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Review Article

Bio-inspired water-driven electricity generators: From fundamental mechanisms to practical applications

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ABSTRACT

Harvesting water energy in various forms of water motion, such as evaporation, raindrops, river flows, ocean waves, and other, is promising to relieve the global energy crisis and reach the aim of carbon neutrality. However, this highly decentralized and distributed water energy poses a challenge on conventional electromagnetic hydropower technologies that feature centralization and scalization. Recently, this problem has been gradually addressed by the emergence of a myriad of electricity generators that take inspiration from natural living organisms, which have the capability to efficiently process and manage water and energy for survival in the natural competition. Imitating the liquid–solid behaviors manifested in ubiquitous biological processes, these generators allow for the efficient energy conversion from water–solid interaction into the charge transfer or electrical output under natural driving, such as gravity and solar power. However, in spite of the rapid development of the field, a fundamental understanding of these generators and their ability to bridge the gap between the fundamentals and the practical applications remains elusive. In this review, we first introduce the latest progress in the fundamental understanding in bio-inspired electricity generators that allow for efficient harvesting water energy in various forms, ranging from water evaporation, droplet to wave or flow, and then summarize the development of the engineering design of the various bio-inspired electricity generator in the practical applications, including self-powered sensor and wearable electronics. Finally, the prospects and urgent problems, such as how to achieve large-scale electricity generation, are presented.

KEYWORDS

bionics, synergy of solid and liquid, electricity generator, surface treatment, energy harvest

1 Introduction

Occupying 70% of the earth's surface, the ubiquitous water intakes 35% solar radiation and contains the energy of around 60 petawatts (10^{15} W) [1–3]. To harvest the gigantic water energy, conventional techniques mainly have received great success in harvesting intensive water energy such as sea wave energy and river potential energy by the use of the heavy and bulk electromagnetic generators, however, fail to harvest the decentralized and small-scale water energy stored in the various forms of water motion, such as raindrops, river flows, ocean waves, and others (Fig. 1). To this end, a myriad of water-driven electricity generators with various mechanisms such as piezoelectric nanogenerators [4, 5], hydrovoltaic technology [6, 7], thermoelectricity [8], and triboelectric nanogenerator (TENG) have been proposed [9–13]. Despite the extensive progress, working in a wide range of working conditions [14–19], the existing water energy harvesting techniques are still susceptible to various issues, such as low energy conversion, poor durability, poor scalability, and low integration, resulting from over-simplified artificial designs [20–27]. For example, symmetrical moisture (invisible water vapor in the air)-driven electricity generators based on homogeneous and isotropic materials exhibit a poor water adsorption capacity, resulting in a decreasing electrical output in severe environments. Besides, some water-driven electricity generators with symmetrical electrode setting lead to a low electrical output due to incomplete solid–liquid interaction.

Fortunately, natural live organisms inspire us with their various abilities to process and manage the water and energy using the least materials yet high efficiency in various environments. For example, the lotus leaf enables the droplet to roll on its surface with an extreme-low resistance benefiting from its hydrophobic micro/nanostructure that holds an air cushion between the

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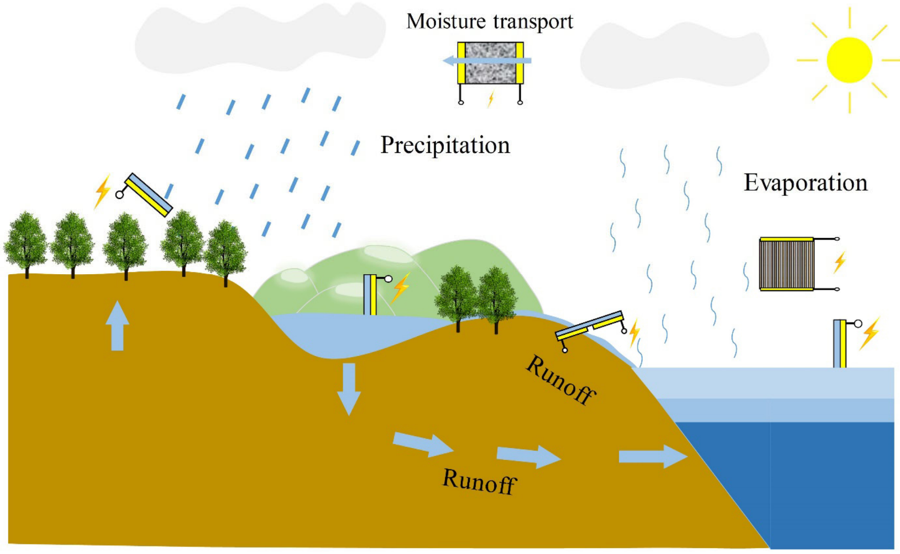

Figure 1 Harvesting energy from the water circle in nature.

droplet and surface, which greatly inspires the study of textured superhydrophobic surfaces [28]. The three-dimensional (3D) asymmetric ratchets of the Araucaria leaf make liquids with different surface tensions flow in different directions [29]. Nepenthes rivet a lot of slippery liquid on the surface through its surface structure, which inspires the innovation of the slippery liquid-infused porous surface (SLIPS) that can repel the liquid efficiently [30]. These unique bio-inspired surfaces provide new sights for designing water energy generators with higher durability and efficiency compared to their artificial counterparts [21, 31–36]. For example, we have demonstrated the lotus-inspired superhydrophobic surface enables energy harvesting from the high-frequency droplet impinging otherwise the electrical outputs decay owing to water retention. Moreover, a water energy generator with durable SLIPS allows for constant electrical output from droplets in harsh environments, such as high humidity, high-salt solution, and even underwater.

Despite the rapid development, the types of the current bio-inspired water-driven electricity generators are too complex and diverse, and lack rational design both in science and engineering to further improve their efficiency and other performances. Therefore, a comprehensive review covering all of the bio-inspired water-driven electricity generators is in urgent need to reveal the fundamentals and preferential applications, which is essential to guide the design, choice, optimization, and fabrication of artificial materials, and then go beyond nature to develop novel water energy generator and systems to satisfy the specific practical application. In this review, the mechanisms of electricity generation for different bio-inspired electricity generators are first concluded. Next, the inspirations got from natural creatures in different bio-inspired electricity generators are reviewed, including bio-inspired waving or flowing water-driven electricity generators, bio-inspired evaporation-driven electricity generators, bio-inspired rainwater-driven electricity generators, and bio-inspired moisture-driven electricity generators. Then the major applications of bio-inspired electricity generators in three fields containing sensors, wearable electricity generators, and self-powered electronics are also summarized. Finally, the remaining challenges and the prospect of the bio-inspired water-driven electricity generator are discussed.

2 Mechanisms of the water-driven electricity generator

Water is the key to the water-driven electricity generator. The bulk water is composed of a huge number of water molecules, distinguished from water molecules and water clusters. Chemically, a water molecule is formed by two hydrogen atoms covalently bonded to an oxygen atom, with an included angle of 104.5° at the oxygen. A hydrogen bond (H…O) can be formed by a negatively charged oxygen atom and a positively charged hydrogen atom in different water molecules, when the distance between two oxygen atoms, and the angle of O-H…O are less than 0.35 nm and 30°, respectively [37]. A hydrogen bond network around a molecule usually has a local tetrahedral coordination in bulk water. The dynamic process of liquid bulk water is the formation and breaking of hydrogen bonds [6]. Besides, water is a weak electrolyte, and there is a reaction in bulk water: $2H_2O \leftrightharpoons H_3O^+ + OH^-$. Physically, the surface tension, heat of vaporization, and boiling point of bulk water in standard state are 72.75×10^{-3} N·m^{-1}, 40.65 kJ·mol^{-1}, and 100 °C, respectively [38, 39]. The bulk water can evaporate into the air, which is accompanied by a decrease in the temperature of the bulk water, so that the bulk water needs to continuously absorb heat from the surrounding environment to sustain evaporation.

