Materials for evaporation-driven hydrovoltaic technology

Chunxiao Zheng¹ | Weicun Chu¹ | Sunmiao Fang¹ | Jin Tan¹ | Xiaofan Wang¹ | Wanlin Guo¹,²

¹Key Laboratory for Intelligent Nano Materials and Devices of Ministry of Education, State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China
²Institute for Frontier Science, Nanjing University of Aeronautics and Astronautics, Nanjing, China

Correspondence
Wanlin Guo, Key Laboratory for Intelligent Nano Materials and Devices of Ministry of Education, State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China. Email: wlguo@nuaa.edu.cn

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Abstract
Water constitutes the largest energy carrier on earth, absorbing more than 70% of the solar energy received by the earth's surface, yet its low exploitation has been a constant concern. The hydrovoltaic effect is an emerging technology that generates electricity through the direct interaction between nanomaterials and water of various forms (raindrops, waves, flows, moisture, and natural evaporation). Especially, the evaporation-driven hydrovoltaic effect is a spontaneous and ubiquitous process that can directly convert thermal energy from the surrounding environment into electricity without the demand for additional mechanical work, which shows unique advantages compared with other hydrovoltaic effects. A variety of nanostructured materials have been steadily developed for evaporation-driven hydrovoltaic devices (EHDs) in recent years. However, there has been a lack of a clear specification on the selection and design of materials for improving device performance. Herein, we first analyze the mechanisms of EHDs followed by a summarization of the recent advances in materials, including carbon materials, biomass-based materials, metal oxides, composite materials, and others. We then discuss the strategies for improving the energy conversion efficiency and the output power in terms of structural design, surface modification, and interface treatment. Finally, we provide an outlook on the potential applications of electricity generation, sensors, and desalination technology, as well as the challenges and prospects for the development of this emerging technology in the future.

KEYWORDS
electric double layer, hydrovoltaic effect, materials synthesis, structural optimization, water evaporation

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Chunxiao Zheng and Weicun Chu contributed equally to this study.
1 INTRODUCTION

As the problems of global warming and the energy crisis become more and more obvious, the development and utilization of environmentally friendly, sustainable, and renewable resources are essential for human beings.\[1\] Recently, a significant objective of modern energy research is to make full use of renewable sources.\[2\] Water is the most abundant clean and sustainable resource on earth, covering about 71% of the earth’s surface and capturing about 70% of solar energy received by the earth’s surface.\[3\] In biological systems, water exists in the form of vapor, liquid, and solid, containing moisture, rains, clouds, rivers, oceans, ice, and so on. The efficient collection and utilization of water resources to generate power directly not only meets the global energy requirement but also achieves the concept of green conservation.\[4\] Therefore, as one of the renewable strategies, the extraction of electrical energy from water has triggered tremendous research interest.

Nanomaterials, such as graphene and carbon nanotubes (CNTs), are extremely sensitive to external reactions, so recent experiments have demonstrated electricity generation at the nanomaterial–water interface on exposure to water flows, waves, rains, moisture, and evaporation.\[5\] Yin et al. dragged a droplet on graphene to generate a voltage of millivolt magnitude in the droplet movement direction for the first time, which was called drawing potential.\[6\] Soon, Yin et al. reported that the insertion and withdrawal of graphene in solution generated a potential difference between the two ends of graphene, named waving potential.\[7,8\] Zhao et al.
generated electricity directly by graphene oxide (GO) in a humid environment. Then water evaporation from the nanostructure of carbon materials was found to generate electricity continuously. Nanomaterials directly interacting with different movement forms of water, such as flowing, waving, dropping, and evaporating, can generate electricity, which is termed as hydrovoltaic effect. Among these hydrovoltaic effects, the evaporation-driven one can directly convert thermal energy in the surrounding environment into electricity. Theoretically, evaporation of 1 g of water absorbs approximately 2.26 kJ of external energy under room temperature and pressure. Globally, the solar energy absorbed by water evaporation produces an average power density of about 80 W/m². Moreover, the natural evaporation process will never be blocked up by weather, time, and location, endowing the evaporation-driven hydrovoltaic effect with great potential for sustainable development.

Since then, a large number of functional materials, such as carbon materials, polymers, metal oxides, and cellulose, have been demonstrated to generate electricity through evaporation-driven hydrovoltaic effect by many independent groups (Figure 1). It is concluded that these materials generally possess the following characteristics. First, good hydrophilic nano-channels are required for continuous, rapid, and efficient transport of water. Second, the material contains high surface charge density and zeta potential, leading to the formation of electric double layers (EDLs) in nanochannels. Third, the size of nanochannels is comparable to the Debye length of water to form the overlaps of EDLs. The hydrovoltaic devices prepared by the above materials exhibit excellent potential in the fields of basic power generation equipment, solar-energy evaporators, and self-powered equipment due to their advantages of no pollution, low cost, and high portability. Although the evaporation-driven hydrovoltaic effect has unique advantages compared with other energy conversion effects, its capacity for practical application still faces bottlenecks. For example, only a small amount of latent heat of evaporation can be utilized by existing technologies, resulting in low output power and poor energy conversion efficiency. Therefore, this new type of technology must be promoted by clarifying mechanisms, selecting suitable materials, optimizing structure, and modifying surface functional groups.

In this review, we begin by describing the mechanism of the evaporation-driven hydrovoltaic effect. Then, we summarize the evaporation-driven hydrovoltaic materials currently in development from the common carbon materials (carbon black [CB] and GO), biomass-based materials (wood, cellulose paper, and cloth), metal oxides to composite materials, and so forth. The physico-chemical regulation and application demonstration of constructing excellent hydrovoltaic devices are discussed emphatically. Finally, we present the challenges and prospects for the emerging technology of evaporation-driven hydrovoltaic effect.

2 | MECHANISMS OF ELECTRICITY GENERATION

Owing to the interaction between water and nanomaterials, it is generally believed multifield coupling at the solid–liquid interface plays an important role in the evaporation-driven hydrovoltaic effect. Therefore, in this chapter, we try to clarify the mechanism of the evaporation-driven hydrovoltaic effect by the recent expansion of the classical electrokinetic effect.

When solid surface contacts with liquid, ions will be selectively adsorbed on the solid surface to form a tight adsorption layer (Stern layer) due to the action of the charge or chemical potential. In the solution, ions with opposite charges to the Stern layer will be attracted to the solid–liquid interface by Coulomb force, and this process forms a diffusion layer. Therefore, an area enriched by two different charged ions is generally formed at the interface, which is called the EDL. Subsequent studies found that the ion distribution in solution was not only a layer of closely packed ions near the solid–liquid interface but the ions from the solid–liquid interface to the solution body were arranged according to the “Maxwell–Boltzmann” distribution as shown in Figure 2A. The electrical potential at the shear plane between the Stern layer and the diffusion layer is named zeta potential. On this basis, in 1924, Stern regarded the potential distribution in the EDL as the simultaneous equations of the Boltzmann distribution of ions and the Poisson equation in the electrostatic field theory and established a relatively complete EDL model. Although theory still does not take the effect of solvent molecules into account, the model is generally applicable.

