adjusting its structure or functionality based on changes in the external environment and internal state, such as wave dynamics. This includes, but is not limited to, changes in structural form, optimization of working parameters, and switching of operational modes, to effectively respond to variations in wave energy.

(3) Environmental adaptation

The design of TENG takes into consideration the adaptation to extreme environmental factors, especially humidity, pH value, and salinity resistance, ensuring long-term stable operation in harsh marine environments. This requires the use of corrosion-resistant materials and protective measures, as well as special surface treatment technologies.

(4) Stable output

Under varying environmental conditions, TENG can provide a stable output of electrical energy. This relies on the efficient design of energy management circuits, including humidity-resistant circuits and intelligent energy management systems, to adapt to environmental changes and meet the demands for a constant and stable power supply.

Through the integration and optimization of these characteristics, TENG not only effectively harvests energy in complex and variable environments but also ensures energy conversion efficiency and systematic long-term stability, offering a solution with high adaptability and reliability for the advancement and utilization of marine energy.

3. Research status of adaptability of TENG

Regarding structural design, the focus is on adaptability to wave environments. In this section, based on the region of wave propagation, waves are classified into surface waves and internal waves. Section "3.1 Research on wave adaptive structure", primarily addresses the energy harvesting of surface waves, while Section "3.2 Research on water depth/working condition adaptive structures" focuses on the energy harvesting of internal waves.

3.1. Research on wave adaptive structure

The various sections primarily stem from the classification based on the TENG structure and the motion characteristics of the waves. The specific content is as follows: Firstly, from the perspective of structural adaptability of TENGs, Sections "3.1.1 Floating structure" and "3.1.2 Self-adjusting structure" discuss the adaptability of the external casing and internal mechanical structures to wave environments. Next, considering the characteristics of wave motion, waves exhibit randomness in both direction and frequency. Sections "3.1.3 Multidirectional energy harvesting" and "3.1.4 Transformation of disordered/ordered wave motion" address these aspects by focusing on harvesting energy from multiple directions and converting disordered energy into useable forms. Section "3.1.5 Frequency amplification through the damper" discusses the conversion of low-frequency motion into high-frequency motion. Finally, Section "3.1.6 TENG network structure" aims at the broad-scale exploitation and utilization of wave energy resources through the networking of TENG systems.

3.1.1. Floating structure

Xu et al. [65] proposed a floating TENG and conducted experimental studies on the energy transition between the floating body and wave, as shown in Fig. 5(a). Using specific dynamic analysis methods, the raw data were calculated to obtain the frequency distribution and eigenvalues of acceleration. By comparing the frequency distribution curves and total acceleration, the characteristics of different structures were identified. Due to the sharp edges and non-streamlined surfaces of the cubic shell, its wave absorption capacity is the highest. The capacity responding water wave of the sphere shuck is related to wave strength in a positive direction, shuck diameter, and height of the center of gravity, and it depicts that the capacity responding to water first decreases and then slightly increases with the increase of weight. Subsequently, Xu et al. [66] expanded the scope of the research to explore the influence of parameters of the floating TENG (F-TENG), the barycenter, weight, size, shape, rollers, and elasticity, which are displayed in Fig. 5(b). Utilizing an infrared optical harvesting system, their movement was monitored. General models controlling F-TENG change were derived through dynamic calculations, statistical theories, and ANSYS dynamic analysis. The results indicated that appropriately raising the barycenter, increasing weight, and changing the shape from ball to cube enhances vertical displacement, horizontal displacement, vertical force, horizontal force, and kinetic energy. However, gradually increasing weight, reducing size, and lowering the barycenter significantly diminishes their ability to rotate and oscillate, leading to a marked decrease in torsional torque, angular acceleration, and rotational energy.

Compared with the structural parameters, the topological form of the structure also has a certain influence on the floating body. Tan et al. proposed an oval symmetric TENG with an elliptic cylindrical structure (EC-TENG) [64] for the efficient harvesting of wave energy, as depicted in Fig. 5(c). Benefiting from the elliptic cylindrical structure, the EC-TENG exhibits high sensitivity and stability under small agitation excitations. The symmetric structure makes the equipment steady in performance at an inverted state. Additionally, in experiments conducted in a water environment, the EC-TENG was able to directly drive 400 LEDs, charge capacitors, and power a small counter. A water-line monitoring system built by EC-TENG was constructed, effectively monitoring water levels and providing real-time alarms.

3.1.2. Self-adjusting structure

Yang et al. [45] developed a TENG featuring a gravity-guided structure, adept at harvesting the kinetic potential of wave energy, which is vividly depicted in Fig. 6(a). Barycenter self-adapting construction realizes the conversion of wave energy, rotation mechanical energy, and electrical energy. In the simulated irregular waters environment, TENG demonstrated significant output performance, delivering a peak power of 0.1 mW. Additionally, the wireless temperature transmission system, entirely driven by the TENG, was developed. This system monitors temperature and achieves ocean forewarning. Yang et al. [46] designed a TENG for efficiently harvesting randomly distributed high-entropy ocean energy, displayed in Fig. 6(b). The self-regulated structure enhances oscillation frequency and resonance effects, thereby improving electrical output performance. Additionally, the output of V_{oc}, I_{sc}, and Q_{sc} increased by a factor of 5.8, 4, and 3.7. Moreover, a wireless temperature system is driven by the SSR-TENG. Zhang et al. [47] crafted an active resonance TENG (AR-TENG), specifically designed to optimize the conversion ability of wave energy, whose innovative design is elegantly showcased in Fig. 6(c), First, the AR-TENG relies on the omnidirectional pendulum and tumbler structures to harvest the kinetic energy in waves setting. Whereafter, pendulum and tumbler elements, are adept at extracting energy from waves across a spectrum of frequencies. Additionally, the

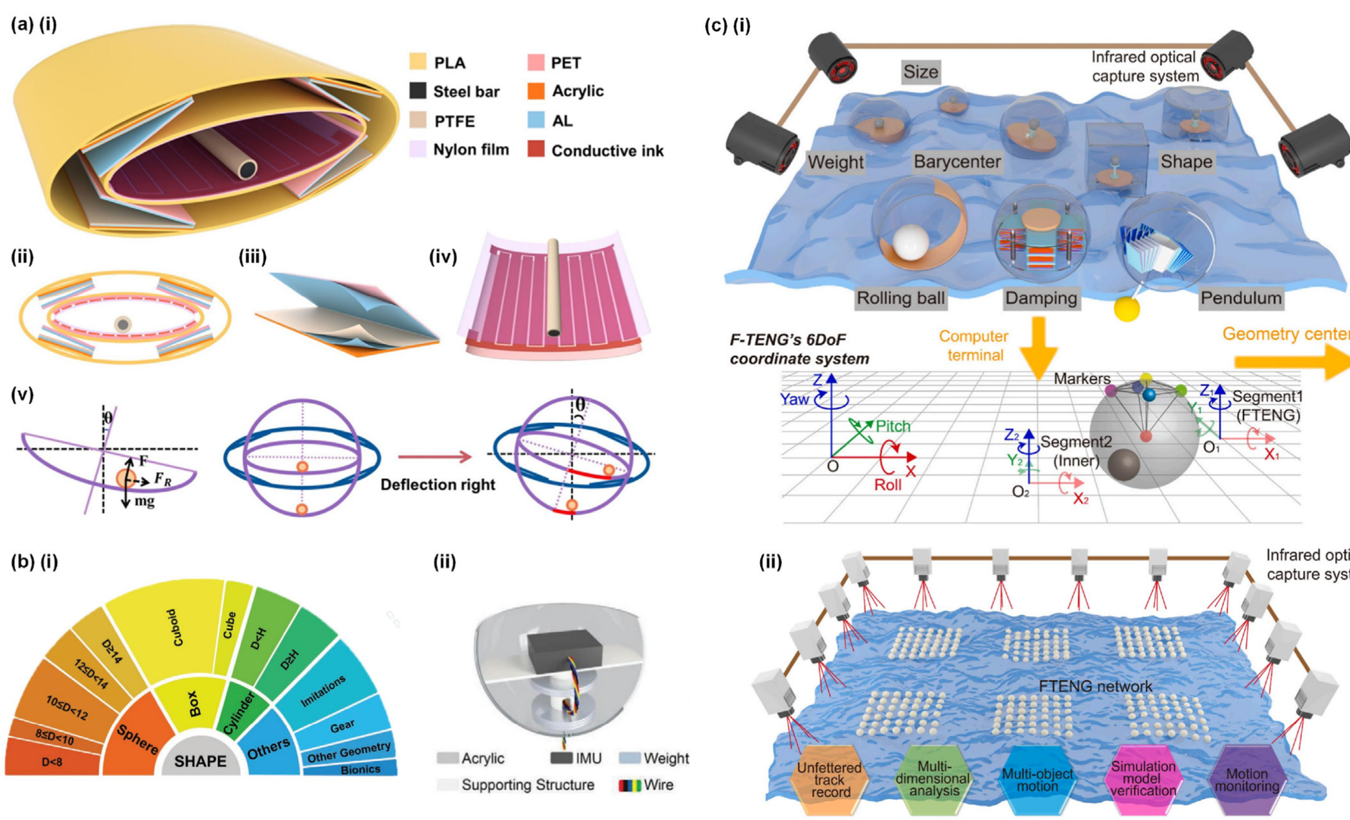

Fig. 5. Study of floating structure. (a) Floating body shape [64]. (b) Dynamic parameters of the floating body [65]. (c) Elliptic cylinder TENG [66].

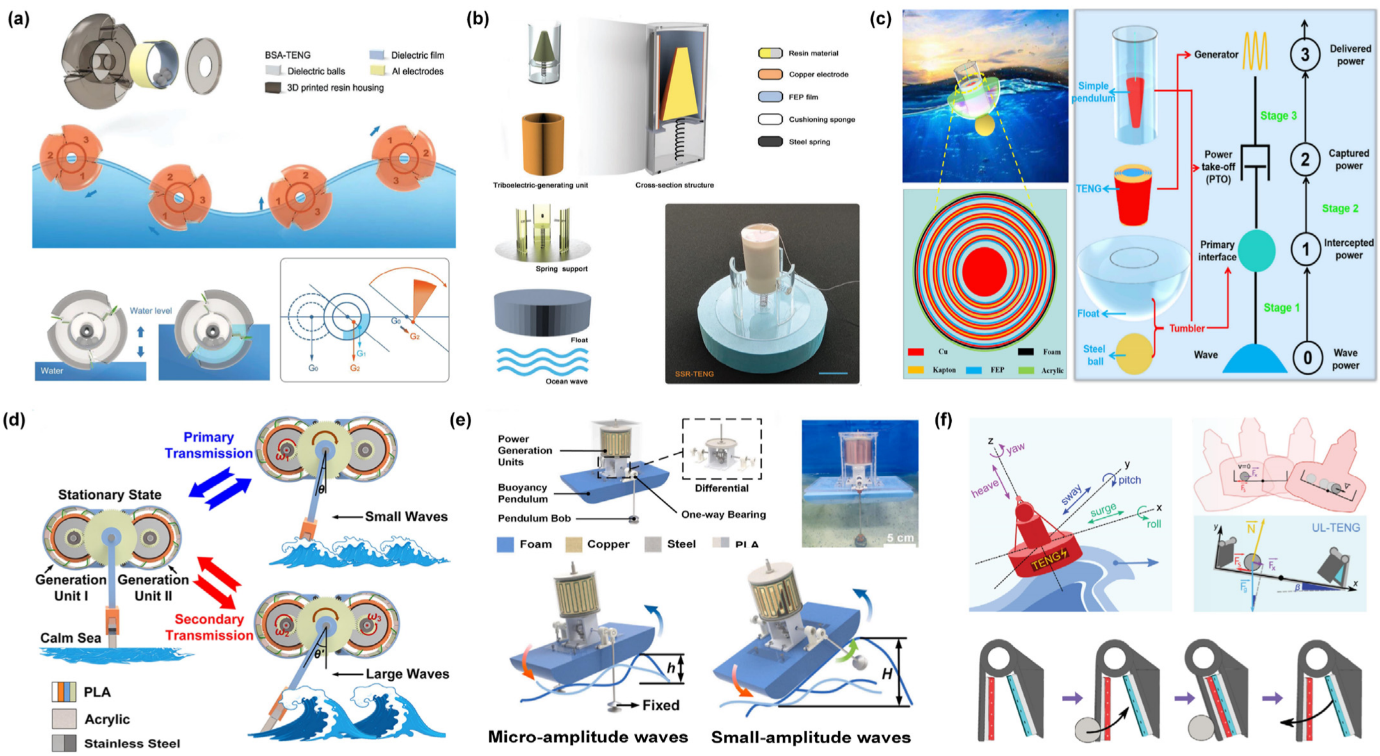

Fig. 6. TENG with the self-regulating mechanical mechanism. (a) Center of gravity adaptive type [45]. (b) Swing adaptive type [46]. (c) Initiative type [47]. (d) Gear self-regulation type [44]. (e) Morphological transformation TENG [43]. (f) Sea state adaptive type [42].

damping movement with high frequency from the pendulum and tumbler structures, motivated through water waves, enhances the energy harvesting efficiency of the AR-TENG. The performance ratio of the AR-TENG system between tests and simulation approaches 0.8.