The electricity generation process at the solid–liquid interface may be accompanied by ion diffusion, moisture absorption, phase transition, and bulk flow [40]. Contact electrification (CE) affects electricity generation, which refers to the phenomenon that excessive charge exists on the surface of the solid after contacting the liquid. However, the mechanism of CE between solid and liquid is controversial, including electrochemical reaction [41], ion adsorption [42], and electron transfer [43–45]. Due to the vast selection of materials and not identical experimental conditions, the debate on the mechanism of contact electrification at solid-liquid interface has never stopped. Some scholars believe that the surface charge of solids is caused by electrochemical reactions between the impurities in the liquid and the solid surfaces [41]. Zimmermann et al. believe that the adsorption of ions in the liquid to the solid surface is the dominant factor for the CE of polymer materials [42]. Kitabayashi et al. believe that electron transfer leads to the CE phenomenon between insulating oil and solid surface [43]. Nie et al. suggest that the contact electrification at the solid-liquid interface is a mixed mechanism caused by electron transfer and ion transfer [46]. The electron transfer dominates the CE, which results from the overlap of electron clouds (Fig. 2(a)) [46–48]. The thermal motion may cause electrons of the liquid to overcome the potential barrier (E_w) and enter the lowest unoccupied molecular orbital of the positive material due to the overlapping of electron clouds. The stronger CE means more excessive charges on the solid surface [49], which will greatly improve the performance of water-driven electricity generator [14]. Based on ab initio calculations, Xu et al. systematically investigated the interaction of water with graphene oxide [50]. It was reported that a hydrogen atom of a water molecule surrounding an epoxide or carbonyl group is more likely to be attracted to form a hydrogen bond. In the case of a hydroxyl group, the oxygen atom of the water molecule tends to form a hydrogen bond together with a hydrogen atom of the hydroxyl group. Thus, an adsorbed water molecule tends to be an electron acceptor for graphene with epoxide and carbonyl groups. For the hydroxyl and carboxyl groups, water molecules tend to act as electron donors. The electron transfer between water molecule and carboxyl group is the strongest, reaching 0.024 *e*. Besides, they found that the density of state of the hydroxyl and carboxyl groups show a shift and broadening of the resonant peaks after the adsorption of the water molecules. The results indicated that there is an electron hybridization between water molecules and the functional groups. According to the studies mentioned above, the characteristics or functional groups of the solid may affect how charges are exchanged between water and solids. Researchers have comparable views on the mechanism of electricity production, despite the fact that there is disagreement regarding the fundamental mechanism of charge exchange at the solid–liquid interface and certain theories are only applicable to particular liquid/solid pairs.

For electricity generator driven by bulk water, the electricity generation is mainly caused by the time-varying charge at the interface [51], which can be revealed by the electric double layer (EDL) and Maxwell's equations. The EDL formed at the solid–liquid interface and Stern model for the EDL considers that the arrangement of ions at the interface is regular, including

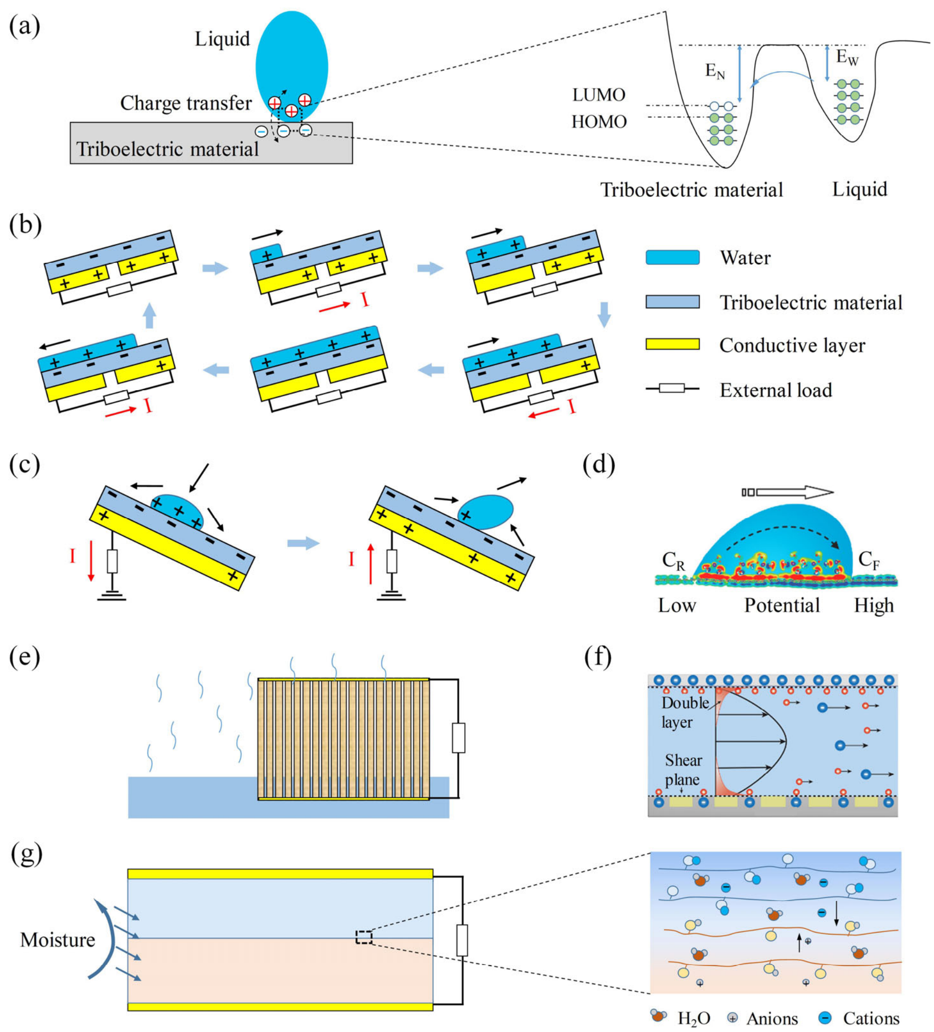

Figure 2 Mechanism of water-driven electricity generator. (a) Electron cloud model of electron transfer between the liquid and triboelectric material. (b) Mechanism of the flowing water-driven electricity generator. (c) Mechanism of the rainwater-driven electricity generator with the conductive layer. (d) Mechanism of the rainwater-driven electricity generator without the conductive layer. Reproduced with permission from Ref. [53], © Nature Publishing Group 2014. (e) Schematic of the evaporation-driven electricity generator. (f) Mechanism of the evaporation-driven electricity generator. Reproduced with permission from Ref. [70], © American Chemical Society 2019. (g) Mechanism of the moisture-driven electricity generator.

the Stern layer and diffusion layer [52–67]. The Stern layer is composed of counter ions, which is strongly attracted onto the surface by electrostatic attraction and van der Waals attraction. And the diffusion layer is composed of ions with opposite charges. The counter ions in the Stern layer play a role in shielding the excessive charge on the surface. When the contact area between bulk water and electricity generator changes, the equivalent charge density at the interface is time-varying. According to Maxwell's equations, this results in a time-varying polarized electric field, leading to an electric current [51, 68].

For waving or flowing water-driven electricity generator (Fig. 2(b)) [69], the surface of the triboelectric material is negatively charged due to the CE. When water covers the left side of the triboelectric material, the counter ions in the Stern layer shield the surface charge on the triboelectric material, and the reduced surface charge density on the left side enables electrons to flow from the right electrode to the left electrode. As the liquid continues to flow toward the right side of the triboelectric material, the electrons flow from the left electrode to the right electrode.

There are two different types of rainwater-driven electricity generators: those with and those without a conductive layer. For the rainwater-driven electricity generator with a conductive layer (Fig. 2(c)), the electricity generation results from the time-varying shielding effect of surface charges. As the droplet hits the surface of the triboelectric material and spreads out, more surface charges are shielded, generating a current flowing from the conductive layer to the ground. As the droplet slides off the surface, less surface charges are shielded, generating an opposite current. For the rainwater-driven electricity generators without the conductive layer, the electricity generation is predominantly attributed to the formation and disappearance of the EDL at the boundary, and the movement of ions in the diffusion layer. For example, when an independent droplet moves along the graphene-based electricity generator surface, the front and tail of the droplet behave as two EDL capacitors, which are charging and discharging, respectively. The formation speed of the diffusion layer is slower than that of the stern layer, leading to the potential difference between the front and the tail of the droplet, known as drawing potential (Fig. 2(d)) [53].