The model discussed above is based on the condition that the solid phase and the liquid phase are stationary. When liquid flows on a solid surface or solid particles move in a liquid, the dynamic variations of the EDL will produce electrokinetic phenomena. The streaming potential is one of the classical electrokinetic effects. When an electrolyte is driven by a pressure gradient through a channel with a size that equals the Debye length of solution, the narrow inner charged wall of the channel will lead to an overlap of EDLs. Due to the Coulomb force, ions with opposite charges to the channel
walls are filled into the channel, which reveals the selectivity of a certain ion. As the electrolyte continues to flow, a difference in ionic concentration develops across the channel, allowing a potential difference to be detected, resulting in streaming potential, as demonstrated in Figure 2B. The directional movement of ions of this singly charged species within the channel also produces the streaming current. Once the ion flow in the channel can be transformed into the electron flow of the external circuit, for example, using Ag/AgCl redox electrode, a continuous flow of electric energy output can be realized.

However, the classical streaming potential only reflects the movement of ions in solution, while the electron movement in the solid is ignored. In 2014, Yin et al. found the drawing potential and waving potential, which extend the classical electrokinetic theory in moving EDL boundaries. The solid–liquid interface on the graphene forms an EDL boundary between graphene and water, and EDL moves along the graphene to generate electric currents. In subsequent studies, substrates beneath the graphene layer were also found to affect the electrical signals produced. Then Zhang et al. proposed an electric triple layer in which an image charge layer in graphene was considered to couple with the EDL. These novel discoveries have pushed forward the development of the century-old electrokinetic effect.

For the evaporation-driven hydrovoltaic effect, electricity can be continuously generated spontaneously if the above three conditions can be met: (i) selecting suitable active materials; (ii) ensuring the continuous flow of capillary force and evaporation-driven water; and (iii) ensuring that the size of nanochannel can overlap the EDL. This is very similar to the streaming potential, but there exist two uncertain issues that cannot be explained by classical electrokinetic effects: (i) how does ionic motion in the nanochannel translate into sustained electron motion in the external circuit; (ii) whether other mechanisms, such as electron drag, coupling of water or molecular dipoles and free carriers, play a role in evaporation-driven hydrovoltaic effect. Recently, Fang et al. found that evaporation of ethanol from nanostructured films can also generate sustainable volt-level electricity without the contribution of streaming potential, which is called evaporating potential. It is a discovery generated by carrier transfer driven by the evaporation of polar molecules. Therefore, the specific mechanism of ion and electron action at the solid–liquid interface of the evaporation-driven hydrovoltaic effect still needs to be proved by appropriate theories and sophisticated experiments.

It should be noted that the evaporation-driven hydrovoltaic effects directly convert latent heat into electrical energy rather than originate from chemical interaction between the bare electrode and flowing water. It is particularly important to make a distinction between the redox reaction and the hydrovoltaic effect. For example, Dhiman et al. found that immersing graphene in a flowing dilute hydrochloric acid aqueous solution could cause graphene to generate a voltage signal. However, less than a year after the publication of this result, Yin et al. proved that the voltage signal was probably the electrochemical potential generated by the reaction of hydrochloric acid solution with a bare copper electrode. Therefore, avoiding the misunderstanding of the high electrical signal generated by the redox reaction between the material and water is also a factor that we need to consider. However, in terms of improving performance, if a mechanism for the coexistence of hydrovoltaic effect and redox reaction can be found, the effective power of hydrovoltaic devices will be greatly improved.

**FIGURE 2** Schematics of electric double layer (EDL) and streaming potential at the solid–liquid interfaces. (A) EDL at solid–liquid interface. (B) Schematic of streaming potential within a nanochannel driven by pressure difference. (C) Schematic of an electric triple layer between graphene and water.
3 | SELECTION OF MATERIALS FOR HARVESTING ENERGY FROM WATER EVAPORATION

3.1 | Carbon materials

Carbon is one of the most important elements in the world, which is most closely related to our daily life. It has the characteristics of multiple electron orbitals of sp, sp², and sp³ hybridization. No other element can be used as a single element to form as many different structures and properties as carbon, such as three-dimensional (3D) diamond crystals, two-dimensional (2D) graphite sheets, one-dimensional (1D) carbines, CNTs, zero-dimensional (0D) fullerene molecules, and so on.[43–46] In addition to variable structure, carbon materials also have excellent controllable properties, their electricity conduction, thermal insulation performance, and light transmittance can be adjusted artificially. These excellent properties have broad application prospects in our life, such as in the fields of material synthesis[47] and energy applications.[48]

3.1.1 | Carbon nanoparticles (CNPs)

CNPs as a typical 0D carbon material with diameters less than 100 nm have the characteristics of high specific surface area, good thermal conductivity, high electrical conductivity, high stability, high chemical inertia, low density, and so on.[49–51] Large quantities of CNPs can be stacked together to form porous materials that have previously been utilized in several applications, such as electrochemical double-layer capacitors, catalytic carriers, organic biomolecular adsorption carriers, highly sensitive biosensor electrodes, solar cells, and so on.[52,53]

In 2017, the research group led by Guo and Zhou found that water evaporation from stacked CNPs can generate continuous electricity up to 1 V for more than 160 h under ambient conditions.[10] CNPs were stacked to form a CB sheet by roasting ceramic pieces over a flame. High-resolution transmission electron microscopy indicated that each of the onion-like CNPs was basically formed of loosely stacked disordered graphene flakes. The bottom of the device is immersed in deionized water and the upper part is exposed to the air to maintain water evaporation as illustrated in Figure 3A. Compared with the classical streaming potential[54] the power generated by the evaporation-driven hydrovoltaic effect needs no external pressure gradient and only converts the latent heat of vaporization into electricity through the natural process of water evaporation.

This novel phenomenon soon aroused widespread interest among researchers, but its fabrication method had the disadvantage of unstable quality. Zhou and his group soon found a new method to make an all-printed porous carbon film that could generate sustainable electricity with a voltage over 1 V.[55] According to Figure 3B, a CB slurry, which was made of toluene CB, ethylcellulose, terpineol, and ethanol stirred in a certain proportion, was printed on the aluminum oxide (Al₂O₃) plate crossing the CNT conductive slurry electrodes. Compared with roasting directly on a spirit lamp, the new method can reduce the thickness and increase the surface flatness of the device. The integration of the five devices provided a stable open-circuit voltage (V_{oc}) of 1.45 V, a short-circuit current (I_{sc}) of 2.85 μA, and a power density of 0.013 μW/cm², which could power low-power consumption electronic devices like electrodeposition of silver microstructure.