Xu et al. [44] proposed a graded energy harvesting TENG (GEH--TENG) that utilizes a hierarchical transmission structure, dual generation structure, and a pendulum to achieve hierarchical energy harvesting, displayed in Fig. 6(d). In small wave environments, one generation unit operates to produce electrical energy, requiring minimal initial torque, making it effortless to launch and capture small wave energy. When its amplitude augments and the pendulum's swing angle reaches a preset threshold, the device shifts to a cooperative operation mode with both generation units. By changing the internal factors of the GEH-TENG, it is possible to modulate the required amplitude to the operational threshold, which adjustment establishes a direct and linear correlation between the amplitude and the threshold. Contrastive tests demonstrate that the GEH-TENG generates more electrical energy under large wave conditions. The dual-structured GEH-TENG achieves an energy output 2.3-fold higher than its single-unit counterpart, efficiently charging a 10 μF capacitor to 5 V within 20 s. Furthermore, in simulation waves, the device can monitor wave conditions based on wave magnitude variation. The hierarchical concept can be applied for energy capturing and ocean monitoring, providing a novel perspective for the structural creation of TENG. Wang et al. [43] reported a morphological transformation TENG (MT-TENG) that actively adjusts its structure to harvest irregular wave energy, which is displayed in Fig. 6(e). This feature detects it significantly from traditional wave energy TENG, which only have a simplex driving unit, thereby giving the MT-TENG stronger adaptability to waves. The result shows that the calculated peak power density reaches 30.62 W m^{-3}, surpassing other W-TENGs using swinging structures or fur as dielectric materials. A 10 mF capacitor is charged to 5 V within 224 s by the MT-TENG. Furthermore, an environment monitoring system has been developed, capable of powering 10 LEDs (30 W) and providing steady energy for the water quality tester. Gonçalves et al. [42] established an electrical performance relation of TENG movement, as depicted in Fig. 6(f). Their research methodology involved numerical and analytical methods. By adjusting the time difference of contact with the cycle, they were enable to increase the speed of the contacting layers through energy transfer from a motion unit to TENG, thereby improving energy output. This finding was demonstrated through numerical simulations and further supported by experimental results, which revealed a comparable correlation between the experimentally derived power output and the simulated sphere velocity, both of which exhibited a similar dependence on wave period and pitch.

3.1.3. Multidirectional energy harvesting

The disorder of wave direction also limits the harvesting ability of wave energy TENG. Currently, there are three common multi-directional energy harvesting methods: multiple sets of power generation units, circular structures, and petal shaped power generation units. In terms of multiple power generation units, Ning et al. [50] introduced a TENG based on a tensegrity structure, as displayed in Fig. 7(a). By employing a tensegrity structure, the device's ability to support loads is amplified across several frictional layers, and its height is notably reduced by half. And the response frequency can be readily tuned by adjusting the prestress, promoting efficient resonance acquisition. Experimental validation demonstrated the superior output performance under various conditions. Specifically, the TENG attained an output of 1024 V and 0.816 mC min^{-1}, demonstrating its capability to directly power 1512 LEDs. In addition, Xu et al. [52] demonstrated an isotropic triboelectric-electromagnetic hybrid generator (I-TEHG) based on guiding liquid for harvesting omnidirectional wave energy, which is depicted in Fig. 7(b). The I-TEHG incorporates a novel design of concentric pairs of electrodes with a tilted substrate that uses gravity cocoa to predict the direction of random and shunt fluids. The manufactured I-TEHG performed well in a natural marine environment with excellent output performance compared to a laboratory setting. A single I-TEHG is capable of continuously lighting up to 320 LEDs, charging a 0.1 F supercapacitor to 3.1 V and driving a wireless sensor, maintaining operation even when there is minimal wave activity. Regarding petal shaped power generation

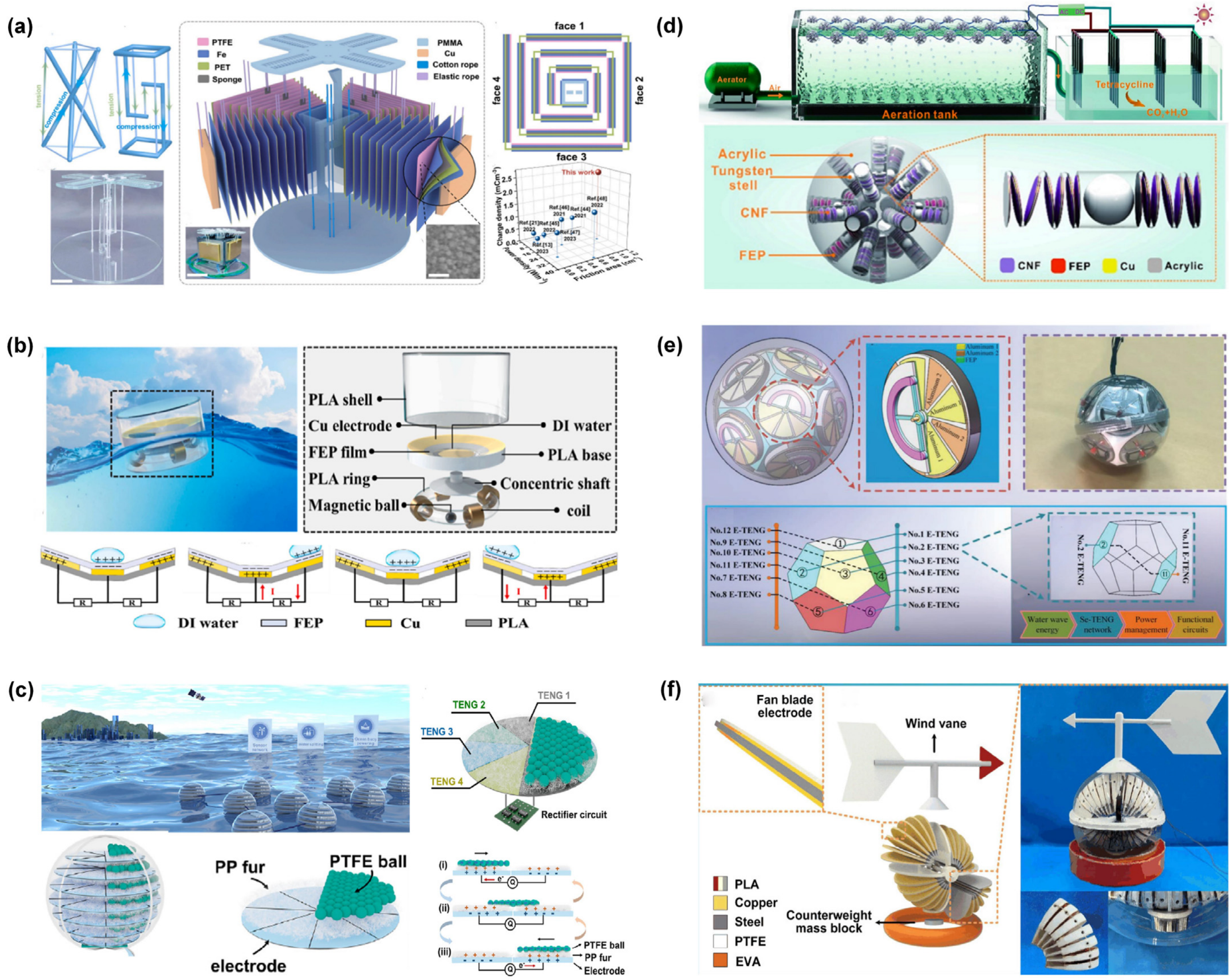

Fig. 7. TENG with multi-directional energy harvesting ability. (a) TENG with a tensegrity structure [50]. (b) Isotropic triboelectric-electromagnetic hybrid generator [52]. (c) A spherical TENG with sliced-pizza-shaped electrodes [104]. (d) Efficient self-powered photocatalytic TENG [49]. (e) TENG based on a spherical eccentric structure [51]. (f) A directional adaptive TENG (DA-TENG) featuring wind-water synergistic [105].

units, Hong et al. proposed a spherical TENG (SP-TENG) featuring a multilayer sliced-pizza-shaped electrode structure designed to efficiently harvest omnidirectional water wave energy [104], as displayed in Fig. 7(c). The SP-TENG utilizes polypropylene fur as a triboelectric material, significantly boosting charge output and enhancing contact efficiency. Testing at a low frequency of 0.6 Hz demonstrated that the SP-TENG achieved impressive volumetric charge and power densities of 2.4 mC m^{-3} and 13 W m^{-3}, respectively. This design fully exploits the internal space of the device, enabling consistent and high-performance energy conversion from waves approaching from any direction. The study highlights the potential of SP-TENG in practical applications, such as powering marine sensors and buoys.

The above structure can effectively harvest the multi-directional wave energy of traveling waves, but it cannot effectively adaptively harvest the energy generated by standing waves. Therefore, Mo et al. [49] indicated a photocatalytic system designed to enhance the removal efficiency of tetracycline, which is shown in Fig. 7(d), and verified the performance at various orientation angles. This system degraded tetracycline in waves, accomplishing a 95.89 % efficiency in tetracycline elimination over a period of 80 min. In addition, Qu et al. [51] proposed a design for a TENG based on a spherical eccentric structure, as shown in Fig. 7(e). By incorporating a dodecahedral structure within the ball shell, they achieved omnidirectional wave energy harvesting. They also designed circuits to reserve the energy. Ultimately, the SE-TENG can supply 40 green LEDs through wave energy. Combined with storing equipment, it could supply temperature sensors.

Usually, wave energy TENG uses multiple power generation units to capture multi-directional energy, which reduces the utilization efficiency of the power generation units. Hence, Liu et al. proposed a directional adaptive TENG (DA-TENG) featuring wind-water synergistic [105], as displayed in Fig. 7(f). The DA-TENG integrates a weather vane structure at the top, enabling it to adaptively adjust its angle according to wind direction, thereby aligning the oscillation direction of the prototype with wave motion. This characteristic increases the likelihood of the DA-TENG maintaining optimal output in complex wave environments. The internal power generation units are integrated with a multilayer fan blade structure, working synergistically to enhance the omnidirectional wave energy capture range, effectively improving overall output performance. A rubber ring at the base ensures that the DA-TENG components remain stable and less prone to toppling, even in turbulent water wave environments, allowing the internal components to maintain optimal output. The optimized DA-TENG is capable of achieving the peak power density of 7.51 W m^{-3}.

3.1.4. Transformation of disordered/ordered wave motion

Wave energy is characterized by its low frequency and irregularity; however, through the implementation of wave energy conversion mechanisms, it can be transformed into regular and orderly mechanical motion, thereby enhancing the efficiency of energy conversion and harvesting.