For the evaporation-driven electricity generator, most of scholars attribute the electricity generation to the directional movement of counter ions. The evaporation of water makes liquid flow directionally along the microchannel (Fig. 2(e)). If the diameter of the microchannel is approximately equal to or less than the Debye length, only counter ions will exist in the microchannel due to the overlap of the EDL. The directionally moving water flow driven by capillary pressure will cause the counter ions to migrate directionally and cause a concentration difference of the counterions in the microchannel, thereby generating a current and potential difference, known as streaming potential (Fig. 2(f)) [70]. Unfortunately, most works can't be perfectly explained by the streaming potential, and further mechanisms need to be explored.

For the moisture-based electricity generator, some scholars attribute the electricity generation to the differential distribution of chemical groups in the host material or the differential distribution of moisture. For example, after the host material with different functional groups in different parts absorb moisture, cations are dissociated from the upper part, and anions are dissociated from the lower part (Fig. 2(g)). The concentration difference of anions and cations between different areas results in the directional flow of the two, which jointly generate an electric current. While some scholars suggest that the fast response of the device to moisture flow stems from chemisorption occurring at the interface instead of the diffusio-osmosis mechanism, and moisture and pressure conveyed by the flow are two prerequisites for the device to produce electricity [71].

3 Bionics in different water-driven electricity generators

Bionics has inspired many elegant designs and plays an increasingly important role in many fields. This chapter summarizes the application of bionics in water-driven electricity generators driven by different forms of water in the water circle, including waving or flowing water, evaporation, rain, and moisture.

3.1 Bio-inspired waving or flowing water-driven electricity generator

A considerable part of the water on earth exists in the form of bulk water, such as rivers, lakes, and oceans. It is reported that the energy contained in a wave farm can power the town [72], and how to harvest the energy from the bulk water is a technical difficulty. The electricity generator driven by waving or flowing water can generate electricity through the screen effect of the Stern layer on the surface charge of the solid. Bionics has contributed a lot of inspiration to the design of water-driven electricity generators.

Since the contact and separation between the solid and the liquid are fundamental to the electricity generation of the water-driven electricity generator, the electrical output performance of water-driven electricity generators is mediated by the contact behavior of the solid-liquid interface. Since the microstructures of organisms such as lotus leaf and water strider were discovered [73, 74], bio-inspired textured surfaces have been rapidly developed. Various methods have been developed to modulate surface wettability, which greatly promote the development of water-driven electricity generators [20, 35, 74–84]. Therefore, an understanding of the effect of texture on the hydrophobicity of materials is necessary. There are three phases involved at the triple-phase interface: liquid, solid, and gas. The thermodynamic equilibrium between these three phases leads to a unique contact angle θ_Y on the ideal surface, which is expressed by Young's equation [85]:

$$\cos\theta_Y = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}} \tag{1}$$

with γ_{sv}, γ_{sl}, and γ_{lv} denoting the surface tensions at solid/gas, solid/liquid, and liquid/gas interfaces, respectively. Surfaces with contact angle larger than 90° are classified as hydrophobic. Based on Young's equation, in 1936, Wenzel extended the basic wetting to the rough surface with chemical heterogeneity [86]. The apparent contact angle θ_W can be calculated as:

$$\cos\theta_W = \frac{r(\gamma_{sv} - \gamma_{sl})}{\gamma_{lv}} = r\cos\theta_Y \tag{2}$$

with r denoting the roughness ratio, defined as the ratio of the actual solid/liquid contact area to its apparent contact area. Distinctly, a more complicated model was developed by Cassie and Baxter to describe the wetting phenomenon on heterogeneous surface consisting of various materials [87, 88],

$$\cos\theta_{C-B}=f_s(\cos\theta_Y+1)-1 \quad (3)$$

where θ_{C-B} is the Cassie–Baxter contact angle, f_s is the fraction of rough solid surface area that is wetted by sessile droplet. According to Young's equation, contact angles endowed by flat surfaces are quite limited. While Wenzel's equation and Cassie–Baxter model suggest that roughness on the hydrophobic surface or the increase of vapor fraction contributes to a higher hydrophobicity, which provides a theoretical basis for surface texture treatment to improve hydrophobicity. In some special cases, re-entrant or double re-entrant structures can even reverse their surface wettability from hydrophilic to superhydrophobic [80]. Although the patterned surfaces with microstructures are beneficial for enhancing the performance of electricity generators [27, 51, 89, 90], the superhydrophobic surface may lead to a lower effective contact area between the solid and the liquid, a perfect tradeoff needs to be gained. The effect of nanostructure roughness on the electrical output of the electricity generator was investigated [91]. Electricity generators with three different surface structures (nanohole-fluorinated (NHF), nanoflake-fluorinated (NFF), and micro/nano-fluorinated (MNF)) were used to verify the effect of structural roughness (Fig. 3(a)). The contact area fraction of NHF was the largest and that of MNF was the smallest. Correspondingly, the contact angle of MNF was the largest and the contact angle of NHF was the smallest (Fig. 3(b)). The experimental results showed that the electrical output was positively correlated with the contact area fraction (Fig. 3(c)). For hydrophobic surfaces, a larger contact angle led to a smaller electrical output under certain conditions. In addition to the uniform wettability of the surface, region-specific wettability can mediate the time-varying shielding of the surface charge by the EDL. The differential time-varying shielding effect will be a novel idea to regulate the output of the electricity generators. For example, an electricity generator with a hydrophobic top layer and a hydrophilic bottom layer was fabricated by using different materials [92]. The wettability of different parts allowed the formation of water bridges. The EDL could be mechanically modulated to generate electricity by adjusting the height of the water bridges, which connect the top layer and the bottom layer.

Compared with open-structured electricity generators, closed-structured electricity generators don't need additional water supply [93]. One of the research focuses of closed-structure electricity generators is the property of the inner surface. A cylindrical closed electricity generator with anodized aluminum oxide (AAO) as the inner surfaces was fabricated. The effect of AAO's parameter on wettability and electrical output was investigated (Fig. 3(d)) [94]. Wettability was controlled by the pore size, anodizing time, and coating of AAO (Fig. 3(e)). The experimental results showed that with the increase of the broadening time of the nanostructure, the hydrophobicity first increased and then decreased sharply, and the roughness ratio decreased. The open circuit voltage decreased with increasing nanostructure thickness due to weakened electrostatic induction (Fig. 3(f)).

In addition to the plant, animals also inspire the design of waving or flowing water-driven electricity generators. Electric eels can generate electricity thanks to the regulation of sodium

