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# Hydrovoltaic technologies for self-powered sensing and pollutant removal in water and wastewater: a review

Shipu Jiao<sup>1</sup> · Yushi Jin<sup>1</sup> · Eric Lichtfouse<sup>2</sup>  · Xiaohong Zhou<sup>1</sup> 

## Abstract

Carbon emissions from the water and wastewater treatment sector account for about 2% of global carbon emissions, calling for the integration of sustainable energies to decrease carbon footprints. Here we review the use of hydrovoltaic technologies in water and wastewater treatment, with emphasis on the hydrovoltaic effect, self-powered sensors, and pollutant removal. The hydrovoltaic effect can be obtained using moisture-induced hydrovoltaic generators and water evaporation-induced hydrovoltaic generators. Strain, pressure, humidity, gas, and liquid sensors can be powered by hydrovoltaic generators. Remarkably, the hydrovoltaic technology-driven liquid sensors can reach a detection limit of 1 femtomolar. The hydrovoltaic technology reduces pollution in two ways, first by generating electricity from environmental moisture and evaporation, thereby reducing fossil fuel dependency. Second, it takes advantage of the photocatalytic properties of materials to decompose organic matter during water treatment, thus minimizing the usage of chemical reagents. Applications comprise wastewater power generation, seawater desalination and organic matter degradation.

**Keywords** Hydrovoltaic technology · Self-powered · Sensor · Pollutant removal · Application · Wastewater · Water treatment

## Introduction

Energy and environmental pollution are two major core issues facing humanity today. According to statistics from the International Energy Agency (IEA), over the past decade, global energy demand has grown at an average annual rate of about 2.1%. Fossil fuels still account for more than 80% of the energy mix, leading to a continued rise in carbon emissions [1]. Taking China's Taihu Lake as an example, the discharge of industrial wastewater has caused eutrophication of the water body. During the blue-green algae pollution incident at Taihu Lake in 2007, the drinking water supply for approximately one million residents in Wuxi was affected.

Given the continuous expansion of global energy requirements and the rising awareness of environmental protection and human well-being, the advancement of highly efficient and sustainable clean energy technologies has emerged as a critical focus of contemporary scientific research. [2–8]. Water is the source of life and contains a tremendous amount of energy, covering about 71% of the Earth's surface and absorbing about 35% of the solar energy received by the Earth [9]. Water evaporation and water vapor are omnipresent. The power of energy conversion from water evaporation alone exceeds 34 petawatt per year, which is 3 orders of magnitude higher than the average annual human primary energy consumption of 18 terawatt. It also far surpasses the current global installed solar power capacity (approximately 2 TW) and installed wind power capacity (approximately 1 TW) [10]. However, its energy density is relatively low, necessitating the use of carefully designed micro- and nano-materials to achieve efficient capture. As a new method of generating electricity by using environmental moisture and water evaporation, hydrovoltaic technology has been widely concerned in recent years [11–15], which not only shows great potential as a power source, but also offers promising

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applications in areas such as self-powered sensing and water pollutant removal.

The core principle of hydrovoltaic technology is the hydrovoltaic effect, that is, after water molecules are in contact with the surface of a specific material, due to the surface charge characteristics and micro-porous structure of the material, adsorption, dissociation, ion migration and other processes occur, thereby generating electrical energy [16]. Since this effect was first discovered in 2003, it has opened up new avenues for the development of advanced energy conversion and storage technologies [17, 18]. In 2014, Academician Wanlin Guo's team reported that when a droplet of NaCl solution moves across a single layer of graphene, it generates a voltage of several millivolts [19]. Subsequently, Professor Jun Zhou made significant breakthroughs in utilizing carbon materials for power generation driven by water evaporation, demonstrating that a centimeter-sized carbon black film could reliably produce a sustained voltage of up to 1 V under ambient conditions during evaporation [20].