To efficiently harvest wave energy, Han et al. devised a wave-powered linking mechanism TENG (WLM-TENG) [58], as shown in Fig. 8(a). A floating plate, T-shaped connections, and a one-way bearing make up the linking mechanism. The floating plate moves vertically acted by the wave, providing more driving force to the TENG's rotor, allowing it to achieve a one-way rotating motion. In addition, Jiang et al. reported a TENG with the ability of transformation between motion and electrical energy to multiply the frequency of the input signal. The screw rod is capable of transforming the linear motion of a wave into high-frequency two-way rotational motion, and the ratchet can achieve a one-way rotating motion [59], as illustrated in Fig. 8(b). Inspired by the Brownian motor, Qiu et al. designed the brownian motor TENG, which can achieve unidirectional continuous rotation and be employed to conduct the harvesting of low-frequency wave energy. The combination of symmetry-breaking effects results in the transformation of randomly generated wave excitations into a monodirectional rotation. This process is facilitated by the deployment of inertia wheels, which serve to store energy for sustained rotational motion over an extended period [60],

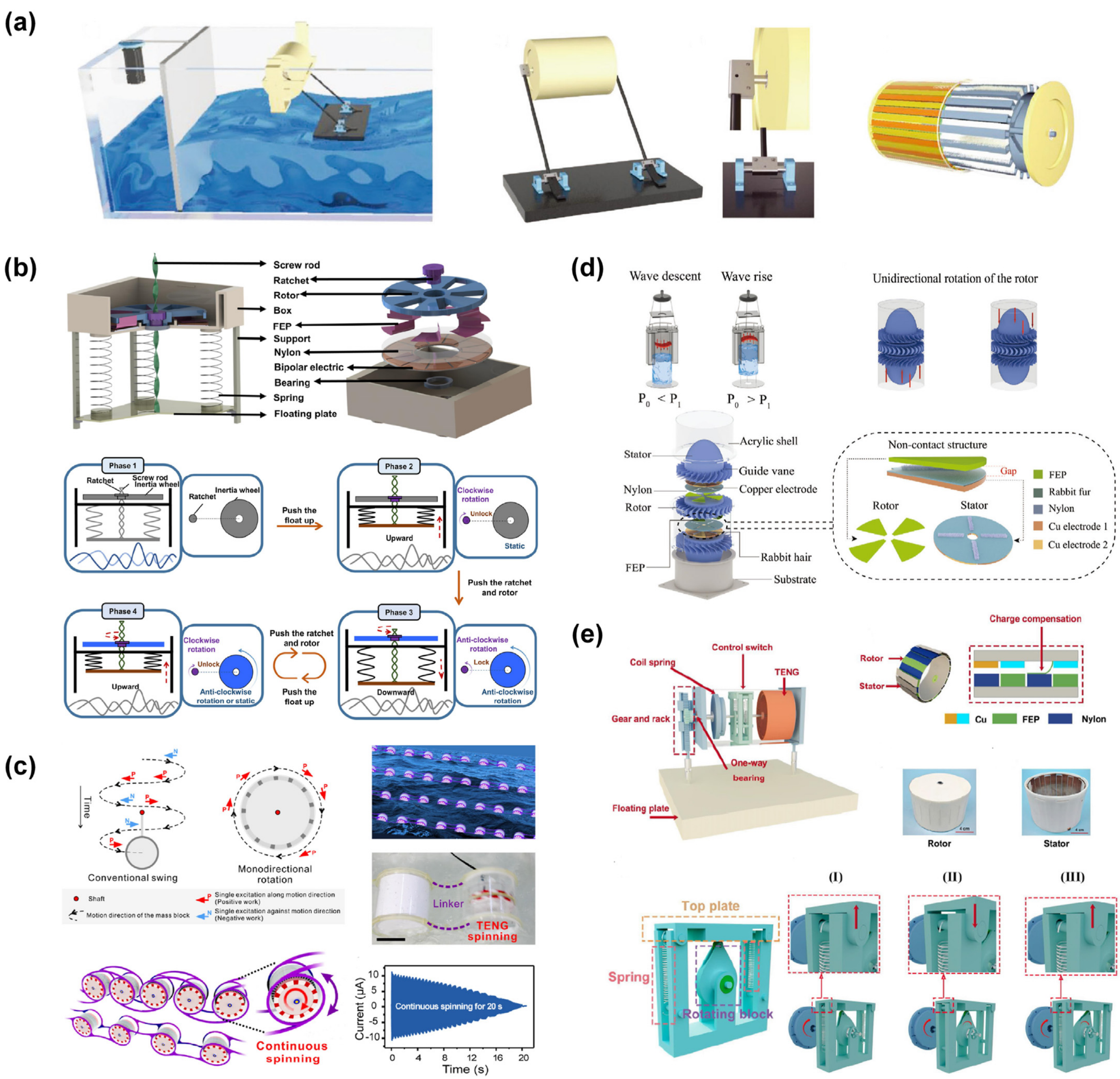

Fig. 8. Motion form conversion structures TENG for wave energy harvesting. (a) Cylindrical wave TENG with a linking mechanism [58]. (b) Schematic diagram of SR-TENG [59]. (c) Brownian motor TENG [60]. (d) Oscillation-driven bi-directional air turbine TENG [62]. (e) Mechanical controlled TENG [61].

which is displayed in Fig. 8(c) and reach the output power density of 4.69 W m^{-3} when operating in a water wave environment. It is worth noting that a number of the devices can be arranged on the water surface to form a distributed blue energy collection network.

To further improve the capture efficiency of wave energy, Yang et al. proposed a non-contact turntable-structured oscillating water column TENG (OWC-TENG). The seawater flow results in a change in pressure within the OWC chamber, and the fluid movement drives the rotor to produce a bi-directional rotating motion through the bidirectional air turbine, enabling full-range energy harvesting. This further improves the utilization of wave energy [62], as illustrated in Fig. 8(d), whose power density achieves 114.8 W m^{-2}. To achieve the conversion of disordered energy into controllable energy output, Yang et al. employed a Mechanical controlled , designated as MC-TENG [61], which is displayed in Fig. 8(f). MC-TENG is capable of maintaining a stable and regularized output no matter how the wave changes under a real wave environment, whose peak power density reaches 38.46 W m^{-3} Hz^{-1}.

3.1.5. Frequency amplification through the damper

The output performance is contingent upon the output frequency. Consequently, researchers have proposed many methods to amplify the operation frequency of TENG. Liang et al. proposed an approach to wave energy collection, namely a spring-assisted swing spherical TENG [55], as depicted in Fig. 9(a). The internal oscillating assembly swings left and right when it is working, and the supporting spring limits the swinging height of the swing component and increases the output frequency. Finally, the achieved output power is 4.1 mW in the wave environment. Ren et al. suggested a hybrid nanogenerator (HW-NG) that employs a magnet as a pendulum to further reduce the driving force required for the device; the spring makes the friction interface fully contact and can limit the swing amplitude [57], as illustrated in Fig. 9(b). The power density of its single TENG reached 0.41 W m^{-2}. Jung et al. reported a cylindrical TENG with frequency-increased, which utilizes the repulsive force of two magnets to store energy, which is converted into rotational motion when mass block overcomes magnet repulsion [54], as depicted in Fig. 9(c). Its peak power density achieves 6.67 W m^{-3}. A self-powered ocean buoy based on TENG with a mechanical frequency converter (MFR) was designed by Jung et al. [53], as shown in Fig. 9(d). The MFR can convert wave motions into rotational motions to increase the output power, whose average power output is 130 mW.

3.1.6. TENG network structure

Since 2014, the idea of a TENG network was introduced with the aim of achieving the broad-scale exploitation and utilization of wave energy resources. TENG network is comprised of many interconnected units, which can be dispersed below or stacked flat on the water's surface.

Li et al. reported a 3D chiral network of TENGs, which can be arranged in three-dimensional water, extending from surface to underwater, and is more suitable for large-scale deployment networks [106], as shown in Fig. 10(a). By building a thorough energy collecting system, increasing the stored energy by roughly 319 times. In addition, Hu et al. introduced a wheel-structured TENG (WS-TENG) with a hyperelastic network designed for efficient wave energy harvesting, which features external blades that enhance interaction with water waves [107], which is depicted in Fig. 10(b). The hyperelastic network structure allows the device to stretch and contract, further amplifying its motion and connecting multiple units into a large-scale network. This design adapts to both wave and wind excitations, utilizing multiple synergistic driving modes to significantly boost energy output. Its design leverages internal eccentric structures that, along with the rolling and swinging motions, enhance energy harvesting. Additionally, the study showcased practical applications of the WS-TENG network in self-powered systems, including wireless sensing and signal transmission, fully powered by harvested wave energy.

In terms of theoretical optimization of TENG networks, Liu et al. conducted a comprehensive study on optimizing the network topology of

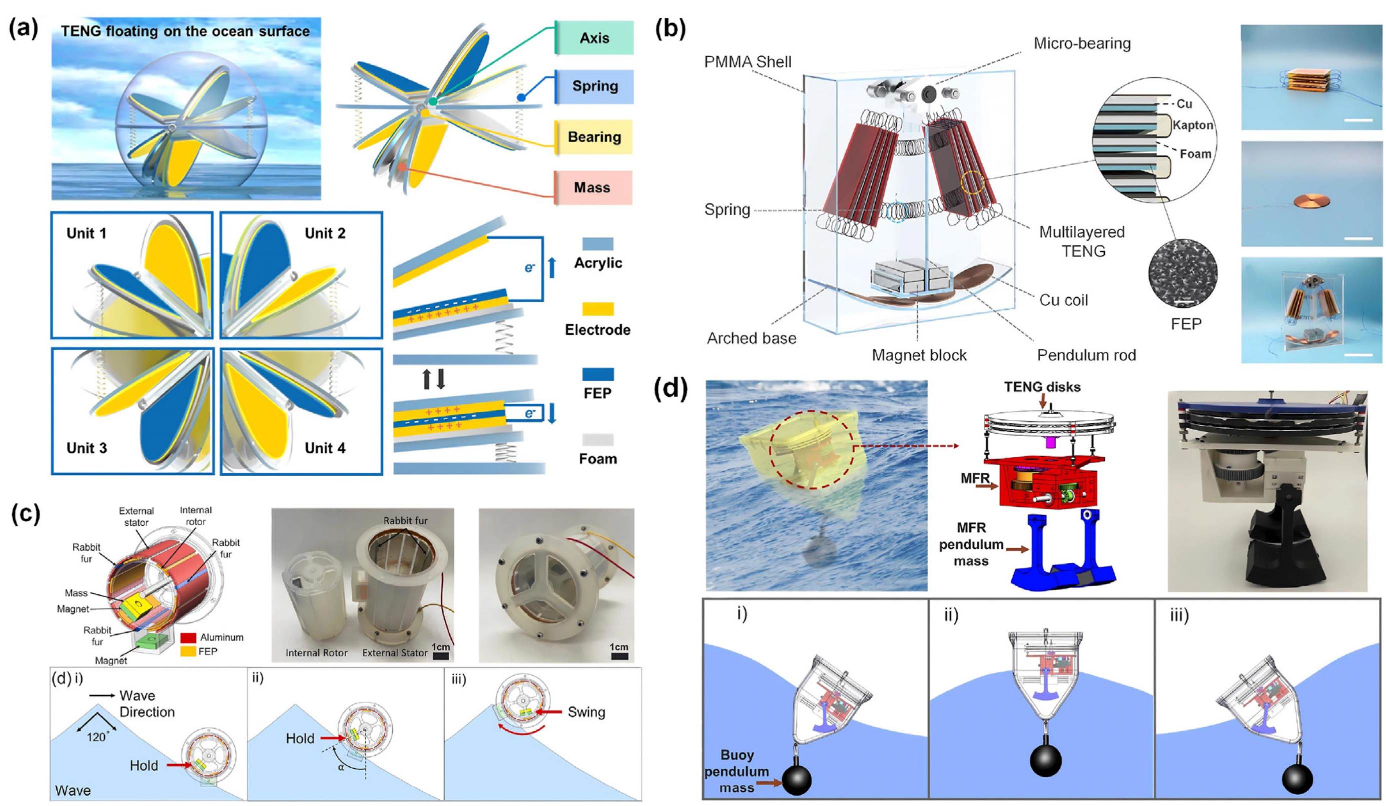

Fig. 9. Damped structural TENG for wave energy harvesting. (a) Schematic diagram of a spring-assisted swing spherical TENG [55]. (b) Pendulum hybrid device [57]. (c) Structure diagram of FMC-TENG [54]. (d) Structure diagram of DSMFR-TENG [53].