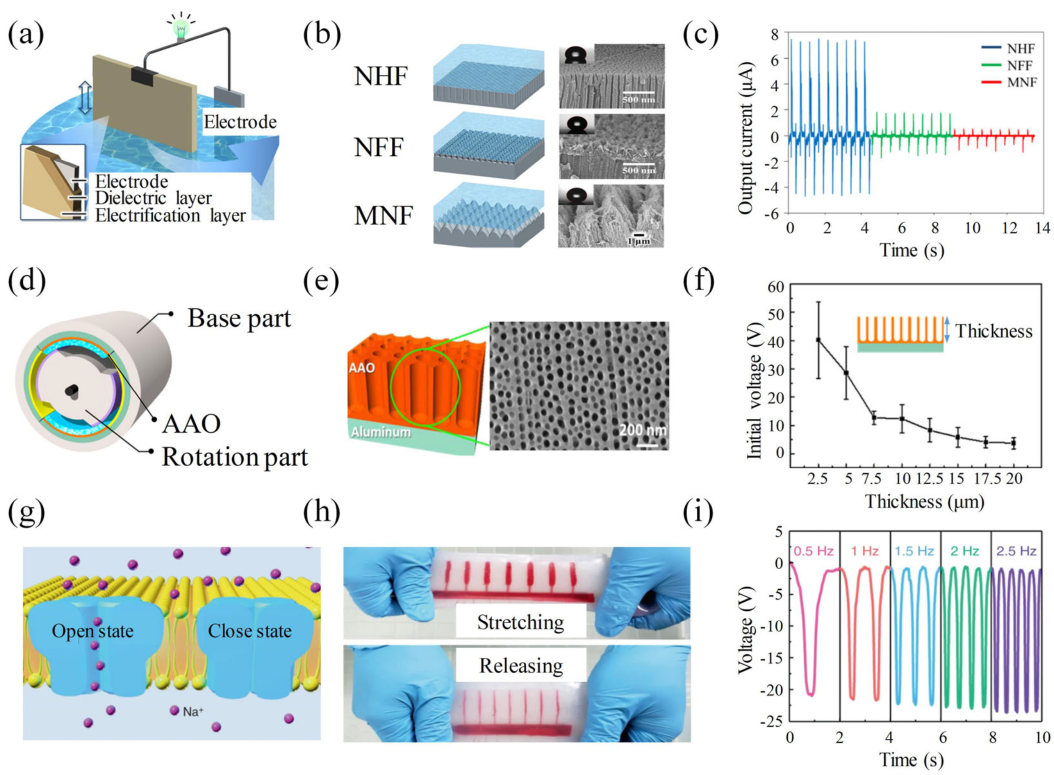

Figure 3 Bio-inspired waving or flowing water-driven electricity generator. (a) Schematic illustrations of a typical waving or flowing water-driven electricity generator. (b) Comparisons of structural illustrations and SEM images of different surface. (c) Comparisons of short-circuit current for different surface structures. (a)–(c) Reproduced with permission from Ref. [91], © Elsevier B.V. 2018. (d) Schematic illustration of the lotus leaf-inspired closed-structure electricity generator. (e) Structure of the AAO. (f) Dependency of electrical output on the thickness of the AAO structure. (d)–(f) Reproduced with permission from Ref. [94], © American Chemical Society 2016. (g) Structural illustration of electric eel cell's ion channel. (h) Electric eel cell-inspired stretchable electricity generator. (i) Electrical output of the electric eel cell-inspired stretchable electricity generator. (g)–(i) Reproduced with permission from Ref. [95], © Zou, Y. et al. 2019.

and potassium ions in and out of electric cells through specific ion channels (Fig. 3(g)) [95]. In the inactive state of the electric cell, the concentration of potassium ions inside the cell membrane is higher than those outside the membrane, and the opposite for sodium ions. When electrical cells are in an active state, neurotransmitters open specific ion channels, which permit the flow of sodium and potassium ions driven by a concentration gradient to generate a voltage. Inspired by the electric eel, a stretchable device containing left and right cavities and channels controlled by mechanical external forces was developed (Fig. 3(h)) [95]. By controlling the opening and closing of the channel, the liquid in the device could flow in the left and right cavities under negative pressure, accompanied by the time-varying shielding of EDL on the inner wall. Stretching and releasing this flexible device could generate a voltage in excess of 20 V, which was slightly affected by the working frequency (Fig. 3(i)).

At present, when using water flow and wave to generate electricity, most devices are semi-submerged in water. While more energy exists underwater, how to harvest energy from underwater remains a challenge. The marine organisms may provide new inspirations to design the electricity generator working entirely underwater in the future.

3.2 Bio-inspired evaporation-driven electricity generator

Evaporation is a process in which water absorbs latent heat from the environment and changes from liquid to gas, which is an essential part of the water cycle. Evaporation is widespread in nature, and this process is accompanied by huge energy conversion. It will be of great significance to research how to obtain electricity from evaporation. Unlike other types of water-driven electricity generators, evaporation-driven electricity generators produce a stable direct current, which is one of its greatest advantages. Bionics has greatly promoted research on evaporation-driven electricity generators.

Conventional evaporation-driven electricity generators are predominantly dominated by nanostructured carbon materials, such as carbon nanotubes or graphene [96–98]. Electrophorus electricus' survival skill is attributed to ion channels and ion pumps regulated by specific proteins [99]. This ion channel fuels a boom in research into one-dimensional channel-based electricity generation [100–102]. An electrogenetic layered graphene hydrogel membrane (GHM) with ion channels was prepared as a macroscopic membrane material for electricity generation (Fig. 4(a)) [103]. Ion channels allowed only opposing ions to pass through (Fig. 4(b)). The electrical output was affected by the pressure gradient of the electrolyte liquid (Fig. 4(c)).

Nonetheless, to achieve efficient energy conversion, complex system design [104] and material treatment [98] are required, which have been met by some natural materials. Layered double hydroxides (LDHs) are naturally inherently hydrophilic ionic layered materials with nano-sized interlayer gaps allowing water to flow through [105]. The LDH-based evaporation-driven electricity generator could achieve continuous electricity generation (Fig. 4(d)) [105]. The Debye length of the DEL on the LDH surface is 0.96 μm, while the interlayer gap is only 50 nm. The strong overlap of the DEL only allows OH^- and

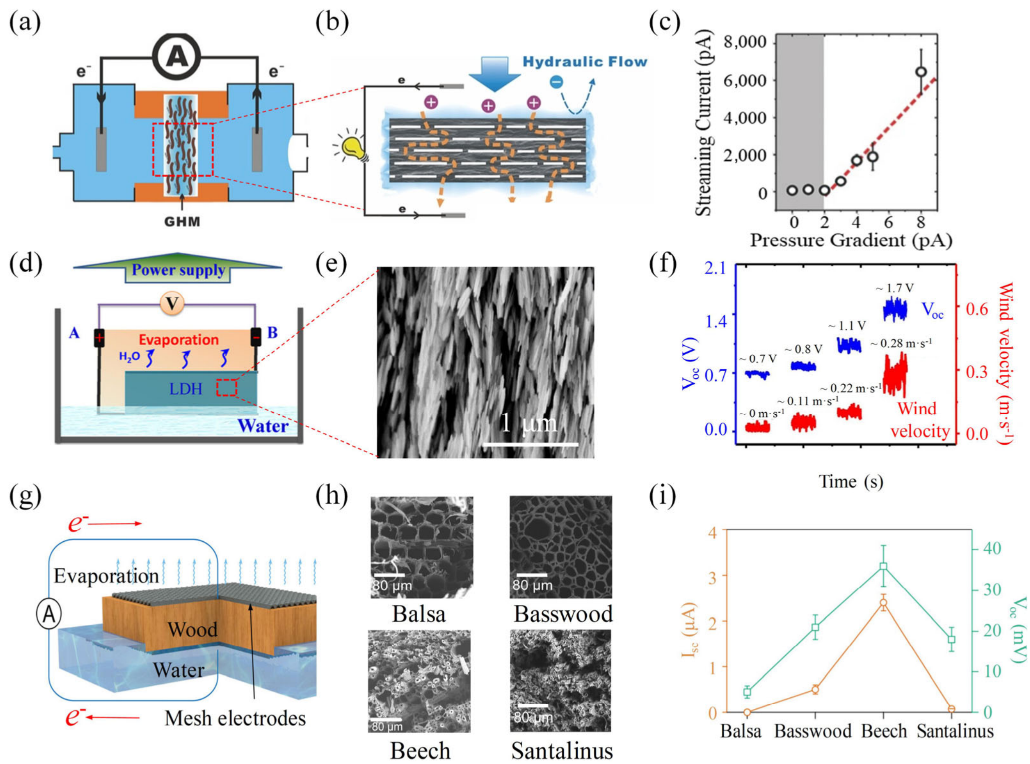

Figure 4 Bio-inspired evaporation-driven electricity generator. (a) Schematic illustration of GHM-based evaporation-driven electricity generator. (b) Working mechanism of the GHM-based evaporation-driven electricity generator. (c) Factors affecting the electrical output of the GHM-based evaporation-driven electricity generator. (a)–(c) Reproduced with permission from Ref. [103], © Wiley-VCH Verlag 2013. (d) Schematic illustration of LDH-based evaporation-driven electricity generator. (e) SEM image of a Ni–Al LDH film, showing natural micro channel. (f) Relationship between the electrical output and wind speed. (d)–(f) Reproduced with permission from Ref. [105], © Elsevier B.V. 2019. (g) Schematic diagram of a wood-based evaporation-driven electricity generator. (h) SEM images of different woods-based evaporation-driven electricity generator (Scale bar: 80 μm). (i) Open circuit voltage and short circuit current of different woods-based evaporation-driven electricity generator. (g)–(i) Reproduced with permission from Ref. [106], © American Chemical Society 2020.

water molecules to be driven through the interlayer gap by the pressure gradient, leading to electricity generation (Fig. 4(e)). A single LDH-based evaporation-driven electricity generator could generate a voltage of 0.8 V and a current of 1.3 μA with a maximum power density of 16.1 $\mu W \cdot cm^{-3}$. The electrical output of the LDH-based evaporation-driven electricity generator was modulated by parameters, which could affect the evaporation rate, e.g. wind speed (Fig. 4(f)).