In 2018, Academician Wanlin Guo formally proposed the concepts of hydrovoltaic effect and hydrovoltaic technology, which garnered widespread attention in academia [21]. In 2020, the research team led by Jun Yao at the University of Massachusetts discovered that bacterial protein nanowires produced by *Geobacter sulfurreducens* could serve as hygroscopic materials for fabricating moisture-driven generators, enabling electricity generation using humidity from the air [22]. In the field of environmental sensors, traditional sensors typically rely on outside power sources, which increases the complexity and cost of the device, and limits the application scenarios of the sensor, such as remote areas [23–26]. In contrast, self-powered sensors powered by hydrovoltaic technology are capable of generating electricity from natural resources, such as ambient humidity and humidity, enabling autonomous operation. This capability provides a promising solution for applications in environmental monitoring, healthcare, smart homes, and other fields [27–30].

In addition, hydrovoltaic technologies show great potential in removing water pollutants. Traditional wastewater treatment technologies often require a large amount of energy and chemical reagents, which leads to high treatment costs and potential secondary pollution problems [31, 32]. The United Nations estimates that global carbon emissions from the water treatment sector, including wastewater treatment, account for about 2% of all carbon emissions [33]. Taking the sewage plants in southern China as an example, the energy intensity of the sewage treatment plants is mostly between 0.4 and 0.5 kWh m<sup>3</sup> [34]. In contrast, hydrovoltaic technologies can efficiently convert pollutants into harmless substances while generating electricity. This can be achieved in two ways. On the one hand, the electricity generated by the hydrovoltaic technologies is directly collected; and then, the pollutants are removed by electrical degradation. The

other is to use the nature of the material itself to remove pollutants [35]. Taking the hydrovoltaic generator prepared by titanium dioxide as an example, titanium dioxide generates photogenerated electrons and holes under light, thus forming active oxygen species such as hydroxyl radicals and superoxide anion radicals. These reactive oxygen species attack pollutant molecules, oxidizing and degrading them into harmless substances [36–38]. This technology is characterized by its high efficiency and environmental sustainability, offering a novel approach to addressing water pollution and even enabling the resource recovery of pollutants.

Nearly 200 review papers on hydrovoltaic technology have been published, mainly focusing on the mechanisms of hydrovoltaic effect and the materials used in hydrovoltaic power generation [9, 39, 40]. To the best of our knowledge, complete hydrovoltaic technologies in the self-powered sensing and water pollutant removal including principle, device configuration and application have not been comprehensively examined in the literatures up to now (Table 1). This review offers a methodical and all-encompassing overview of hydrovoltaic technologies in the self-powered sensing and water pollutant removal, predominantly over the last one decade, describing its basic principles, application prospects and challenges, and propose future research directions and development trends (Fig. 1). Hydrovoltaic technologies for construction of self-powered strain sensors, pressure sensors, humidity sensors, gas sensors and liquid sensors are described. Hydrovoltaic technologies can capture energy and degrade pollutants from a variety of wastewater, including wastewater containing oxides, oxides-containing wastewater, high-salt wastewater, dye wastewater and bacteria-containing wastewater. Hydrovoltaic technologies will play a more important role in the field of environmental protection and sustainable development.

## The hydrovoltaic effect

Hydrovoltaic technologies harness the natural evaporation of water and ambient moisture in the atmosphere to constantly transform the energy contained in water into electricity. Accordingly, hydrovoltaic generators can be classified into two types: moisture-induced hydrovoltaic generators and water evaporation-induced hydrovoltaic generators [46]. The following section provides a brief overview of the electricity generation mechanisms for these two types of hydrovoltaic generators.