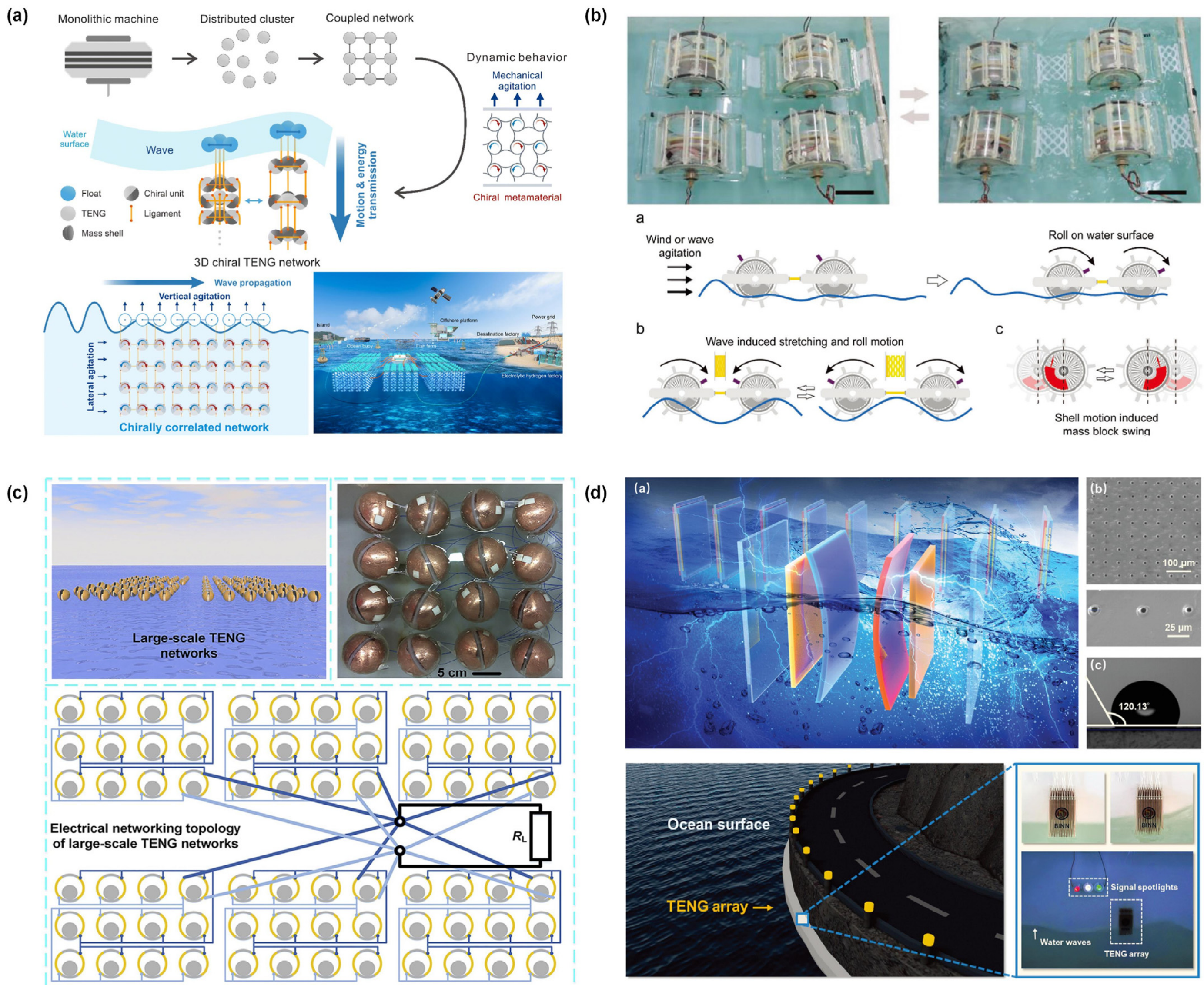

Fig. 10. TENG network for harvesting wave energy. (a) 3D chiral network of TENG [106]. (b) Wheel-structured TENGs with hyperelastic networking [107]. (c) Topological diagram of the TENG network [108]. (d) Liquid-solid network of TENG [109].

TENGs for efficient ocean wave energy harvesting [108], as shown in Fig. 10(c). The research focused on developing large-scale TENG networks, which show great promise for clean wave power generation. The authors analyzed four fundamental electrical networking topologies, examining the impact of cable resistance and output phase asynchrony on the network's overall performance. Their findings revealed that the configuration of the network significantly affects the output power, providing critical theoretical insights and a universal method for optimizing large-scale TENG networks. The study is the first to strategically analyze TENG network topologies, offering a valuable framework for improving the design and scalability of TENG networks for practical applications in renewable energy harvesting from ocean waves.

To further improve wave capture ability, a flexible adaptive power generation unit is integrated into the TENG network. Liang et al. proposed a compact energy harvesting device and its array based on liquid-solid TENG, which offers a novel conceptual framework for the advancement of TENG networks [109], which is displayed in Fig. 10(d), whose TENG array can finally achieve the average power density of 5.38 W m^{-3}.

3.2. Research on water depth/working condition adaptive structure

The underwater energy harvesting is considered from three angles: conventional underwater energy harvesting devices, bio-inspired structures that enhance energy harvesting from waves, and flexible structures that autonomously adapt to changes in underwater wave conditions.

3.2.1. Underwater energy harvesting structure

Beneath the dynamic surface wave energy lies a substantial reservoir of energy, offering substantial potential for development and serving as a pivotal domain for forthcoming exploration in human energy research. The extraction of subaqueous energy in situ holds strategic importance for ensuring the enduring and reliable functionality of underwater sensor networks and detection systems. Consequently, the utilization of the TENG for harvesting underwater energy has garnered significant attention both nationally and internationally. Du et al. introduced a chain-flipped plate TENG (CFP-TENG) [110] for efficiently harvesting underwater energy, which is illustrated in Fig. 11(a). The CFP-TENG is characterized by a structural design of a longitudinal arrangement of power

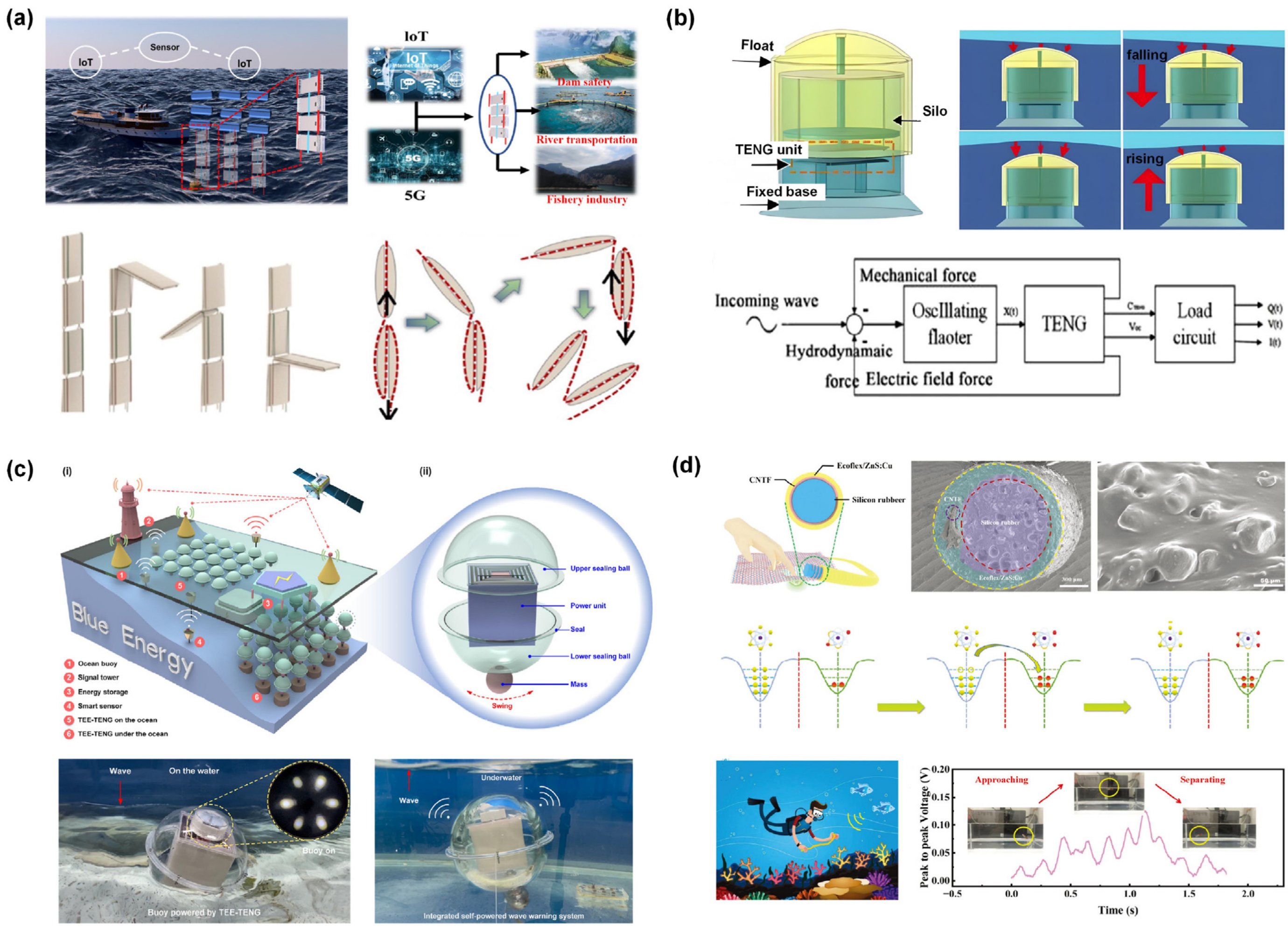

Fig. 11. TENG for harvesting underwater energy. (a) The structure and application of CFP-TENG [110]. (b) The AWS-TENG's structure and working principle [111]. (c) TEE-TENG system and underwater application experiment [112]. (d) A stretchable and self-powered mechanoluminescent TENG [113].

generation units that convert erratic and highly oscillating motion into electrical energy. Notably, the CFP-TENG achieves a peak power density of 1.5 W m^{-2} when operating with a load resistance of 30 MΩ. Large numbers of CFP-TENG arrays can be deployed underwater to harvest wave energy steadily and sustainably facilitating exploitation of ocean resources.

As is well known, wave energy harvesting at the bottom of the ocean is of great significance for powering underwater sensors. Yang et al. reported an archimedean wave swing TENG (AWS-TENG) [111] for energy harvesting from the seabed [Fig. 11(b)]. Through the construction of a hydrodynamic model and finite element simulation, the detailed operational principles of the AWS-TENG are elucidated. Finally, the experimental findings demonstrate that the AWS-TENG is capable of achieving a maximum power density of 7.9 mW m^{-2}, presenting a reliable energy strategy for seabed wave energy harvesting applications in offshore marine environments. In addition, Yu et al. proposed a novel triboelectrification enhancement effect (TEE) to significantly improve the performance of TENGs, particularly for marine applications [Fig. 11(c)] [112]. The study demonstrates that by increasing the surface electrostatic states between tribo-materials, the TEE can enhance charge generation by 14.8 times and output energy by 173.2 times. An integrated prototype, designed specifically for ocean environments, successfully harnesses energy both on the water surface and underwater, proving its practical feasibility. This TEE-TENG system effectively powers devices like wave warning systems with wireless transmission, showcasing its potential for large-scale blue energy harvesting and providing a robust solution for self-powered ocean monitoring systems. The work presents a significant advancement in TENG technology, emphasizing its broad applicability and potential for sustainable energy generation in marine environments.