The microchannels of porous materials (such as carbon nanotubes, graphene oxide, metal oxides, etc.) for evaporation-driven electricity generators are mostly tortuous, which are hydrodynamically unfavorable, resulting in reduced electrical output. There are a large number of nutrient transport channels in the xylem of plants. Inspired by natural wood, several evaporation-driven electricity generators by using diverse woods were fabricated (Fig. 4(g)) [106]. Wood is predominantly composed of hydroxyl-rich cellulose and lignin. When water flows through the microchannels smoothly driven by evaporation, the hydroxyl groups are hydrolyzed and the concentration difference progressively accumulated to form a continuous current. Different woods produced different voltages depending on the dimension of the delivery channel (Fig. 4(h)), among which beech generated the highest electrical output (Fig. 4(i)). The streaming potential, capillary pressure, and hydrodynamic flow resistance were analyzed. Theoretical calculations showed that reducing the pore size and tube length could enhance the output, while too small pore size brought a significant increase in flow resistance, which inhibited the water flow and even made the current disappear. The highest electrical output of beech is due to the optimal pore size. The treatment of wood with citric acid could effectively increase the hydrophilicity and zeta potential, leading to increase of the electrical output. The study of the electrokinetic effect of single nanopores can help boost energy conversion efficiency [107]. The electrokinetic properties of individual circular nanopores were investigated using orbital etching. It was found that the orbital-etched nanopores had higher surface charges, indicating better electricity generation capacity [108].

3.3 Bio-inspired rainwater-driven electricity generator

As one of the most common natural phenomena, precipitation converts the gravitational potential energy of the droplet into kinetic energy. More and more researchers are now turning to the study of harvesting energy from water droplets [17, 109]. The rainwater-driven electricity generator relies on the time-varying shielding effect of the EDL on surface charge. And the elegant design based on bionics considerably promotes its development.

The key to the performance of rainwater-driven electricity generators is to control the contact behavior of droplets and solids, which has been extensively researched [110–112]. Surfaces with micro-structure derived from natural creatures' structures have great applications in rainwater-driven electricity generators [16, 113]. The effect of structure on the electrical output and stability of rainwater-driven electricity generators was investigated (Fig. 5(a)) [114]. The electricity generator with a nanostructured

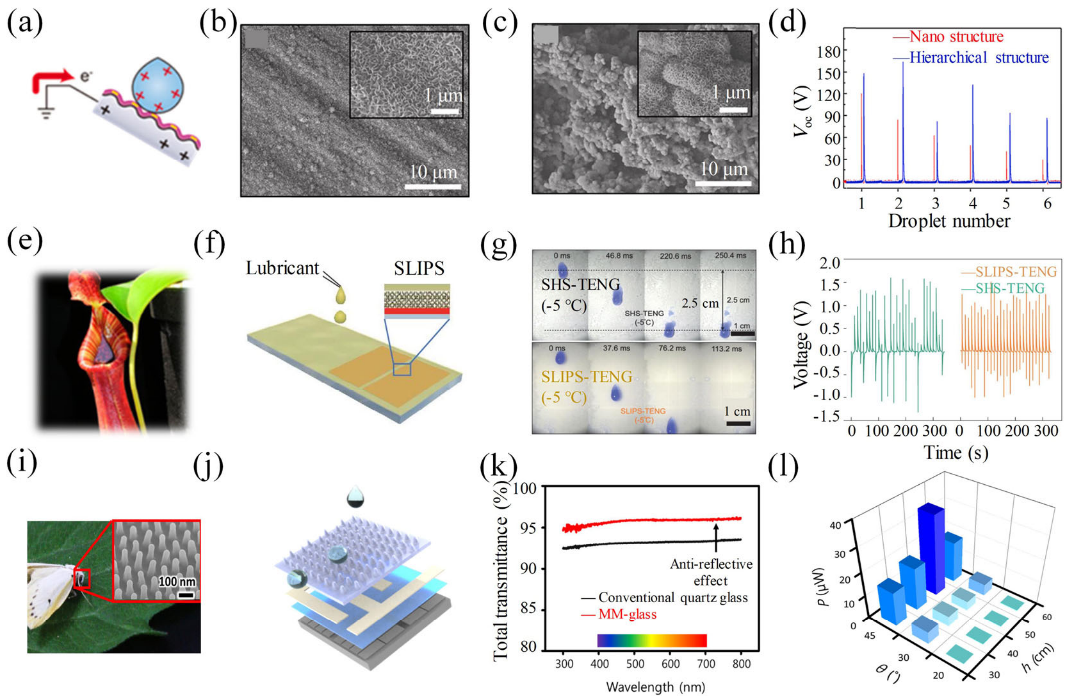

Figure 5 Bio-inspired rainwater-driven electricity generator. (a) Schematic images of a rainwater-driven electricity generator. (b) SEM image of nanostructured superhydrophobic surface of the rainwater-driven electricity generator. (c) SEM image of hierarchically structured superhydrophobic surface of the rainwater-driven electricity generator. (d) Electrical output comparison of a rainwater-driven electricity generator with nanostructured superhydrophobic surface and a rainwater-driven electricity generator with hierarchically structured superhydrophobic surface. (a)–(d) Reproduced with permission from Ref. [114], © Elsevier B.V. 2019. (e) Image of the Nepenthes Pitcher. Reproduced with permission from Ref. [117], © American Chemical Society 2014. (f) SLIPS-based electricity generator. (g) Separation of droplets from different surfaces at low temperatures. (h) Electrical output of the SLIPS-TENG and SHS-TENG. (f)–(h) Reproduced with permission from Ref. [120], © Oxford University Press 2019. (i) SEM image of the moth's eye. (j) Schematic of the hybrid system with the MM-glass-based TENG and solar cell. (k) Total transmittance of conventional quartz glass and MM-glass at the wavelength ranging from 300 nm to 800 nm. (l) Power of the MM-TENG at different impacting conditions. (i)–(l) Reproduced with permission from Ref. [121], © Elsevier B.V. 2019.

superhydrophobic surface and the electricity generator with a hierarchically structured superhydrophobic surface were assembled, respectively (Figs. 5(b) and 5(c)). The comparative experimental results demonstrated that the initial voltages generated by the hierarchically structured and nanostructured electricity generators were similar, while the electrical output of the hierarchically structured electricity generator was more stable (Fig. 5(d)). The droplet hits the surface and splits into numerous small droplets. The small droplets merged into larger droplets on the hierarchically structured surface and slipped off the surface, and converged on the nanostructured surface to form a water film to shield the surface charge, resulting in a rapid decrease in output.

As we mentioned above, lotus leaf-inspired three-phase contact is most often used to improve surface hydrophobicity, while these conventional hydrophobic or superhydrophobic surfaces are prone to failure under extreme conditions, such as low temperature and high humidity [115], which restricts the efficiency and application scope of the electricity generator. Thanks to the infinite wisdom of nature, natural organisms have evolved another way to keep water away from them, liquid-liquid contact, e.g. nepenthes. Nepenthes rivet a lot of liquid on the surface through the surface structure, and this slippery liquid-lubricated surface is suitable for dust proofing and catching bugs (Fig. 5(e)) [116, 117]. This liquid film has been proven effective in reducing friction [118, 119]. The fluorinated lubricating fluid was injected into a porous PTFE film to fabricate a novel slippery lubricant-impregnated porous surface-based TENG (SLIPS-TENG), as shown in Figure 5(f) [120]. The fluorinated lubricating liquid converted the liquid-solid friction into liquid-liquid friction, which achieved effective separation of droplets and surfaces. Even in cold environments, SLIPS-TENG could still be effectively separated from the water droplets instead of superhydrophobic surface-based TENG (SHS-TENG) (Fig. 5(g)). When its thickness was less than the critical thickness, SLIPS-TENG had unexpected charge transparency and it could generate a voltage comparable to SHS-TENG (Fig. 5(h)).