To further dig into the mechanism, Zhou and his group systematically studied electricity generation through the transformation of water droplets into water flow via the capillary force produced by a hydrophilic porous CB film.[56] The fabrication method of the device was the same as that of the all-printed porous carbon film. The superhydrophobic modification was carried out for droplets flowing in a specified direction. With the different dropping positions of water droplets, the water flow direction in the membrane can be controlled, resulting in different electrical signals as shown in Figure 3C, the following results can be drawn: (i) only directional flow over the carbon film causes the voltage to be generated; (ii) in the state of the same flow direction, there was no obvious correlation between induced voltage and position of the droplet; and (iii) the sign of induced voltage was determined by the water infiltration direction. Furthermore, the relationship between ion concentration, surface properties, and generated voltage was also discussed. When the ion concentration was increased from 10⁻⁷ to 1 mol/L, the trend of voltage change was highly similar to the streaming potential on the ionic concentration.[59] Zeta potential had also been found to determine the sign and magnitude of output voltage.

3.1.2 | Graphene

Graphene is a newly developing material in which carbon atoms linked by sp² are densely packed into a single 2D honeycomb lattice structure. As a 2D monoatomic-thick sheet of hexagonally arranged carbon, graphene has sparked tremendous interest in multiple disciplines owing to its extraordinary properties,
including a large theoretical specific surface area (∼2600 m²/g), the high carrier mobility of 200,000 cm²/Vs, the remarkable thermal conductivity of 3000–5000 W/m K, and excellent optical transparency of 97.3%.[57,58]

Unlike the 2D monolayer graphene, evaporation-driven hydrovoltaic devices (EHDs) require a 3D porous structure to allow water flowing through the nanochannels. So the researchers set their sights on GO and reduced graphene oxide (rGO). Meanwhile, GO is modified with oxygen-related functional groups, which improve its hydrophilicity and surface activity,[60] making it an ideal material for EHDs. Zhang et al. found a porous freestanding GO sponge, as exhibited in Figure 3D, could convert ambient heat to electricity, and the Voc reached as high as 0.63 V.[61] And then poly (3,4-ethylene dioxythiophene):poly(styrene sulfonate) and graphene oxide (PPGO) sponges were fabricated, which could generate electric power not only from water evaporation but also from the violent fluctuations of the low-grade waste heat flow, and increased the Voc up to 2.13 V with a piece of 1.25 cm² PPGO sponge.[30] Except for the modification of GO, the structure design is also a feasible subject.[26] As demonstrated in Figure 3E, printed honeycomb-structured rGO film increases the transmissibility of water molecules and accelerates the evaporation rate under the design of the water channel, achieving a Voc of 0.83 V.[62]

3.2 | Biomass-based materials

Biomass-based materials are mainly composed of three elements in chemical composition: carbon, hydrogen, and oxygen. They are easily degraded by natural microorganisms into small molecules, such as water and carbon dioxide, without chemical modification, and their products can enter the natural cycle again. Therefore, biomass-based materials
have excellent properties of being renewable and biodegradable. Currently, common biomass-based materials, including wood, cotton fiber, and cellulose paper, have been studied for EHDs.

On the basis of the high cellulose content and anisotropic 3D continuous microchannel structure of natural wood, Zhou et al. used the citric acid (CA)-modified beech wood to prepare EHDs (Figure 4A). This device constructed a typical sandwich structure in which two polyethylene terephthalate (PET) meshes coated with conductive carbon paste were used as external electrodes in the vertical direction of the wood, and two inert electrodes were inserted into the reservoirs at both ends of the capillary for measurement. A $V_{oc}$ of 300 mV, an $I_{sc}$ of 10 μA, and a power density of 0.045 μW/cm² might be generated by a single device, remaining the long-term stability of the electricity output in 24 h. When water infiltrated into the channel, a large number of hydroxyl groups in cellulose hydrolyzed to negative charges, facilitating water molecules and ions to migrate. As a result, driven by natural evaporation, wood successfully generated the constant direct current to promote the development of sustainable, environmentally friendly, and cost-effective hydrovoltaic devices.[27]

In addition, Das et al. designed an EHD using a piece of commercial wearable fiber fabric, imitating the structure of plants in which water was passed through fabric nanochannels to generate electricity because of capillary action and transpiration.[18] On this basis, also driven by transpiration, Yun et al. created a kind of wetted cotton fabric reinforced with CB, which utilized the capillary flow of water to produce a potential difference between the asymmetric wet and dry sides of cotton fabric (Figure 4C). A $V_{oc}$ of 0.53 V was obtained with the cotton fabric of 90 mm × 30 mm × 0.12 mm.[63]

To further improve the utilization of environmental energy, a flexible and foldable portable device consisting of carbon cloth and graphene was proposed that combined electricity generation with water desalination. This approach not only established a green power supply system but also opened up a new application of fiber cloth in hydrovoltaic devices. Due to the disorderly state of fibers in the carbon cloth, the transport pathway of water molecules is uncontrollable. Thus, control of proton flow direction is the key to effective electricity generation.[3] As shown in Figure 4D, Xiao et al. further demonstrated a bilayer solar evaporator implementing the directional water flow efficiently. Specifically, large-area CNT films were covered on the surface of cellulose paper, and then the hydrophobic polydimethylsiloxane was encapsulated at a specific position on one side of the cellulose paper, forming an asymmetric modification to achieve centimeter-sized channels of water flow. Under solar irradiation, it could realize efficient water evaporation and electricity generation so that the maximum output power reached up to 2.1 μW.[28] In addition to the direct utilization of green biomass-based materials, Venkateshaiah et al. found that nanoporous carbon with

![Biomass-based materials](image)

**FIGURE 4** The typical of EHDs based on biomass materials: (A) Mechanism of a piece of wood and 24 h direct electricity output.[27] Copyright 2020, American Chemical Society. (B) Photograph of fiber cloth-based generator.[18] Copyright 2019, American Chemical Society. (C) Schematic illustration of the operation method of CB coated cotton fabric device.[63] Copyright 2019, American Chemical Society. (D) The fabrication process of all-in-one evaporator toward cellulose paper and CNTs.[28] Copyright 2020, Elsevier. CB, carbon black; CNT, carbon nanotube; EHD, evaporation-driven hydrovoltaic device; PDMS, polydimethylsiloxane.
high specific surface area and abundant micro/mesopores could be synthesized from nonfood-grade tree gum by carbonization and exfoliation. This ideal property of nanoporous carbon was perfectly suited to the basic characteristics of hydrovoltaic materials.[34]

The development of biomass-based materials in hydrovoltaic technology not only ensures the concept of green and environmental friendly of hydrovoltaic devices, but also realizes the further exploration of converting environmental resources into energy in the field of materials. This direction is expected to become a leading research topic in the future.