Wu et al. developed a stretchable and self-powered mechanoluminescent TENG fiber (MLTENGF) designed for use in amphibious electro-optical sensor textiles, with significant implications for marine applications [Fig. 11(d)] [113]. The MLTENGF exhibits remarkable stretchability and stability, capable of withstanding strains up to 200 % without performance degradation. The fiber efficiently converts mechanical stimuli into both electrical and optical signals, making it ideal for underwater sensing and communication. In marine environments, the MLTENGF demonstrated a strong non-contact sensing capability, detecting objects up to 35 cm away. It also showed potential for underwater rescue operations through its ability to transmit information via Morse code, offering a self-powered, durable solution for ocean monitoring and communication. This innovative fiber represents a significant advancement in the development of smart, amphibious textiles, with broad applicability in marine safety, environmental monitoring, and human-machine interaction.

3.2.2. Bionic structure

The application of bionics has emerged as a pivotal strategy in various TENG design and optimization efforts. By emulating the structural, surface morphological, material property, and sensing/power generation principles of nature, bionic design markedly enhances its energy conversion efficiency and environmental adaptability. Some bionic

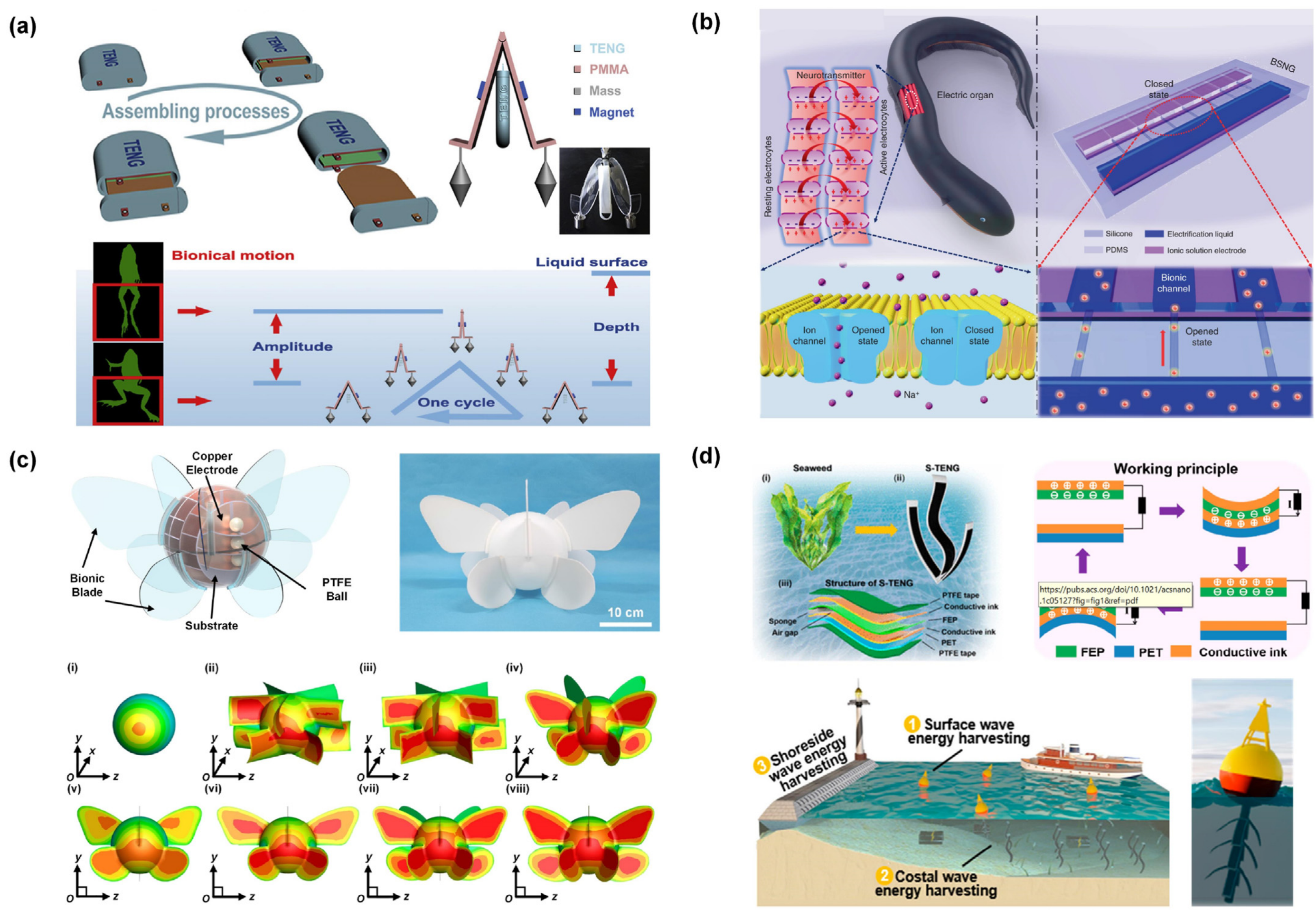

Fig. 12. TENG with bionic structure design. (a) The assembly process and working mechanism of bjTENG [67]. (b) Bionic principle and structure of BSNG [70]. (c) Schematic structure of the BBW-TENG and application demonstrations [84]. (d) Bionic origin, structural composition and applications of the S-TENG [114].

applications have been demonstrated to realize the significant enhancement of performance and expand applicability in a range of application scenarios.

Chen et al. demonstrated a bionic-jellyfish TENG (bjTENG) [Fig. 12(a)] [67], which has excellent properties such as shape-adaptive and unique elastic resilience, and addresses the challenge of efficiently converting potential energy stored in elastic materials into electrical energy. Furthermore, the established self-powered sensing system is constructed to enable self-powered ocean hydrographic monitoring. Zou et al. proposed an underwater bionic stretchable nanogenerator [70] (BSNG) for marine monitoring, as depicted in Fig. 12(b). The incorporation of soft materials, such as liquid electrodes impart exceptional flexibility and resistance to tensile fatigue (over 50,000 cycles) to the BSNG. The BSNG, drawing inspiration from the electric eel, mimics the ion channel structure of its cell membranes, resulting in an open-circuit voltage that can surpass 170 V in dry conditions and 10 V in liquid environments.

Wang et al. proposed a bioinspired butterfly wings TENG (BBW-TENG) [Fig. 12(c)] [84], which derives its design from the structure of butterfly wings. The results of the experiments confirm that the BBW-TENG can successfully extract energy from underwater waves coming from diverse directions and at various depths. In particular, the utilization of a meticulous encapsulation strategy significantly mitigates dielectric shielding effects, enabling the BBW-TENG to maintain exceptional durability and sustained electrical performance even after immersion in water for 45 days. This resilience underscores the BBW-TENG's potential for long-term power provision in underwater sensor applications. Wang et al. proposed a flexible seaweed-like TENG (S-TENG) with low-cost, strong adaptability, and high stability to provide power for distributed sensors in a marine environment [114], whose unique structure converts bending and recovery under wave excitation into electrical energy, as depicted in Fig. 12(d). The experimental results show that a single S-TENG can generate a maximum output of 24.8 V and 2.6 μA, respectively. When operated in parallel with multi-group, the output power can reach 79.023 μW.

3.2.3. Flexible structure

The structure of the TENG unit with rigid contact is constrained in its overall energy conversion efficiency due to problems such as small contact areas and inefficient separation, which greatly restricts the large-scale utilization of wave energy. To overcome these challenges, the researchers are committed to innovations in structural design and optimization of flexible materials to enhance the environmental adaptability and stability of TENG. This will facilitate the effective harnessing of low-frequency, large-scale, and irregular water wave energy.

Wang et al. developed a fish-wearable data snooping platform (FDSP) designed for underwater energy harvesting and real-time monitoring of fish behavior [115], as depicted in Fig. 13(a). The FDSP integrates an air sac TENG (AS-TENG) with a wireless communication module and an antibacterial coating. The AS-TENG harvests mechanical energy from fish swimming movements, converting it into electrical signals that can be used to monitor various aspects of fish kinematics, such as tail swing angles and frequencies. The platform's flexible and waterproof design ensures it can be securely attached to a fish without hindering its natural

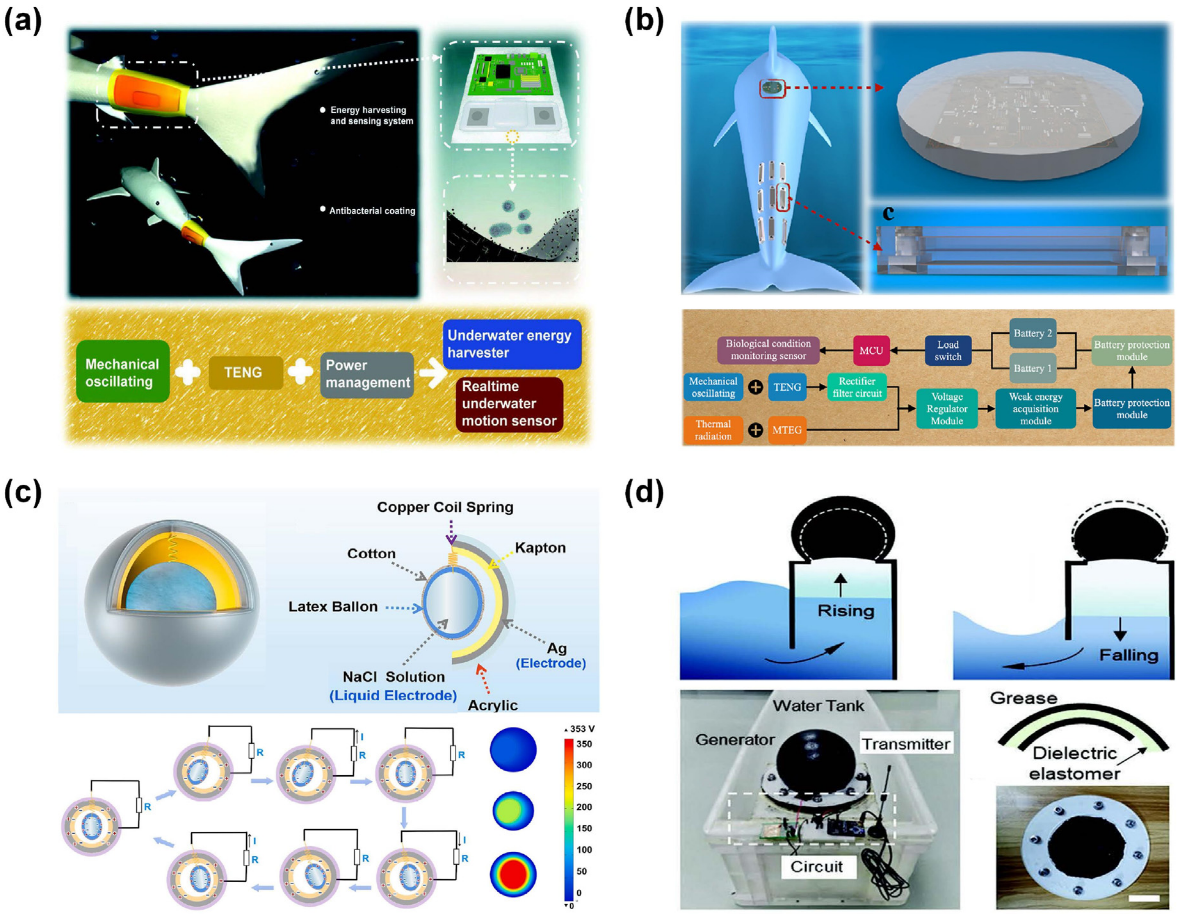

Fig. 13. Flexible structure TENG. (a) A multifunctional fish-wearable data snooping platform [115]. (b) A self-powered marine mammal condition monitoring system [116]. (c) Schematic diagram of the whole configuration and structural details of the SSEP-TENG, generation principle, and electrostatic field simulation of power generation units [74]. (d) Operation mechanism of TENGs, a self-powered remote temperature reading system [73].

movements. The antibacterial coating enhances biocompatibility, making the FDSP suitable for long-term deployment in marine environments. The wireless system transmits real-time data to a remote receiver, enabling continuous monitoring of fish behavior in their natural habitat. This innovative approach holds significant potential for advancing underwater sensing technologies, particularly in ecological studies, marine biology, and the development of self-powered, eco-friendly monitoring systems. Liu et al. developed a self-powered marine mammal condition monitoring system that leverages a hybrid energy harvesting approach, combining a TENG and a micro thermoelectric generator (MTEG) [116], which is illustrated in Fig. 13(b). It addresses the challenge of sustaining long-term monitoring by harnessing both the mechanical energy generated from the movement of marine mammals and the thermal energy from the temperature difference between the mammal's body and the surrounding water. The integrated system demonstrated enhanced energy collection efficiency, improving battery charging performance by 4.93 % compared to using MTEG alone. This advancement allows for extended operation of monitoring devices, enabling continuous real-time data collection essential for the conservation of endangered marine species. The study highlights the potential of this hybrid system to significantly improve the durability and effectiveness of marine environmental monitoring technologies.