To improve the efficiency of electricity generation, all-weather electricity generators can be fabricated by combining the rainwater-driven electricity generator with a solar cell. Typically, a rainwater-driven electricity generator is designed as the top of the device, while the solar panels are placed at the bottom of the device. However, it is a challenge to the transparency of the rainwater-driven electricity generator. In order to avoid predators, the surface of moths' eye has a periodic array of cone-shaped nano-arrays (Fig. 5(i)). These nano-arrays allow the refractive index to increase smoothly from the air to the surface of the moth's eye, which can reduce the reflection of light on the surface of their eyes and increases light transmission. Inspired by the surface structure of the moth's eye, a superhydrophobic moth-eye-mimicking glass (MM-glass) was prepared, which was used as the functional surface of the rainwater-driven electricity generator (Fig. 5(j)) [121]. In addition to the ultra-high light transmittance improving the conversion efficiency of solar cells (Fig. 5(k)), the superhydrophobicity of MM-glass enabled the electricity generator to have a dust-proof property and high output power, which could reach more than 30 μW by adjusting the angle and droplet height (Fig. 5(l)).

3.4 Bio-inspired moisture-driven electricity generator

Ambient moisture, arising from liquid water after absorbing heat, is a "high-energy" substance. Due to technical limitations, energy harvesting from ambient moisture was once considered difficult [40], and the invention of the moisture-driven electricity generator makes it easy.

Graphene and its derived materials are usually used for the materials choice of the moisture-driven electricity generator [122], however, material modification and structural design are required, which undoubtedly increases the cost. Various biofibers are suited for generating electricity from moisture due to their inherent hydrophilicity and naturally charged surface. Natural biofibers, like cellulose, chitin, silk fibroin, and amyloid can be used to prepare the asymmetric natural biofibers aerogel-based moisture-driven electricity generator with better biocompatibility and degradability (Fig. 6(a)) [123]. The moisture is absorbed by the hydrogel and evaporates continuously to generate a continuous electrical current (Fig. 6(b)). The electrical output of the moisture-driven electricity generator is usually improved by adjusting relative humidity (RH), moisture flow rate, and functional group content (Fig. 6(c)).

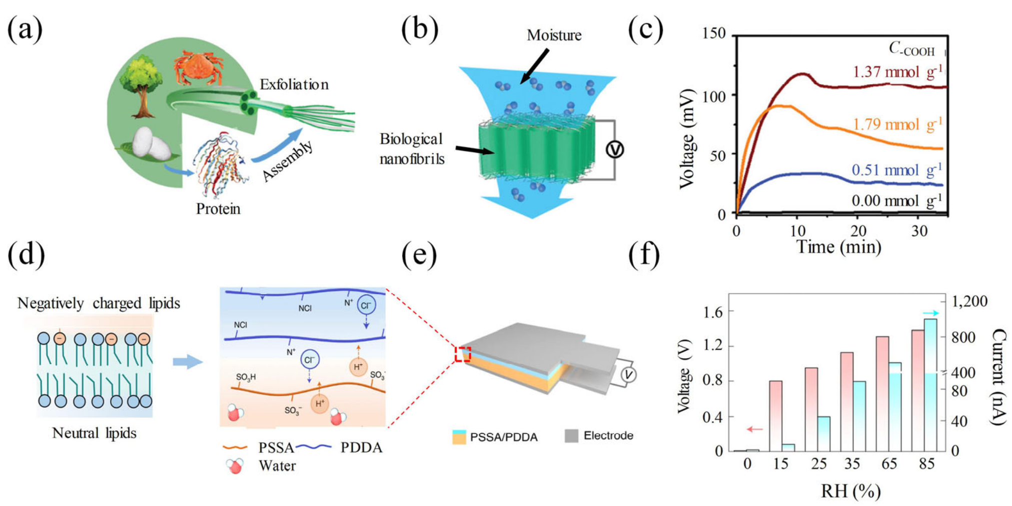

Figure 6 Bio-inspired moisture-driven electricity generator. (a) Schematic illustration of natural nanofibers. (b) Schematic illustration of biological generator under moist air flow. (c) Effect of carboxyl content on V_{oc}. (a)–(c) Reproduced with permission from Ref. [123], © Wiley-VCH Verlag 2019. (d) Asymmetrical lipid bilayer inspired material for moisture-driven electricity generator. (e) Schematic illustration of bio-inspired structure of the HMEG. (f) Voltage and current in response to variation in RH. (d)–(f) Reproduced with permission from Ref. [124], © Wang, H. Y., et al. 2021.

The electrical outputs of the conventional moisture-driven electricity generators predominantly rely heavily on changes in RH of the experimental environment, while the change in the RH of the actual natural environment is slow. The asymmetric lipid bilayers of cell membranes inspired the material design of a moisture-driven electricity generator to efficiently extract energy (Fig. 6(d)). A heterogeneous moist-electric generator (HMEG) with a bilayer of polyelectrolyte membrane was fabricated (Fig. 6(e)) [124]. This bio-inspired asymmetric design enabled a single HMEG to generate a voltage of 0.8 V at very low RH (15%) and a peak voltage of ~1.38 V at RH 85% in the air (Fig. 6(f)). The integrated HMEG even generated a voltage over 1,000 V, which enabled the commercial application of moisture-based electricity generators.

For environments with low RH, another possible way to increase the electrical output of the moisture-driven electricity generator is to increase its ability to absorb moisture. Rhacocarpus purpurascens (Rhacocarpaceae), a moss living in dry African environments, can efficiently and directionally absorb water from the air owing to its hydrophilic cell wall and hierarchically porous structure [125]. Inspired by the rhacocarpaceae, Cheng et al. designed a Rhacocarpus-inspired porous surface (RIPS) containing an array of micro-pores whose sidewall was decorated with nanogrooves [22]. The top material of the RIPS was hydrophilic, and the side walls of the micro-holes were more hydrophilic by increasing the roughness. This unique structure allowed water to penetrate the material from the outside, which was anticipated to was anticipated to improve the water absorption efficiency of the electricity generator.

4 Application of water-driven electricity generators

Compared with other electricity generation technologies, the inherent advantages of water-driven electricity generator are impressive, which can obtain energy from abundant water resources [23, 126–130]. Based on the unique interaction between solid and liquid, and material deformability, the water-driven electricity generator can be used as sensors [131–134], wearable/implant electricity generator [135–137], or self-powered electronics [138–142].

4.1 Sensor

Modern intelligent processing systems include task setting, environmental perception, data processing, and task execution, among which environmental perception requires a large number of sensors. In the electricity generation process, the electrical output signal is related to the state of the water-driven electricity generator, and the kinematics and the properties of the liquid. Thus, water-driven electricity generators can be used as sensors to monitor parameters related to these three aspects. For example, an electric eel-inspired electricity nanogenerator was fabricated by using stretchable polydimethylsiloxane and silicone, and liquid [95]. The electric eel-inspired electricity nanogenerator could be stretched over 60%, which could be made into a wearable sensor (Fig. 7(a)). Since the electrical output was related to the strain, this wearable sensor can monitor movement differences between the elbow and knee during swimming (Fig. 7(b)). A seaweed-like electricity generator can work under the water (Fig. 7(c)), and the electrical output varies with the vibration frequency of the bulk water (Fig. 7(d)), which can be used as an ocean wave sensor [134]. Since the EDL is modulated by the properties of the liquid, a cell membrane-inspired electricity generator can monitor the change in pH (Figs. 7(e) and 7(f)). Outperforming the conventional water-driven generators, bio-inspired water-driven electricity generators feature high stability in converting the surrounding inputs to electric output in various environments owing to the unique biomimetic surface design. For example, inspired by the slippery surface of nepenthes, our previous work has reported a slippery lubricant-impregnated porous surface (SLIPS)-based electricity generator that could maintain electricity generation performance in harsh environments [120]. The SLIPS based electricity generator eliminated contact line pinning and random surface defects, which allowed the droplet to slip smoothly at −5 °C. In contrast, for conventional superhydrophobic water-driven electricity generators, the superhydrophobic state of the surface was easily broken down due to the formation of ice/frost, resulting in a decrease in the electrical output. It was found that the electrical output of SLIPS-based electricity generator is dependent on the droplet size and velocity, and thus, it is very suitable for using as a rain sensor. Currently, conventional water-driven electricity generator-based sensors have realized the monitoring of liquid species [131, 143], temperature [132], velocity [144], displacement [144], flow [133], humidity [145], etc. However, limited by materials and structures, the stability and scalability of these sensors are still poor. More bio-inspired biocompatible and environmentally friendly materials need to be developed in time to advance the field.