3.3 Metal oxides

Metal oxides attract widespread attention of their unique nanostructure and highly charged surface. At present, researchers have developed hydroelectric devices made of common metal oxide nanomaterials, such as titanium dioxide (TiO₂), silicon dioxide (SiO₂), and Al₂O₃.[64] These 1D materials are characterized by large surface area, super-hydrophilic surfaces, and good electron transport properties. The streaming potential is generated when water molecules flow over the surface of metal oxides.

An innovative, smart self-powered device concept was developed by Ji et al. (Figure 5A). This concept exploited Jaboticaba-like carbon nanospheres at TiO₂ nanowire to create high-efficiency and light-sensitive liquid evaporation power generation (EPG), involving liquids, such as water, methanol, acetone, and ethanol. It was shown that different liquid states produced a different induced flow-induced voltage (FIV) underwater evaporation. For example, in the presence of methanol, FIV reached up to 2.0 V. The EPG device that water as a power source had the potential to scale up to nearly 20 V, which provided a basis for the production of low-cost, high-output power hydrovoltaic devices.[65] Zhao et al. suggested a three-mixture mixing method that used TiO₂ or SiO₂ as the power generation materials, glass fiber as the mechanical support material, and polyvinylidene fluoride as the bonding medium to create a wearable device with superior lightweight, flexibility, and adhesion stability (Figure 5B).[22] Even after repeated cleansing with water flow and large-scale deformation, the performance of the device remained unchanged, which reached the standard of practical application in flexible and wearable electronic devices.

As shown in Figure 5C, Shao et al. described the mass manufacture of flexible hydropower films (HEFs) made of

![FIGURE 5](image-url)
solid oxides (e.g., Al₂O₃). The solvent evaporation-induced self-assembly method was used to create a narrow tunnel closely packed with Al₂O₃ nanoparticles. Due to capillary action, water diffused upward through charged nanochannels to generate electricity. A single HEF unit could deliver output voltages of more than 2.5 V and a power density of 0.025 μW/cm², and continually generated for more than 10 days in normal conditions. In addition, a capillary-driven hydrovoltaic device used an Al₂O₃ membrane as a fluid channel, which could output a maximum current of 9.6 A and a voltage of 40 mV with an evaporation surface area of 4.9 cm². In the latest research, the results showed that the stable open-circuit voltage of hydrovoltaic devices was up to 6.4 V under 1 standard sun, which was the best value at present. This value was derived from Li et al., who enhanced the hydrovoltaic device by integrating ionic thermoelectric gelatin materials and porous dual-size Al₂O₃ into the heat conduction effect to increase the evaporation rate and generate a constant temperature difference for the thermostatic generator (Figure 5D). This ingenious design was a major step forward in the development of improved output voltage for hydrovoltaic devices.

Apart from the common TiO₂, SiO₂, and Al₂O₃, other metal oxide nanomaterials also can generate electricity driven by water evaporation, such as zinc oxide (ZnO), copper oxide (CuO), and vanadium pentoxide (V₂O₅), which expands the material design for applications. For example, Yoon et al. prepared the resistance-grown but produced an unsatisfactory open-circuit current. Then, their group continues to experiment with porous CuO nanowire films, demonstrating the possibility of generating electricity by water evaporation. Saha et al. created a V₂O₅ membrane with 2D nanofluidic channels. In particular, the hydrovoltaic device by V₂O₅ membrane possessed the self-healing function through modification in agar, lithium chloride, and glycerol, meaning that the addition of a drop of water repaired its physical damage and increased its service life.

At present, the design of metal oxide-besides hydrovoltaic devices usually uses a planar membrane structure. Most researchers only apply surface modifications to membranes, such as plasma treatment, initially improving the hydrophilicity. However, understanding the impact of these modifications on water interactions and charged carrier dynamics on electricity generation remains in the early stages.

### 3.4 Composite materials

Composite material is a new material that is optimized by using advanced material preparation technology. It not only maintains the advantages of each component but also obtains comprehensive properties that cannot be achieved by single-component materials through complementation and correlation of each component's properties. Common reinforcement materials mainly include glass fiber, carbon fiber, and so on. Li et al. reported that a freestanding carbon membrane prepared by glass fibers reinforced CNPs (GCF) for EHD. This glass fiber reinforced structure was considered to be the reason for the excellent mechanical properties and flexibility of the hybrid membrane. Surprisingly, when poly ethylene imine (PEI) modified carbon membrane, 1,2,3,4-butane tetracarboxylic acid (BTCA)-modified carbon membrane, and three symmetric CNT electrodes were assembled into a 5 cm × 5 cm hybrid device, the maximum open-circuit voltage reached 5.0 V (Figure 6A). However, improving the output current needs further research.

Polymers are suitable for a variety of processing technology because of their good biocompatibility, lightweight, good mechanical strength, and low cost. Many conductive polymers like poly(vinyl alcohol) (PVA), poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS), and hydroxyethylcellulose have demonstrated the capability to apply the EHDs. Li et al. constructed a wearable flexible hydrovoltaic device, ingeniously combining functionalized conductive carbon black with PVA hydrogel, and then further assembled it with a 3D sponge (3DS; Figure 6B). Inside the PVA hydrogel, driven by capillary action and water evaporation, water through the nanochannels generated sustainable electricity (V₀ = 0.658 V, I₀ = 63 μA, and power density ~0.675 μW/cm²). Due to the superabsorbent and stable 3D network structure of PVA hydrogel, the device could withstand several bending deformations without affecting the output. Especially, the equipment may maintain normal operation through continuous water absorption, prolonging the service life. The experiment's progress provided the possibility of EHDs in the application of flexible wearable devices. On the basis of the excellent performance of PVA hydrogel, a sandwich membrane strategy for building a 3D asymmetric evaporator integration of water desalination and evaporation-driven electricity generation was proposed (Figure 6C). In simulated seawater, a device with a surface area of 14 cm² created a circuit current of 5 A, an optimal output power of 0.60 W, and a power density of 0.15 μW/cm².