Zhao et al. designed a soft-contact and self-adaptive ellipsoidal-pendular-structured TENG (SSEP-TENG) [74], as depicted in Fig. 13(c). The SSEP-TENG utilizes a novel spring-driven soft-contact mechanism to enhance the contact area, minimize TENG wear, and facilitate rapid contact separation, thereby optimizing output performance and enhancing the durability and environmental resilience of SSEP-TENG. Additionally, the integration of the SSEP-TENG with GPS and its attachment to the tracking target enables the successful implementation of self-powered wireless sensing and real-time positioning. Xu et al. present a dielectric elastomer nanogenerator (DENG) [73], as depicted in Fig. 13(d). Through the adjustment of individual capacitor parameters, the DENG can achieve a peak charge density of up to 26 mC m^{-2} and an energy density of up to 140 mJ g^{-1}. In addition, a water-wave energy harvesting device design based on this principle can enable self-powered meteorological monitoring.

3.3. Research on environmental adaptability

The power generation units are designed with consideration of environmental conditions, such as the high humidity and corrosiveness of seawater. Conventional energy harvesting units are prone to irreversible damage due to environmental influences, leading to performance degradation. Designing corrosion-resistant, highly moisture-tolerant materials is critical to the stable operation of TENGs and significantly enhances their adaptability to wave environments.

3.3.1. Humidity resistance

In 2021, Sun et al. carried out research that the performance of TENG is how to be affected by humidity in oceanic conditions. Understanding the challenges posed by high humidity, the researchers aimed to develop effective waterproof and moisture-proof designs to reach the reliable operation of TENG [117]. Polytetrafluoroethylene (PTFE) film and polyvinyl alcohol (PVA) film are used as friction layers to generate electric charge. The cathodic protection system receives the charge that is generated through friction. The optimized output of flexible TENG is 695.18 V, 29.72 μA, and 1.74 mW at 95 % relative humidity (RH). The hydrophobic PTFE film prevents condensed water droplets from sticking to its surface, but these droplets tend to move to the PVA film surface in high humidity environments. The presence of hydroxyl groups in the top layer of the PVA film allows water droplets to stick to its surface by forming hydrogen bonds with certain water molecules on the PVA film surface. Given that PTFE macromolecules lack charged groups capable of forming hydrogen bonds with water molecules, it can be deduced that PVA film's surface is prone to water film formation, which means the friction in the TENG arises from interactions between PTFE/PVA and PTFE/water films. It is important to note that water molecules possess a greater propensity for positive charge characteristics than PVA, resulting in a higher triboelectric output for the PTFE/water combination compared to the PTFE/PVA pair. Therefore, an increase in the ambient relative humidity results in an expansion of the water film on the PVA film's surface, which in turn enhances the output performance of the TENG. Fig. 14(a) shows a self-powered cathodic protection system driven by the structure of TENG at 95 % RH.

Additionally, in 2022, Liu et al. employed a straightforward spraying technique to fabricate a range of robust ultra-hydrophobic fluorinated silica (F-SiO_2)/epoxy resin (FE) coatings [85]. As shown in Fig. 14(b). When the F-SiO_2 content is below 33.3 wt%, the contact angle (CAs) of the FE coating remains below 150° due to the incomplete coverage of F-SiO_2 on the coating surface. On the contrary, when the F-SiO_2 content exceeds 36.8 wt%, the FE coating is completely covered by F-SiO_2, forming a superhydrophobic state characterized by CAs exceeding 150°. The wetting properties of the coating can be demonstrated by the phenomenon of the coating reflecting a rough surface. On the horizontally positioned coating surface, water droplets take on a spherical form and readily bounce off, leaving no residue of water stains. It is worth noting that the hydrophobicity of the FE coating remains largely unchanged even after 100 rounds of polishing.

To better select suitable materials based on different natural environments, Yu et al. conducted research on material selection principles for different environments [75], as shown in Fig. 14(c). The study first uncovers the mechanism by which environmental factors impact the performance of TENG. Furthermore, two integrated TENGs are displayed to demonstrate the practicality and applicability of these selection rules. Notably, when exposed to a relative humidity of 95 % for 36,000 s, the materials exhibit exceptional moisture resistance of up to 124 %. This work provides crucial guidelines for selecting frictional electrical materials and promotes their practical applications.

3.3.2. Corrosion resistance

In practical applications, energy harvesting devices like TENG frequently face complex and challenging environments, including conditions of acidity, alkalinity, and exposure to saltwater. Despite the protective encapsulation of the entire device, including the electrodes, there is still a risk of minor leaks that can lead to the electrodes being exposed to an unfavorable external environment. This exposure can result in significant damage to the electrode materials. Therefore, developing durable TENG materials that are corrosion-resistant and resistant to harsh environments under various extreme conditions is of great significance. Jiang et al. prepared a kind of cyc hydrogel with high chemical strength and super durability through self-polymerization at room temperature [118], as depicted in Fig. 15(a). The cyc hydrogel electrodes underwent pretreatment under exceptionally harsh conditions, including exposure to strong acids, strong bases, and highly concentrated saltwater. Surprisingly, the TENG output performance remained relatively stable throughout these challenging conditions. Moreover, even when subjected to pretreatment in simulated seawater with high salinity, the cyc hydrogel electrodes demonstrated consistent and stable electrical output performance. Liquid-solid TENG has attracted considerable research interest owing to its beneficial features of minimal wear and efficient contact. In their study, Zhang et al. fabricated an SL-TENG that operates in seawater, with a dielectric film serving as the organic coating and steel shells, both with and without coatings, acting as the electrodes [86], as shown in Fig. 15(b). LS-TENG demonstrates remarkable performance, thanks to the meticulous selection of dielectric membrane materials, which contribute to its excellent triboelectric properties and minimal ion adsorption effects. Additionally, there is a high potential for the uncoated steel electrode in the highly corrosive environment of seawater, effectively serving as a corrosion prevention measure in marine environments.

Ji et al. conducted research on an efficient cathodic corrosion protection system that combines a high-performance TENG with a step-down rectifier circuit [119], which is depicted in Fig. 15(c)(i). TENG's shell incorporates a gyroscope structure that integrates with the internal components, enabling efficient operation on the wave surface, which is

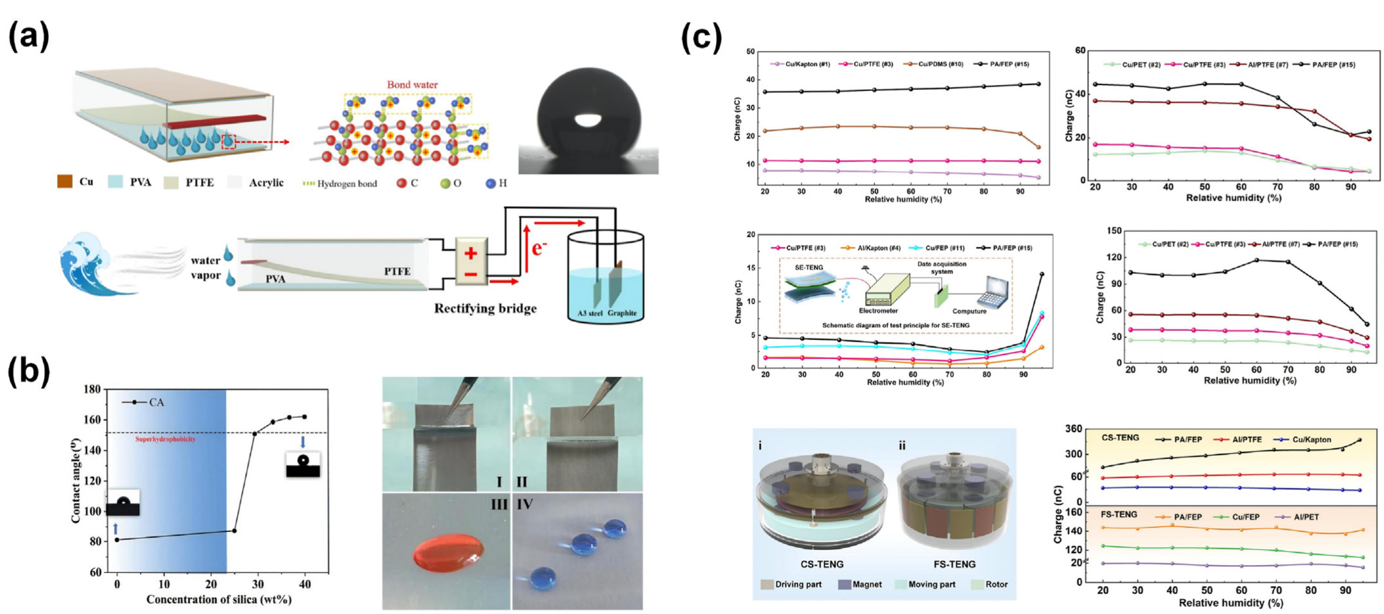

Fig. 14. Humidity resistance TENG. (a) Humidity-resistant TENG system for self-powered cathodic protection [117]. (b) TENG of durable superhydrophobic F-SiO_2/epoxy resin coating [85]. (c) Material properties of TENGs under different humidity levels [75].