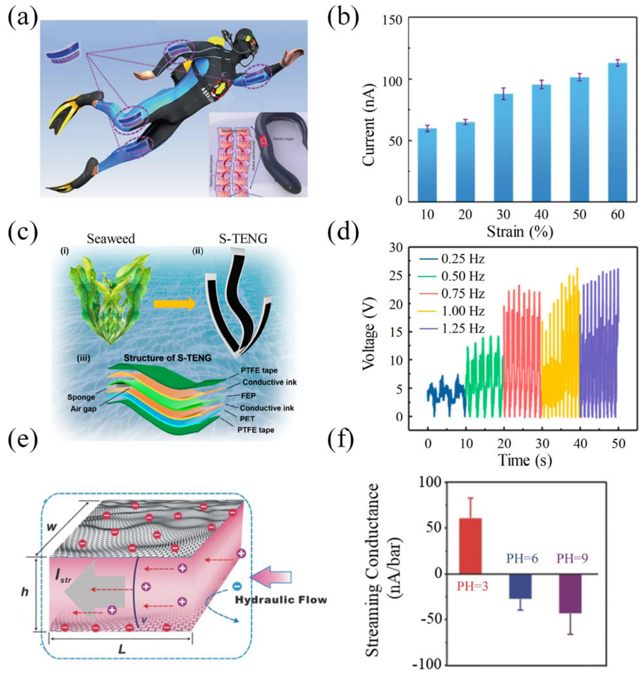

Figure 7 Bio-inspired water-driven sensor. (a) Schematic diagram of an underwater wearable sensor. (b) Relationship between the output current of an underwater wearable sensor and the strain. (a) and (b) Reproduced with permission from Ref. [95], © Zou, Y., et al. 2019. (c) Schematic illustration of a seaweed inspired electricity generator. (d) Typical voltage response of a seaweed-like electricity generator to vibration frequency of the bulk water. (c) and (d) Reproduced with permission from Ref. [134], © American Chemical Society 2021. (e) Working mechanism for the electricity generation of a cell membrane inspired electricity generator. (f) pH-induced change in streaming conductance, which suggests that water-driven electricity generators can act as pH sensors. (e) and (f) Reproduced with permission from Ref [103], © Wiley-VCH Verlag 2013.

4.2 Wearable/implant electricity generator

Unlike other emerging power generation technologies, water-driven electricity generators are well suited for harvesting energy from human motion due to their deformability and compact size. Inspired by the anterior and posterior membranes of electric eel's electrocytes (Fig. 8(a)), a printed artificial electric organs was fabricated by four compositions of hydrogel arrays as analogues of the four major components of an electrocyte (Fig. 8(b)) [137]. It was reported that a voltage of about 110 V was generated by 449 gels stacked in series (Fig. 8(c)). Compared with the degradable or even environment-harmful materials of the traditional water-driven electricity generator [32], one of the advantages of the bio-inspired water-driven electricity generator is its excellent biocompatibility and deformability owing to the use of the biomimetic material, which is more suitable for wearable/implant electricity generator. Inspired by the microstructure of the lotus leaf, a compact-sized water-driven electricity generator with a micro-nano binary structure was fabricated to harvest energy from the arm swing (Figs. 8(d) and 8(e)) [136]. During exercise, a voltage of about 6 V can be generated due to the arm swing (Fig. 8(f)). In the future, this wearable water-driven electricity generator may become the main power supply unit for portable electronic devices.

4.3 Self-powered electronics

Some single-function electronics consume very little energy and only require a small battery to drive. Nonetheless, it is problematic to collect a massive number of batteries, which will cause serious damage to the environment. Hence, it is indispensable to develop self-powered electronics, which can be satisfied by water driven electricity generators [138, 139, 141]. Li et al. fabricated a natural biofibers aerogel-based biologic electricity generator-driven by moisture with better electrical output performance and degradability, which could be used as a portable self-powered sensor or self-powered PM 2.5 removal device (Fig. 9(a)) [123]. Compared with other moisture products, the output voltage was increased by about 30–70 mV due to the charge asymmetry of the biofibers aerogel [146–149]. The superior properties of the bio-inspired material allowed it to have longer persistence under moisture [21, 147, 149, 150] and higher PM 2.5 removal efficiency [151–153]. Besides, the good degradability allowed the biofibers aerogel to quickly decompose itself without polluting the environment (Fig. 9(b)). Inspired by the cellular bilayer, an asymmetric electricity generator driven-driven by moisture was fabricated, called a heterogeneous moist-electric generator (HMEG) [124]. The asymmetric structure helped adsorb moisture efficiently and resulted in ion concentration differences in different areas, providing excellent electrical output. The HMEG had sufficient capacity to power commercial electronic devices to form self-powered electronic devices, such as a self-powered electronic ink display (Fig. 9(c)). The molybdenum disulfide (MoS_2) channels in the self-powered field effect transistor could be controlled by HMEG. When the HMEG generated a positive voltage of 100 V, the MoS_2 channel was turned on, and when the voltage was reversed, the MoS_2 channel was completely turned off (Fig. 9(d)). In addition, bio-inspired water-driven electricity generators had the potential to serve as energy units embedded in a wide variety of electronic devices, such as self-powered calculators [138], self-powered gas detection devices [139], self-powered smart windows [141], and self-powered forest environment detection systems [142].

5 Conclusions and future perspectives

Water is one of the most abundant substances in the world and contains enormous energy. The water-driven electricity generator can obtain energy from various forms of water, which is an emerging technology, attracting more and more attention. However, the development of water-driven electricity generators has been hindered due to technical limitations. Natural selection has made many organisms with perfect and unique designs, and biomimicry has gradually developed on this basis. At present, bionic has been applied to water-driven electricity generators and various bio-inspired water-driven electricity generators are introduced using a parallel approach in this review.

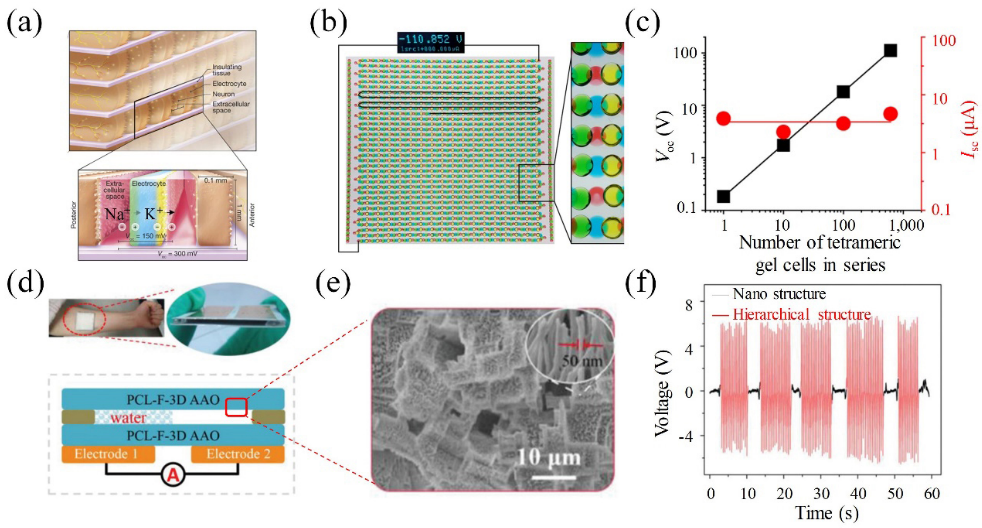

Figure 8 Bio-inspired water-driven wearable electricity generator. (a) Electrocytes' arrangement within the electric organs of the electric eel. (b) Printed artificial electric organs fabricated by four compositions of hydrogel arrays. (c) Output characteristics of printed artificial electric organs. (a)–(c) Reproduced with permission from Ref. [137], © Macmillan Publishers Limited, part of Springer Nature 2017. (d) Photos and schematic diagram of a wearable water-driven electricity generator. (e) SEM image of micro-nano binary structure. (f) Voltage generated by arm swing in different motion states. (d)–(f) Reproduced with permission from Ref. [136], © Wiley-VCH Verlag 2021.