The introduction of conductive polymers is essential for the improvement of conductivity. PEDOT:PSS and CNT with PVA sponge were designed and prepared for an integrated 3D dual-function solar evaporator capable of high-throughput seawater desalination and evaporation-driven electricity generation (Figure 6D).
The 3D structure expanded the evaporation area and enhanced the interaction between the PVA sponge and water molecules, which greatly reduced the enthalpy of evaporation. Meanwhile, the addition of PEDOT:PSS resulted in the formation of negatively charged ion channels inside the PVA sponge. In seawater evaporation driven by solar energy, Cl\(^-\) selectively passed through ion channels to generate stable voltage.\(^{[21]}\) Qi et al. also used PEDOT:PSS to combine with GO constructing asymmetric nanocomposite aerogel sponges for EHDs in Figure 6E. The beauty of this study was that the device generated electricity not only through water evaporation but also through the violent fluctuations of the low-grade waste heat flow. The proposed method provided a reference for the combination of hydrovoltaic and pyroelectrics.\(^{[30]}\)

In addition, Wang et al. found an interlayer catalyst of α-FeOOH for modifying graphene aerogel films (Figure 6F). The output current of the device was commonly influenced by different concentrations of hydrogen peroxide (H\(_2\)O\(_2\)) and sodium chloride (NaCl).\(^{[29]}\) Furthermore, Yoon et al. also tried metal oxide hybrid membranes, in which molybdenum disulfide (MoS\(_2\)) mixed with SiO\(_2\), discovering the possibility of evaporation-driven generation.\(^{[71]}\)
3.5 Other

In addition to common carbon materials, biomass-based materials, metal oxides, and composite materials, other materials, such as silicon nanowire arrays (SiNWs), metal-organic frameworks (MOFs), layered double hydroxides (LDHs), and so forth, have been extensively studied due to their unique characteristics.

Owing to the large surface area and excellent carrier transport properties of SiNWs, Sun’s group has developed a series of studies on the EHDs since 2020. They first designed a simple SiNWs-based hydrovoltaic device, which produced a $V_{oc}$ over 400 mV with an output power density of $6 \mu W/cm^2$ (Figure 7A). They considered that the streaming potential was the main reason for the hydrovoltaic effect in SiNWs. In particular, the internal of SiNWs was filled with vertical nanochannels; based on the Debye shielding effect, hydronium ions ($H_3O^+$) were produced by water due to its natural evaporation and capillary action inside the passing nanochannels, and the continuous water flow led to a different concentration inside electrons, resulting in hydrovoltaic effect. To further optimize the electrode structure of devices, their group next created graphite and PEDOT:PSS hierarchical porous fabric electrodes to obtain a rapid evaporation rate of water. Up to date, they utilized the TiO$_2$ transition metal oxide layer to customize the interface between active materials and electrodes, thereby increasing the output power density. Therefore, Sun’s group not only expands the variety of hydrovoltaic materials but also opens up more possibilities in electrode structure and interface treatment.

**FIGURE 7** (A) Schematic diagram of the SiNWs hydrovoltaic device. The output voltage and current density curve, and output power density curve of the device with different resistance. Copyright 2020, Wiley-VCH. (B) Device structure and mechanism of AlOOH/UIO-66-based device and the curve of real-time voltage. SEM image of the AlOOH/UIO-66 film. Copyright 2020, Wiley-VCH. (C) Construction process of hydrovoltaic device based on layered Cu (BDC- OH) MOFs. Copyright 2021, Wiley-VCH. (D) The synthetic process of Cu-BTC nanorod arrays. Copyright 2021, Wiley-VCH. (E) Structure of PCG membrane. Schematic diagram and mechanism of the device integrating solar desalination and evaporation-driven electricity generation. Real-time voltage change under dark conditions and 1 sun irradiation. Copyright 2021, Royal Society of Chemistry. APS, ammonium persulfate; BTC, benzene-1,3,5-tricarboxylate; CBA, copper-BTC MOFs [Cu$_2$(OH)BTC(H$_2$O)]$_{n-2}$H$_2$O; CHN, copper hydroxide nanostrands; HHIP, 2,3,6,7,10,11-hexahydroxyltriphenylene hydrate; KOH, sodium hydroxide; MOF, metal-organic framework; PANI, polyaniline; PCG, paper-based Cu-CAT-1 nanorod array/gelatin; PVDF, polyvinylidene fluoride; SEM, Scanning Electron Microscope; SiNW, silicon nanowire; SP, stone paper.
Recently, MOFs have been identified as potential candidates in various energy-related applications due to their high porosity, wide surface areas, variable functionality, and distinct pore architectures.\[^{[75]}\] Using 2D aluminum hydroxide (AlOOH) nanosheets as templates, Ma et al. grew UIO-66 nanoparticles with high surface potential on the AlOOH surface to obtain an AlOOH/UIO-66 film that can effectively generate electricity from natural water evaporation with a $V_{oc}$ of $\sim$1.63 V, and a power density of 0.015 $\mu$W/cm\(^2\). The reasons for the excellent potential were as follows: First, the direction of water movement was consistent with capillary channels formed by the accumulation of AlOOH/UIO-66 hybrid nanomaterials during evaporation (Figure 7B). Second, the structural defects of UIO-66 nanoparticles contribute to AlOOH/UIO-66 hybrid nanomaterials with a high zeta-potential and positive charge. When water molecules pass through the positive charge capillary channels, the counterions within the EDLs move in the same direction leading to a potential difference.\[^{[30]}\]

On the basis of the excellent performance of MOF-composites materials in EHDs, the idea of “Hierarchical Oriented MOFs” was arisen that manufactured the layered Cu (BDC-OH) MOFs by hydrolysis, anion exchange reaction, and heteroepitaxy growth in Figure 7C. These results indicated that MOFs, 1D porous nanomaterials with a certain density of surface charge, had an “aggregation effect” through layered directional treatment, which could play an important role in evaporation-driven electricity generation.\[^{[24]}\] However, degradation of MOFs usually occurs on surfaces with defects or no functional groups, causing instability in water.\[^{[76]}\] As shown in Figure 7D, Li et al. designed a hybrid membrane, which combined MOFs (Cu-BTC complex nanorod arrays) with polyaniline (PANI) conductive polymers to improve the stability of MOFs. In the absence of solar irradiation, the $V_{oc}$ and $I_{sc}$ generated by natural evaporation-driven of the membrane were 47.4 mV and 0.06 A.\[^{[62]}\]

According to previous reports, hydrovoltaic devices have high internal resistance, resulting in extremely low output currents in the nano-amperes range.\[^{[10]}\] Ma et al. discovered that seawater was a low-resistance natural electrolyte. Thereby, they created a flexible and programmable 2D/3D structure of paper-based Cu-CAT-1 nanorod array/gelatin (PCG) membrane ($V_{oc}$ $\sim$ 620 mV, $I_{sc}$ $\sim$ 41 $\mu$A, and power density $\sim$1.82 $\mu$W/cm\(^2\)), which achieved all-day continuous electricity generation even in the night (Figure 7E).\[^{[46]}\]

4 | OPTIMIZATION STRATEGY

Since the first EHD was discovered in 2017, a large number of researchers around the world have been attracted to join this novel field. The ability of electricity generation based on spontaneous water evaporation without any external force makes EHDs a green energy production method. As mentioned above, various materials are available for EHDs, but low output still limits its application. On the basis of the mechanism of hydrovoltaic effect, the flow rate of water, the pore size of nanochannels, the zeta potential of the material surface, and the charge collection efficiency are several key factors affecting the output power density. In this section, we will focus on the following aspects as porous structure, surface modification, interface treatment, and environmental influence to introduce a series of recent discoveries and advances.