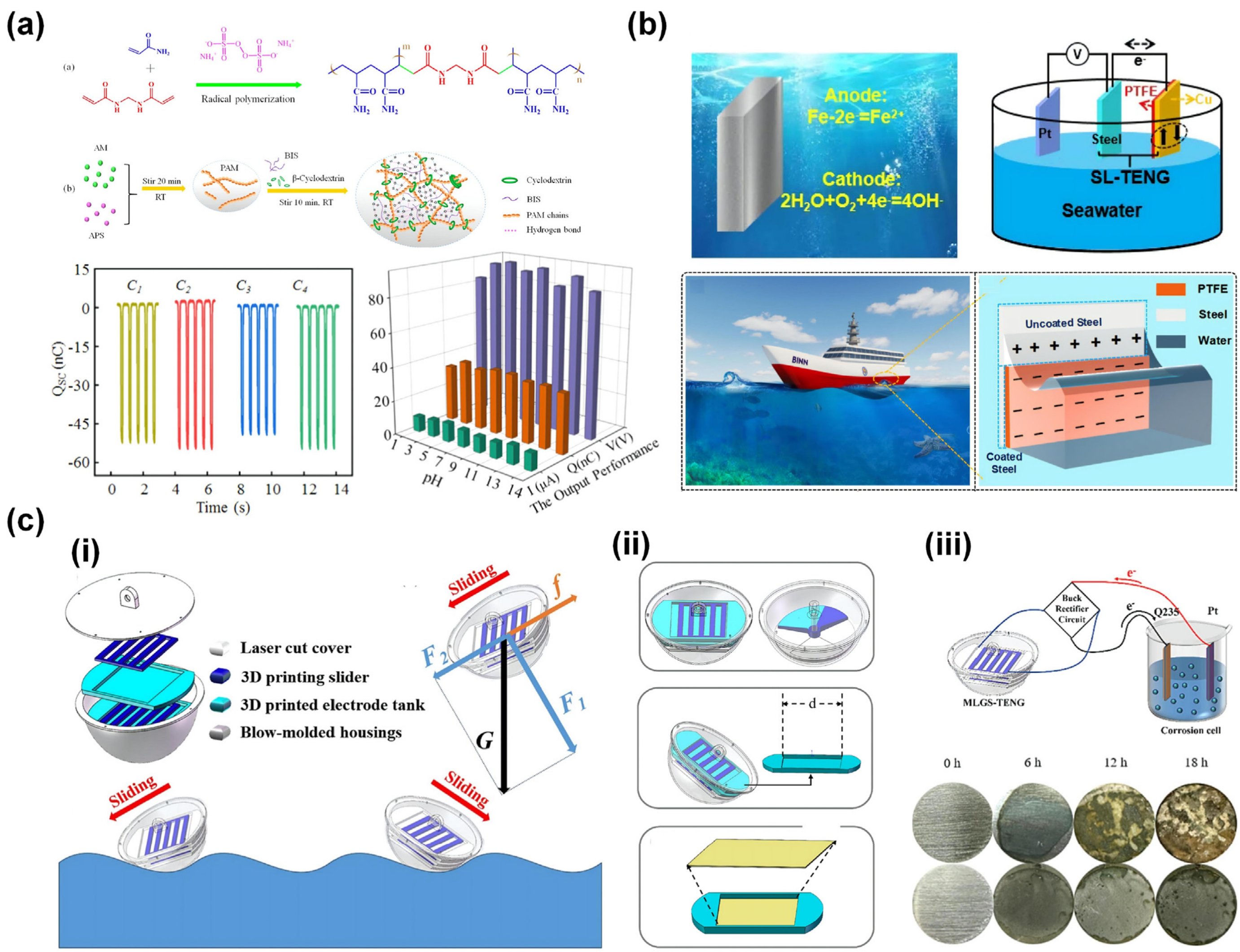

Fig. 15. Corrosion resistance TENG. (a) A kind of hydrogel triboelectric nano power generation material that is stretchable, resistant to harsh conditions, and stable in the environment [118]. (b) Liquid-solid TENG with marine corrosion protection [86]. (c) High-efficiency self-powered cathodic corrosion protection system. (i) The working state, (ii) the different internal structures of TENG, (iii) the principle of a self-powered anti-corrosion system and the change diagram of corrosion traces [119].

displayed in Fig. 15(c)(ii). Additionally, it adeptly collects low-frequency wave energy, which is then changed into mechanical energy, and subsequently, via the friction between self-assembled layers, into electrical energy. This TENG, known for its exceptional energy harvesting capabilities, has been employed in collaboration with a step-down rectifier circuit to create an efficient cathodic corrosion protection system, as illustrated in Fig. 15(c)(iii).

3.4. Energy management circuit with stable output

Regarding the stable output of the TENG, the power management circuit plays a vital role in the wave energy harvesting system. It enhances the stability, efficiency, and flexibility of the power generation system, thereby improving the adaptability of wave energy technology to various application scenarios.

3.4.1. Charge excitation circuit for humidity resistance

The efficient utilization of mechanical energy harvested by TENG provides promising technology for powering smart sensors. However, due to the water sensitivity of the material, its durability is low, which greatly limits its practical application. Zhou et al. proposed a wear-free dual-capacitor enhancement system enhanced TENG (DCE-TENG), which facilitates the transfer of the charge injected by the TENG, enhancing the longevity and output efficiency of TENGs in high-humidity conditions [Fig. 16(a)] [78]. In this work, the DCE-TENG can still maintain an output of about 95 % at a relative humidity of 90 %, almost unaffected by high-humidity environments. Liu et al. developed a criterion air breakdown model for quantitative evaluation of contact efficiency based on charge excitation to enhance and measure charge density. Simultaneously, a high mean charge density of 2.38 mC m^{-2} was generated in an ambient atmosphere with a relative humidity of 5 % [Fig. 16(b)] [76]. Wang et al. proposed a coupled output method that integrates charge excitation and phase coupling transfer to achieve nearly constant high-performance DC output. They also design a DC-TENG to harness the energy from water flow [Fig. 16(c)] [77]. This work further proves the effectiveness of the scheme through current comparison and quantification. At the same time, when the ambient humidity was increased to 90 % RH, the amount of transferred charge decreased by only about 10.84 %, further demonstrating the ability of the system to operate in a water environment.

3.4.2. Energy management and storage optimization

The majority of wave energy is characterized by its low frequency, inherent randomness, and relatively low intensity. The technology of

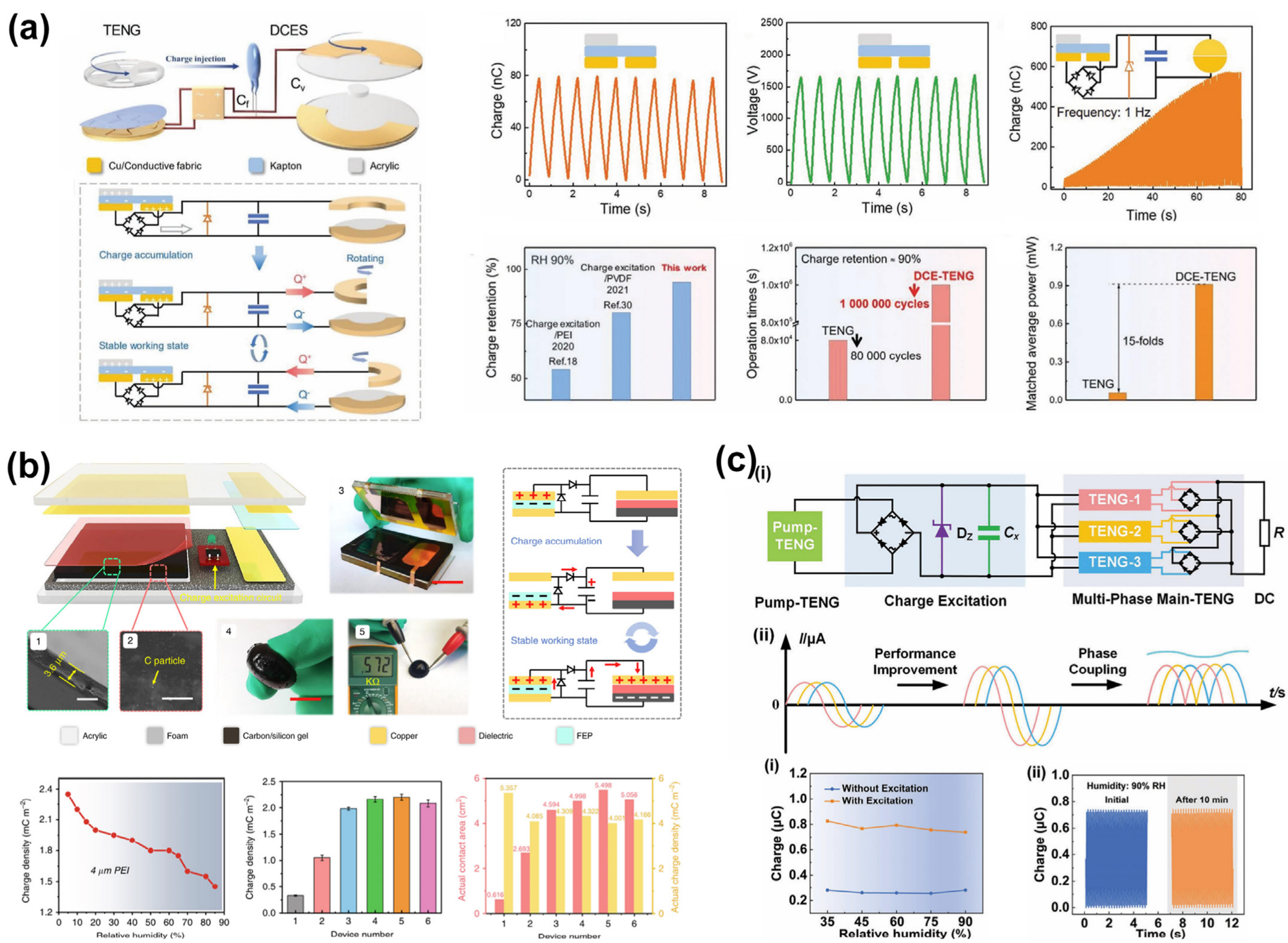

Fig. 16. Charge excitation circuit for humidity resistance. (a) Humidity-resistant TENG with a dual-capacitor enhancement system [78]. (b) Charge-excitation TENGs with maximize charge density [76]. (c) Direct-current TENG with high-performance and humidity-resistant [77].

TENGs provides substantial benefits in the harvesting of energy from sources with high entropy; however, the variability in input can impede the optimal utilization of the generated energy. Therefore, an energy management circuit is employed to intelligently adjust the storage and distribution of energy according to real-time energy demand, and convert scattered energy into continuous energy output. At present, a variety of energy management circuits have been successfully designed and realized efficient energy conversion. Cao et al. introduced an innovative energy storage/release strategy (SR-TENG) to significantly enhance the bandwidth, output efficiency, and longevity of wave energy harvested by the TENG [Fig. 17(a)] [79]. Wang et al. presented a straightforward and adaptable automatic spark switch mechanism for efficient energy storage and swift discharge. Additionally, they establish a standardized design methodology for aligning transformers in electrostatic energy conversion systems, resulting in the attainment of remarkably high output charges of 660 μA per cycle [Fig. 17(b)] [82].

Wang et al. demonstrated a comprehensive design methodology for optimizing inductor matching in electrostatic energy conversion systems, ensuring efficient and effective energy conversion processes [Fig. 17(c)] [83]. A super high voltage power management circuit is established by using a spark switch. In terms of the module, the energy conversion efficiency reaches 90.7 %, and the constant energy efficiency is 81.6 %. Liang et al. proposed a voltage reduction circuit using a gas discharge tube (GDT) as a discharge switch [Fig. 17(d)] [80]. The circuit can increase the instantaneous power by 15 times to 30 mW.

4. Summary and perspectives

4.1. Summary

As a plentiful source of renewable energy, wave power is crucial in advancing the shift towards sustainable and green energy systems. Against this backdrop, TENG has risen to prominence in the field of wave energy harvesting, owing to its unique energy conversion mechanism. This review comprehensively depicts the research progress of TENG in terms of wave adaptability, initially describing the fundamental working principle of TENG and analyzing the working modes that are more suitable for wave energy harvesting. Further, by collating existing research on wave energy TENG, this paper summarizes the energy conversion processes and working mechanisms and discusses in detail the key factors affecting the adaptability of wave energy TENG.