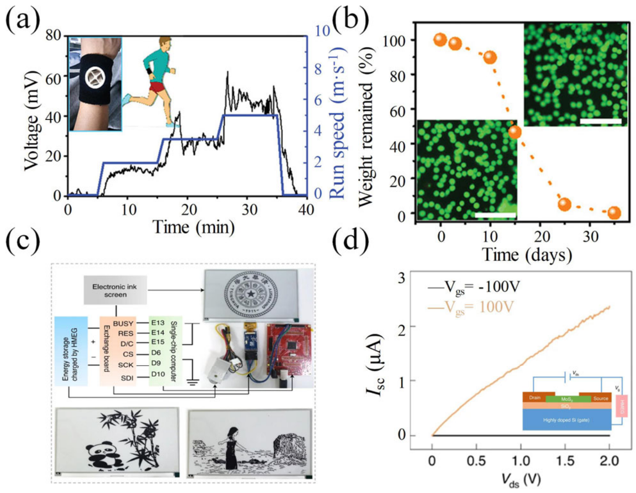

Figure 9 Bio-inspired water-driven self-powered electronics. (a) Portable perspiration-driven self-powered sensor. (b) Mass change during degradation of biologic electricity generator in soil. (a) and (b) Reproduced with permission from Ref. [123], © Wiley-VCH Verlag 2019. (c) Schematic of self-powered electronic ink display. (d) Schematic of self-powered field effect transistor. (c) and (d) Reproduced with permission from Ref. [124], © Wang, H. Y. et al. 2021.

Despite the rapid development of water-driven electricity generators in the past decade, there are still many fascinating questions that need to be further explored. The understanding of the mechanism of water-driven electricity generators is the key, and the underlying mechanisms of charge transport and transfer, as well as the mechanism of energy conversion, still need to be further understood. For example, the type of charge carriers in the charge transfer process at the solid-liquid interface is still controversial, and the existing mechanisms can only explain specific experimental phenomena. The general theory of charge transfer at the solid–liquid interface still needs to be further explored, which is crucial to developing more robust and efficient water-driven electricity generators. The wettability of the solid material is also crucial to the electrical output of water-driven electricity generators. Although bionic has been applied to the designs of the material, and structure of the water-driven electricity generator, more problems need to be solved, such as unsatisfactory surface charge density, unstable hydrophobic state, and timely recovery of the hygroscopicity of some materials. All these questions require us to further explore the mysteries of nature and get more inspiration from natural organisms. The ultimate goal is to improve its electrical output, including voltage, current, power density, and energy conversion efficiency.

Water-driven electricity generation sources from the interaction between solids and liquids, and improving the electrical output performance requires optimization in three aspects: (1) device structure, (2) efficiency in the solid-water contact and separation or water absorption, and (3) charge exchange. For device structural optimization, new ideas are needed based on an in-depth understanding of the mechanism of electricity generation. For example, our previous work has reported a water droplet-based electricity generator (DEG), which transformed the electricity generation mechanism of "interfacial effect" into "bulk effect" by adding an additional electrode, greatly enhancing the electricity generation performance. Moreover, some innovative structures of solid–solid triboelectric nanogenerators (TENGs) may be applied to the design of water-driven electricity generators [154]. Besides, the stability and lightness of the structure need to be taken into consideration. Natural organisms usually evolve elegant characteristics that combine lightness and firmness, which is worth studying to optimize the structures of water-driven electricity generators.

For some water-driven electricity generators, promoting the contact and separation between solids and water is beneficial to enhancing the electrical output performance. In general, the droplet spreading time on the surface of a water-driven electricity generator takes tens of milliseconds [23, 155], and thus the spread speed of liquid on a solid surface may be a limiting factor for output improvement. Besides, it has been well known that liquid residues on solid surfaces will significantly reduce electrical output. How to suppress the liquid residue is a worthy research topic. Existing methods usually texture microstructures on hydrophobic solid surfaces to realize an incomplete contact between liquid and solid, resulting in a superhydrophobic surface. This method reduces the liquid residue but results in a smaller solid-liquid contact area, which leads to less charge induction and potentially lowers the electrical output. Notably, the superhydrophobic surface may fail due to the invasion of the micro-droplet, which will greatly shorten the life of the electricity generator. Addressing this problem, a SLIPS-based generator may be expected to become a better research topic owing to the stability of SLIPS in water-repellency in various environments. In the other research line of moisture-driven electricity generators, improving the ability to absorb water from the environment is the key to improving electricity generation. Some organisms that have evolved over a long period of time in extremely arid areas, such as deserts, have developed some elegant structures that may shed light on us.

Further, the study of the charge exchange mechanism of the water-solid interface is very difficult and important, requiring joint efforts. Several teams have made some key breakthroughs in mechanism research through experiments and theoretical calculations [46, 50, 116, 156–160], which will greatly contribute to performance improvements of water-driven electricity generators in the future.

At present, both the design and the related application of the bio-inspired water-driven electricity generator are in the laboratory stage with relatively mild experimental conditions. Although we have developed a SLIPS-based low-temperature resistant water-driven electricity generator [120], more work still needs to be done to develop water-driven electricity generators with higher environmental stability. In addition, various parameters, such as energy conversion efficiency for moisture-driven electricity generators and concentration change in functional groups before and after power generation are difficult to evaluate, which calls for a standard performance evaluation system. The life span of water-driven electricity generators is also one of the issues to be considered. The existing life span of water-driven electricity generators is from a few days to a few months, which is far less than the life span of solar cells of several decades. The unsatisfactory lifetime greatly limits their large-scale application.

Different water-driven electricity generators are applicable to various scenarios according to the form of water. Waving or flowing water-driven electricity generators are suitable for producing electricity near the sea or river. Evaporation or moisture-driven electricity generators can generate a continuous direct current. Rainwater-driven electricity generators, although limited by weather conditions, can output extremely high instantaneous power. Various water-driven electricity generators have their own characteristics and deserve to be studied. Automation and intelligence are the development trends in science and technology. In the future, plenty of sensors, wearable intelligent equipment, and distributed self-powered electronic devices will be widely used. Because of the wide availability of water, water-driven electricity generators can meet these needs perfectly, and we believe that water-driven electricity generators based smart devices will be widely used, which requires us to continuously improve their performance. As we discussed above, bio-inspired materials/structures can enhance the electrical output, stability, and durability of water-driven electricity generators greatly. In addition, better biocompatibility of bio-inspired water-driven electricity generators will greatly improve the comfort of wearable devices. We should also pay attention to the sustainability of the electricity generator. We believe that bionic will greatly promote the development of water-driven electricity generators and provides new ideas for the design of water-driven electricity generators.

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Declaration of conflicting interests

The authors declare no conflicting interests regarding the content of this article.

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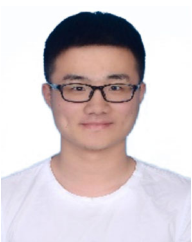

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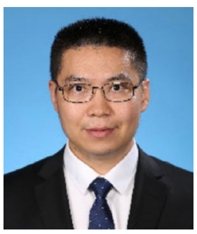

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