4.1 | Porous structure

The nanochannels of material play a crucial role in both the water flow rate and the overlap of the electrical double layer. Molecular dynamics simulations showed that the evaporation rate in the nanochannel was higher than that of bulk water, and was related to the width and length of the channel.\[^{[77]}\] Therefore, different kinds of porous structures have become the object of attention. In recent years, researchers have made great efforts to find a structure that not only makes a fast-moving stream but also forms an overlapping EDL.

4.1.1 | Nanoparticles

Nanoparticle stacking was first exploited to form nanochannels because of their agile fabrication. CNPs could be formed by directly firing alumina ceramic sheets over a flame.\[^{[10]}\] Another more convenient method is the suspension deposition method, which directly evaporates the solvent of the suspension to tightly adhere nanoparticles to the substrate. The bonding between nanoparticles and the adhesion of the particles to the substrate were ascribed to the van der Waals forces and hydrogen bonds, which is a capillary-driven self-assembly process.\[^{[64]}\] As shown in Figure 8A, Scanning Electron Microscope (SEM) images show that interconnected nanopores are tightly packed with a large number of nanoparticles, which could serve as nanochannels for water flow.\[^{[55]}\]

The diameter of the nanochannels can be modulated by adjusting the size of nanoparticles. Taking $\text{Al}_2\text{O}_3$ nanoparticles as an example, nanoparticles with an average size of 200 nm were adhered to the substrate by the suspension deposition method. A single device with a size of 10 cm × 4 cm could generate a $V_{oc}$ of $\sim$2.5 V, an $I_{sc}$ of $\sim$0.8 $\mu$A, and a power density of 0.008 $\mu$W/cm\(^2\).\[^{[64]}\] When changed the mass ratio of m200:m20 to 50:1 (m200 and m20 are the mass of 200 and 20 nm $\text{Al}_2\text{O}_3$, respectively), the maximum $V_{oc}$, $I_{sc}$,
and power density of the EHD with the same size increased to 1.34 μA, 4 V, and 0.046 μW/cm², respectively. However, filling the voids with excessive 20 nm Al₂O₃ particles (m200:m20 ≤ 5:1) could significantly reduce the channel size, increase the flow resistance of water in the channel, and bring a large number of cracks, thereby reducing the device performance. Therefore, it is important to find a balance between the channel size and flow resistance to achieve maximum power output.

Up to now, the current research is generally limited to CNPs and solid oxide nanoparticles. In the near future, maybe more nanoparticles of different materials can be added to these systems to pursue higher power. Note that structural instability is also a key factor to influence the durability of devices. If only the van der Waals forces act to connect nanoparticles, the structure will be very loose. In this case, the part of the device immersed in water is extremely easy to be damaged by nanoflow. Motivated by this problem, some adhesives like PVA could be used to strengthen the bonds between nanoparticles, and then prevent nanoparticles from falling off the substrate.[24] Moreover, recent research about a kind of glue that can be used underwater also deserves our attention.[79]

4.1.2 | Filament

One-dimensional filament structures have large specific surface areas, unique optoelectronic properties, and geometric features, which are beneficial for electron transport. Nanofibers can be made from a variety of materials, ranging from natural products (such as silk, wool, and cotton) to synthetic compounds (such as peptides, polyamides, and polyesters), many of which are porous and environmentally friendly.[80] This is exactly the characteristic needed for EHDs. So far that nanofibers have been used in thermal insulation,[81] wastewater treatment,[82] photocatalytic reaction,[83] biochemical energy harvesting,[84] and so on. Compared with the rapid advances in these fields, more research is needed on the ability of nanofibers to harvest energy from the natural environment, especially in EHDs.

Since carbon cloth[85] and simple wet fabric pieces[18] were used to fabricate EHDs, growing interest has arisen in 1D nanofiber materials. But the large internal resistance of the fiber membrane will affect the output power density of EHDs. So, combining nanofibers with other materials is a feasible method. For example, mixing CNPs into TiO₂ nanofibers can not only reduce the resistance of the overall device but also pad the interspace of nanochannels. As expected, the hybrid carbon@TiO₂ EHDs produced a higher $V_{oc}$ of 1.6 V and an $I_{sc}$ of 170 nA, with a size of 2.5 x 4.5 cm².[65] PANI has high electrical conductivity, mechanical flexibility, and good photothermal properties. By rationally designing the structure of MOFs nanorod arrays to effectively combine with PANI not only the stability of MOFs can
be improved but also the electrical energy driven by water evaporation can be simultaneously achieved.\textsuperscript{132}

In addition, the improvements in material fabricating processes are also noteworthy. For metal oxide nanowires, such as CuO\textsuperscript{67} and ZnO,\textsuperscript{86,87} the liquid phase growth method is usually used to form ordered arrays with water flowing through slits between the nanofibers, creating a \( V_{oc} \) of 0.45 and 0.134 V, respectively. Electrospinning is another universally feasible technique for producing ultrathin fibers,\textsuperscript{88} which has been utilized on hydrovoltaic devices by some researchers.\textsuperscript{117,89} As shown in Figure 8B, a ceramic nanofiber-based EHD with significant softness prepared by the electrospinning technique exhibits a \( V_{oc} \) and an \( I_{sc} \) of 0.47 V and 0.38 \( \mu \)A, respectively. SEM images demonstrated that the ceramic nanofibers possessed high length-to-diameter (\( L/D \)) ratios, endowing the device with excellent mechanical properties, while the power generation performance was not affected.\textsuperscript{17}

Filamentous hydrovoltaic materials have attracted the attention of researchers because of their excellent mechanical properties, which can be applied in flexible electronics and wearable products. However, the key factors restricting their application still lie in the low output power. The utilization of new technology, for example, 3D printing, for ordered structure design and adjustable fiber diameter may be a way to solve this problem.\textsuperscript{90,91}