This review delves into four dimensions: adaptive structures on the wave surface, underwater adaptive structures, environmental adaptability, and adaptive circuits. Considering the uncertainty and stability issues of energy fluctuations on the wave surface, this paper summarizes the development progress of adaptive TENG from multiple perspectives such as buoy design, PTO optimization, and networking strategies. As the underwater environment is a crucial area for energy harvesting, this paper explores how the adaptability design of underwater structures and biomimetic strategies can enhance the output performance of TENG. Meanwhile, in response to challenges such as high humidity and salinity

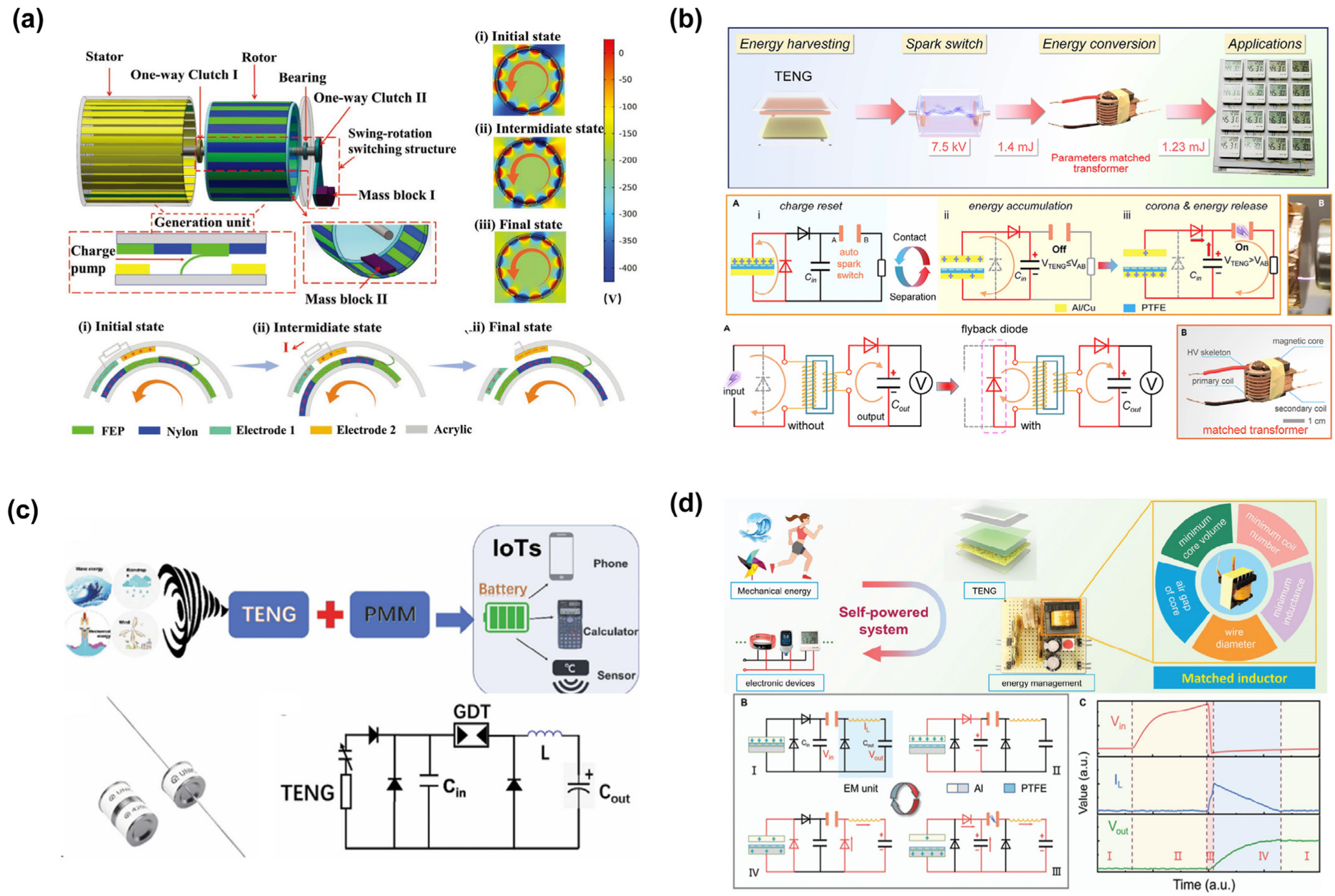

Fig. 17. Research on energy management circuit. (a) A TENG with energy storage/release strategy [79]. (b) An adjustable automatic spark switch circuit [82]. (c) A step-down circuit using a gas discharge tube [83]. (d) A universal design procedure of matched inductors [80].

in the marine environment, this paper summarizes effective strategies for TENG to resist external environmental impacts. Lastly, addressing the need for the orderly energy output of wave energy TENG, this paper reviews the current design concepts of energy management circuits, emphasizing the importance of using power management circuits to effectively collect and orderly release environmental energy, thereby significantly improving energy utilization efficiency.

4.2. Perspectives

To enhance the adaptability and stability of TENG in unordered wave environments, this review proposes some future development directions and applications to meet adaptive design requirements, as shown in Figs. 18 and 19.

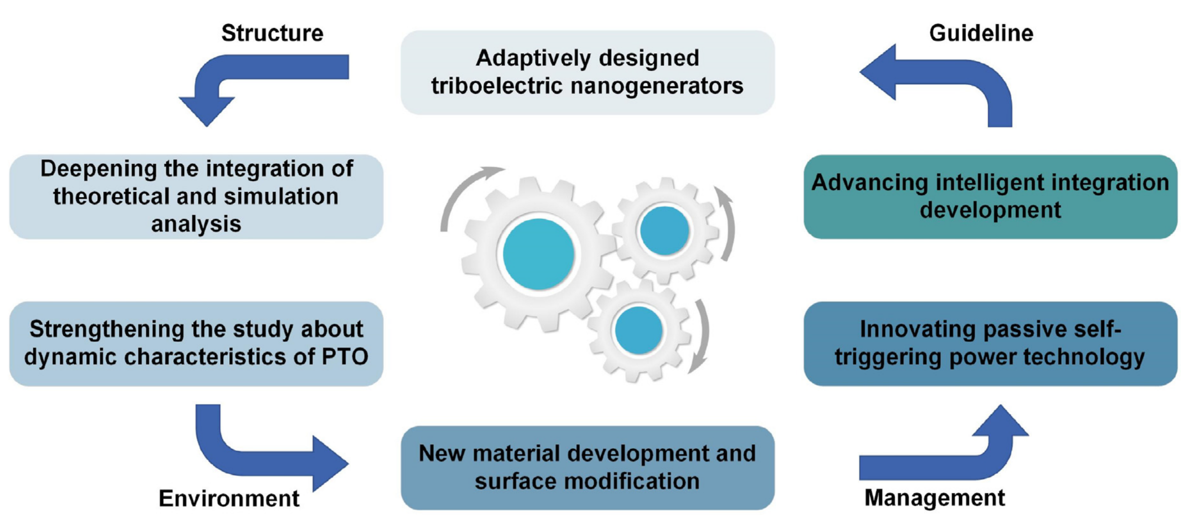

Fig. 18. Perspective on the development direction of TENG in marine science.

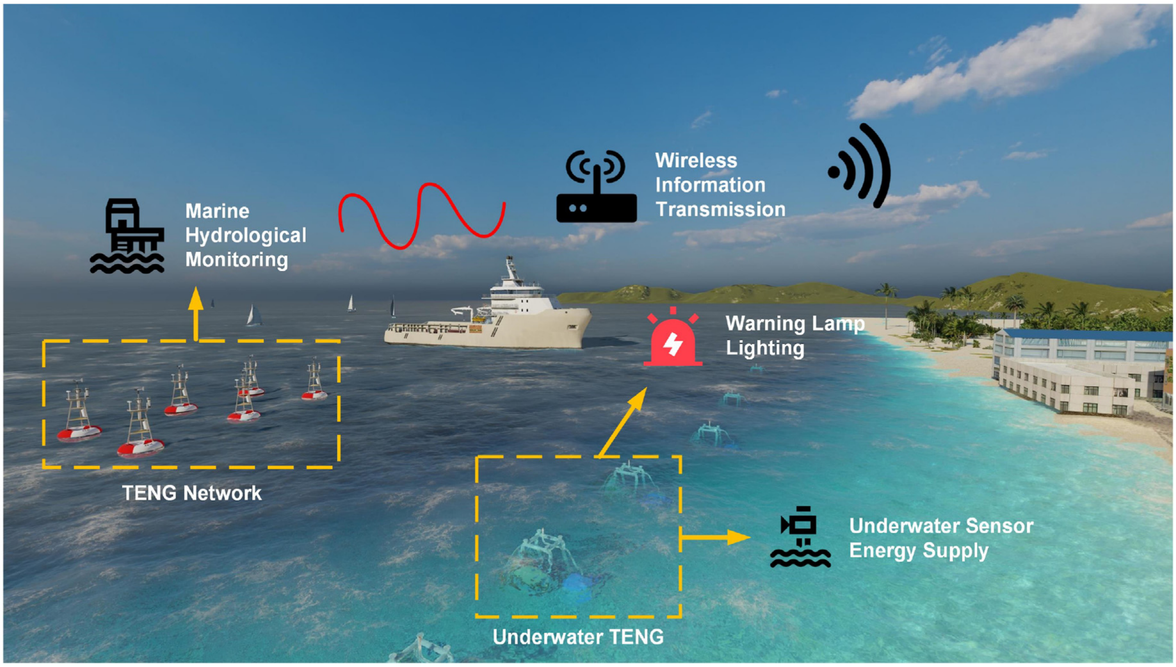

Fig. 19. The application prospect of TENG in the marine environment.

(1) **Deepening the integration of theoretical and simulation analysis:** Through simulation software, it is possible to dynamically model these fluctuating wave conditions, aiding in the design of highly adaptive shell structures. These structures can autonomously adjust their stress distribution and movement patterns based on varying wave states, allowing TENGs to maintain efficient operation in diverse environments. This adaptive design not only enhances the TENG's survivability in different wave conditions but also ensures long-term stability and energy conversion efficiency.
(2) **Strengthening the study about dynamic characteristics of PTO:** Studying the dynamic motion characteristics of the PTO and designing an adjustable PTO system for TENG enables it to adaptively adjust to different wave frequencies and amplitudes, thereby maximizing energy capture. Additionally, precise dynamic analysis allows for the PTO system to distribute stress more evenly under varying wave conditions, preventing localized overloading that could lead to structural damage.
(3) **New material development and surface modification:** Developing corrosion-resistant materials and surface treatment technologies is crucial for ensuring the long-term stable operation of TENG in wave environments. For instance, chemically stable polymer materials can be selected for the triboelectric layer, and the electrode surface can be treated with anti-corrosion coatings. Additionally, nanoscale waterproof and anti-corrosion coatings can enhance the weather resistance of TENG surfaces, reducing the impact of saltwater corrosion on its electrical performance.
(4) **Innovating passive self-triggering power technology:** Current power management circuits primarily rely on buck-chopper technology to improve capacitor charging efficiency, but two critical issues remain unresolved: first, the controlled release and triggering mechanisms are not yet fully optimized, and second, there are challenges in the storage and effective utilization of excess energy. To address these issues, the development of a high-efficiency passive self-triggering switch technology can significantly reduce energy waste and enable more precise energy regulation. Furthermore, incorporating adaptive power management chips can effectively harvest excess environmental energy during idle periods and provide stable energy supply during peak load times.
(5) **Advancing intelligent integration development:** An intelligent management system is developed to monitor and adaptively adjust the output of TENGs after grid connection, optimizing energy distribution. Exploring the integrated application of TENGs with other renewable energy sources, and utilizing intelligent technology to achieve multi-energy complementarity, enhance the overall energy supply stability and efficiency of the system, promoting the widespread application of TENGs in complex grid systems.

CRediT authorship contribution statement

Jianlong Wang: Writing – original draft, Data curation, Visualization, Conceptualization. **Zhenjie Wang:** Writing – original draft, Data curation. **Xinxian Wang:** Writing – original draft, Visualization. **Jiacheng Zhang:** Writing – original draft. **Yanrui Zhao:** Writing – original draft. **Zisen Li:** Writing – original draft. **Borui Yang:** Writing – original draft. **Hengyu Li:** Writing – review & editing, Resources, Conceptualization. **Tinghai Cheng:** Writing – review & editing, Resources, Conceptualization. **Zhong Lin Wang:** Writing – review & editing, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful for the support received from the National Key R & D Project from the Minister of Science and Technology (Nos. 2021YFA1201604 & 2021YFA1201601), the Beijing Natural Science Foundation (No. 3244038) and the China Postdoctoral Science Foundation (No. 2024M753185).

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