4.1.3 Lamellar

LDHs are typical naturally synthetic ionic lamellar materials, which have the following properties: (i) natural high surface positive charge density, (ii) inherent hydrophilic properties, and (iii) the presence of nanochannels or pores between LDH sheets\textsuperscript{92-96} making them ideal materials for EHDs. Sun et al. fabricated an EHD by painting Ni–Al LDH on PET substrates.\textsuperscript{78} Under ambient conditions, the device generated a \( V_{oc} \) of 0.7 V, \( I_{sc} \) of 1.3 \( \mu \)A, and a power density of 0.012 \( \mu \)W/cm\(^2\) with 10 \times 1.5 cm\(^2\). As shown in Figure 8C, SEM images show that LDH sheets are regularly arranged in parallel on PET substrate, forming plenty of nanochannels between the layers. The estimated average channel width between nearing parallel Ni–Al LDH flakes was less than 50 nm, which was enough to form the hydrovoltaic effect.\textsuperscript{78}

MOFs are emerging materials featured by their high porosity, large surface area, and tunable physicochemical property.\textsuperscript{197,98} Ma et al. prepared a novel AIOOH/UIO-66 hybrid nanomaterial by the growth of UIO-66 nanoparticles on AIOOH nanoflakes, which structures were similar to LDHs.\textsuperscript{20} After that, hierarchical oriented Cu (BDC-OH) MOFs assemblies-based EHDs containing long-ranged ordered microporous channels that \( V_{oc} \) increased significantly from 0.3 to 0.6 V.\textsuperscript{74} Oriented continuous nanochannels have the characteristics of reducing flow resistance and enhancing fluid transport capacity.

4.2 Surface modification

Surface modification is a key factor affecting the performance of EHDs, mainly changing the hydrophilicity and zeta potential of the materials. Adjusting hydrophilicity can promote capillary force and water evaporation rate, hence accelerating the flow of water in the nanochannel. The zeta potential profoundly affects the polarity and number of ions in the EDL and directly controls the Debye length.

Annealing and plasma treatment are commonly used to increase hydrophilicity by adding functional groups on the surface of materials. After treatment, as shown in Figure 9A, Fourier transforms infrared spectroscopy (FTIR) shows that the vibration peaks of O–H, C–O, and C=O bonds are obviously enhanced.\textsuperscript{103} Meanwhile, X-ray photoelectron spectroscopy confirmed that C–OH, C–O–C, C=O, and O=C–OH groups existed, which meant functional groups, such as hydroxyl (–OH), carbonyl (–CO), and carboxyl (–COOH) groups were successfully modified on the surface. The insets of Figure 9A show that the CB sheet changes from hydrophobic to hydrophilic, with the contact angle decreasing from 143.25° to 10.15°. The treated CB EHD immediately absorbed water and generated a \( V_{oc} \) of 1 V, while water could not enter the untreated hydrophobic CB EHD and only a \( V_{oc} \) of 45 \( \mu \)V was measured.\textsuperscript{104} In addition to hydrophilicity, ionization of functional groups on the surface can also change the surface charge and zeta potential.\textsuperscript{104} Four types of polymer molecules, containing PEI, BTCA, poly dimethyl diallyl ammonium chloride (PDADMAC), and poly sodium-\( p \)-styrene sulfonate (PSS), were modified on the surface of CB sheets. Figure 9B shows the chemical modification process of CB
sheets and the corresponding dominant functional groups. The zeta potential of untreated CB sheets was $\sim -30$ mV, while BTCA/PSS increased zeta potential to $\sim -40$ and $\sim -60$ mV, generating $V_{oc}$ of $-2.8$ and $-3$ V, respectively. On the contrary, PEI/PDADMAC-modified CB sheets induce positive surface charges and positive zeta potential of $\sim 25$ and $\sim 55$ mV, with the negative $V_{oc}$ of $\sim -2.5$ and $\sim -1.5$ V.\[69\]

Some other surface modification methods, such as ultraviolet + O$_3$ treatment and CA modification, have also proved to work well in enhancing the zeta potential and hydrophilicity of materials.\[27,61\] However, the specific mechanism of interaction between surface functional groups and water is still a mystery. In addition, there are few quantitative studies on surface functional groups. For example, we agree that the addition of hydroxyl groups increases hydrophilicity and thus speeds up evaporation. In fact, excessive hydroxyl groups can not only promote the adsorption of water molecules at the same time but also inhibit the desorption of water molecules and reduce the evaporation rate of water.\[105\] Therefore, further studies are needed to figure out how surface functional groups work in EHDs.

4.3 | Interface treatment

In addition to structural treatment and surface optimization, compared with other energy harvesting methods, the research on the charge collection efficiency of EHDs is still
in its infancy. Much research has focused on active materials, which directly interact with water, while the choice of electrode materials has received little attention. Usually, the electrodes are simply attached to both ends of the material without considering the charge transfer at the interface between electrode and material. After reporting EHD based on nanostructured SiNWs arrays,[31] Shao et al. were acutely aware of this problem. For the vertical structure hydrovoltaic device as shown in Figure 9C, a hierarchical porous and conducting electrode consisting of graphite/conjugated PEDOT:PSS/fabric was designed.[72] This novel electrode adopted PEDOT:PSS as the core and graphite as the shell. The hierarchical porous structure ensured efficient water evaporation,[106] a large specific surface area enhanced charge collection capacity,[107] and high conductivity improved charge transport capacity. The EHD reached a $V_{oc}$ up to 550 mV, $I_{sc}$ of 22 μA, and peak output density of 10 μW/cm$^2$. After that, as shown in Figure 9D, the TiO$_2$ transition metal oxide layer is used to impede the interface charge recombination between the rear Si and Ag cathode. This device achieved a $V_{oc}$ of 0.82 V, $I_{sc}$ of 30 μA, and a peak output density of 15 μW/cm$^2$.[73]

As mentioned above, compared with the photovoltaic device, less attention has been paid to the interface between active materials and electrodes. An effective interface modification layer can reduce the efficiency of interface charge recombination to obtain higher performance devices by introducing a barrier layer to physically separate electrons and holes, or by improving energy level matching at the interface, which provides a reference in EDHs.[108,109]

### 4.4 Environmental influence

Water evaporation is ubiquitous on earth. Temperature, humidity, wind speed, and other external factors will have an impact on the evaporation rate, and appropriate evaporation acceleration is helpful to the power outputs of the EHDs. To be specific, the absorption of ambient thermal energy accelerates the rate of water evaporation, this property can link electricity generation to solar and thermal energy. Li et al. utilized ionic thermoelectric gelatin materials to take advantage of the thermal difference between Al$_2$O$_3$ film and the surrounding environment, thus improving the output voltage up to 6.4 V.[33] Furthermore, Qi and his group researched the electricity generation performance of PEDOT:PSS and GO aerogel sponges based on EHD in different relative humidity (RH). They discovered that under natural convection, the device could create a maximum voltage of 2.13 V and the best output power density of 18.5 μW/cm$^2$ at RH of 73%.[80] In nature, wind also accelerates the evaporation of water. Windmills and wind turbine generators have already been in the public view, and further integration of wind energy and EHDs is another strategy to improve generation performance.

## 5 APPLICATION

In recent years, more and more attention has been paid to EHDs, but their practical applications have been troubled by problems, such as low output power and poor energy conversion efficiency. Although existing a significant power output gap between EHDs and traditional power supplies, continued research has driven EHDs to be used in self-powered systems and low-consumption equipment.[3,4,110]

At present, the application of EHDs focused on electricity generation, sensors, and water desalination. Wu et al. demonstrated that EHD consisting of a honeycomb-structured rGO film achieved output power enhancement in seawater, with the advantages of high spontaneity, continuous generation, and low cost, which is a significant step toward practical applications of EHDs (Figure 10A).[62] Due to the power of individual EHD being relatively poor, researchers mostly improve the power through series and parallel. Furthermore, Li et al. proposed that an EHD integrated with a supercapacitor could capture energy from the environment while also storing energy.[69] In the future, EHDs may promise development in the medical system, outdoor illumination, indoor air conditioning, and so forth.

With the development of self-powered technology, self-powered sensing systems have gradually come into our view. Since there are no issues such as battery replacement and environmental pollution, a self-powered sensing system based on hydrovoltaic effects is expected to take a share of the market of sensors in the future.[110,111] Due to its output stability and structure flexibility, a heat-enhanced EHD was applied to power wearable electronic devices. As shown in Figure 10B, EHD, a flexible CNT pressure sensor, and a Bluetooth device were integrated into a wearable power-sensor system to detect and monitor physiological signals sensitively, which was sent to the mobile phone for graphical display and digital analysis of personal health.[33] Besides physiological monitoring, environmental monitoring is also possible. Zhong et al. created a new self-powered/self-cleaning atmospheric monitoring system using TiO$_2$ nanoparticles (Figure 10C).[23] The TiO$_2$ nanoparticle membrane can be used as both a power source and gas sensor. Therefore, the system can transmit sensing information to external platforms for real-time atmospheric
monitoring without an additional power supply. This novel method design demonstrated the great potential of EHDs in sensing systems.

To alleviate the increasing demand for freshwater resources, people have great interest in the combination of desalination technology and evaporation-driven hydrovoltaic effect. A type of 3D solar-thermal evaporator was composed of PVA, PEDOT:PSS, and CNTs for simultaneous high-flux desalination and electricity generation in Figure 10D. Under continuous solar irradiation, multiple evaporators in series could satisfy both individual drinkings for the user and sufficient electricity for small electronic devices. Actually, the most direct way to improve solar water evaporation performance is to improve space utilization at the macroscale. Liu et al. conducted a detailed experimental study on the novel PCG membrane evaporator structure (Figure 10E). The results indicated that a satisfactory evaporation rate could be obtained by placing a 3D evaporator with a slope of 45°. This kind of 3D evaporator makes promising for the coproduction of drinkable clean water and electricity at the same time.

6 | CONCLUSIONS AND OUTLOOK

Herein, we introduce the basic concept of the evaporation-driven hydrovoltaic effect. The recent developments in various types of materials have been used in hydrovoltaic devices, including carbon materials, biomass-based materials, metal oxides, composite materials, and other novel materials. We put emphasis on discussing several strategies for improving electrical output by physicochemical regulation. Specifically, by adjusting the porous structure to the appropriate size, carrying out hydrophilic treatment to improve the hydrophilicity, adding functional groups to increase surface zeta potential, as well as optimizing the electrode material to promote charge collection efficiency, more efficient hydrovoltaic devices are fabricated. Currently, the evaporation-driven hydrovoltaic effect has developed rapidly in addition to generating electricity, the combination with desalination technology and sensor has been widely demonstrated for applications. These green and sustainable methods of energy
conversion hold great promise for new sustainable development solutions like carbon neutrality.

While the merits of the evaporation-driven hydrovoltaic effect have been extensively validated, as an emerging research field, there are still noteworthy challenges that need to be addressed before being widely used in abundant applications:

1. The mechanism of the hydrovoltaic effect is still in a preliminary study, and future research should focus on the solid–liquid interface, specifically the in situ characterization of the charge generation and transfer process under water–solid interaction.

2. The selection and design of hydrovoltaic materials remain to explore a set of standards. Regulating the structure and surface properties of materials, including ordered nanochannel formation and surface functional group modification, for establishing a reliable rule between material properties and output power is an important direction to improve the performance of hydrovoltaic devices.

3. The application area of hydrovoltaic devices is still restricted. Limited by the low output power of a single device, large-scale automatic integration of devices is ought to be on the agenda.

4. In real-service situations, materials and structures for the evaporation-driven hydrovoltaic technology are typically operating under harsh conditions with ions, solutes, and impurities and contaminants in water, which could cause chemical reactions with the materials used. As a result, the long-term stability of EHDs against structural and functional degradations in harsh conditions, especially under extreme conditions, should be an essential issue in future research and development. For example, the output stability and life of devices can be improved by introducing features, such as filter layer, self-healing, self-cleaning, shape memory, and charge-storage capacity functions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

Wanlin Guo conceived and supervised this review. Chunxiao Zheng and Weicun Chu prepared the outline of this review. Chunxiao Zheng and Weicun Chu cowrote the abstract, introduction, selection of materials, optimization strategy, conclusion, and outlook with advice from Wanlin Guo, Sunmiao Fang, and Jin Tan. Weicun Chu wrote the mechanism with suggestions from Xiaofan Wang. Chunxiao Zheng prepared the figure design and drawing. All authors contributed to the editing and agreed to the final version of the manuscript.
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AUTHOR BIOGRAPHIES

Chunxiao Zheng is currently a Ph.D. candidate in the Key Laboratory of Intelligent Nano Materials and Devices of Ministry of Education at NUAA. She obtained her M.S. degree in Materials Science and Engineering from Nanjing Forestry University in 2020. Her current research focuses on energy conversion at solid-liquid interfaces.

Weicun Chu is currently a Ph.D. candidate in the Key Laboratory of Intelligent Nano Materials and Devices of Ministry of Education at NUAA. He received his B.S. degree in College of Science from NUAA in 2020. His main research interest is to focus on energy conversion at solid-liquid interfaces.

Wanlin Guo obtained his Ph.D. from Northwestern Polytechnical University in 1991 and was elected as an academician of the Chinese Academy of Science in 2017. He is a Chair Professor at NUAA and the founding director of the Key Laboratory of Intelligent Nano Materials and Devices.
of Ministry of Education. His research focuses on intelligent nanomaterials and devices, novel conception and technology for efficient energy conversion, molecular physical mechanics for neuronal signaling and molecular biomimics, as well as the strength and safety of aircraft and engines.

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