### Moisture-induced hydrovoltaic generators

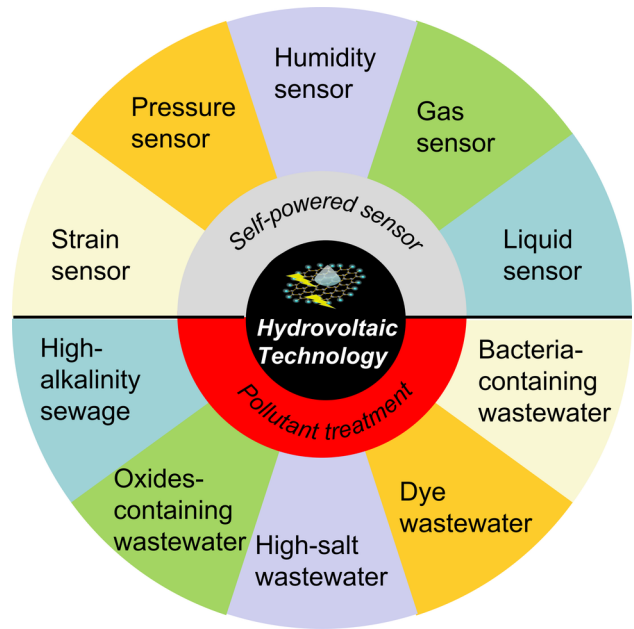
The fundamental mechanism underlying the operation of moisture-driven hydrovoltaic generators is the formation of an ion gradient [47]. These generators are characterized by

**Table 1** Comparison of this review with other hydrovoltaic technology reviews

| Year | Main content  | Innovation point   | Future research direction   | References |
|------|---|--|---|------------|
| 2025 | Power generation mechanism of hydrovoltaic effect                           | The application of hydrovoltaic technologies in the fields of self-powered sensing and water pollution treatment is systematically summarized  | Material performance improvement                                      | This work  |
|      | Application of hydrovoltaic technologies in self-powered sensing            | The application of a variety of materials in hydrovoltaic technologies is summarized   | Application expansion   |            |
|      | Application of hydrovoltaic technologies in water pollution treatment       | The synergistic effect of hydrovoltaic effect with other effects is explained, such as the combination with Joule thermal effect, photocatalytic effect  |   |            |
| 2024 | Mechanism of moisture-induced power generation                              | The hydrovoltaic effect of electrical energy generated by the interaction between moisture and materials is revealed   | Mechanism research deepening  | [41]       |
|      | The application of various materials in hydrovoltaic technologies           | The application of carbon materials, polymers, biomaterials and semiconductor materials in moisture power generation is systematically studied   | Multi-factor coupling analysis<br>Large-scale application exploration |            |
| 2024 | Water motion power generation   | The energy harvesting from water movement, evaporation and ambient humidity in hydrovoltaic technologies is systematically reviewed  | Accurate modeling and optimization                                    | [42]       |
|      | Water evaporation power generation  | The energy conversion mechanism of different forms of water interaction with solid materials in the hydrovoltaic effect is deeply discussed  | In-depth study of moisture-induced power generation                   |            |
|      | Ambient humidity power generation   | According to the current research situation, the technical roadmap of hydrovoltaic technology is formulated  |   |            |
| 2023 | Generation mechanism of biofilm-based hydrovoltaic generator                | Biofilms are universal, renewable, low-cost, non-toxic and environmentally friendly  | Improve power generation performance                                  | [43]       |
|      | Characteristics of different types of biofilm-based hydrovoltaic generators | Biofilm hydrovoltaic technology enables hydropower conversion in a variety of ways, and can be coupled with other energy harvesting methods such as photovoltaic   | Expanding microbial resources   |            |
|      | Effect of microbial species on electrical performance                       | The research progress of various kinds of materials (including carbon materials, biomass-based materials, metal oxides, composite materials and other new materials) used in evaporation-driven hydrovoltaic technology is summarized systematically | Industrial application of biofilm                                     | [44]       |
| 2022 | The mechanism of evaporation-driven hydrovoltaic effect:                    | How the properties of different materials affect their power generation performance in evaporation-driven hydrovoltaic generators is discussed in detail   | In-depth exploration mechanism  |            |
|      | Materials used for evaporation-driven hydrovoltaic generators               | Based on the hydrovoltaic effect mechanism, a series of optimization strategies are proposed for the key factors affecting the output power density  | Establishment of material standards                                   |            |
|      | Optimization of hydrovoltaic generator driven by evaporation                |  | Expand application scale<br>Enhanced power generation stability       |            |

**Table 1** (continued)

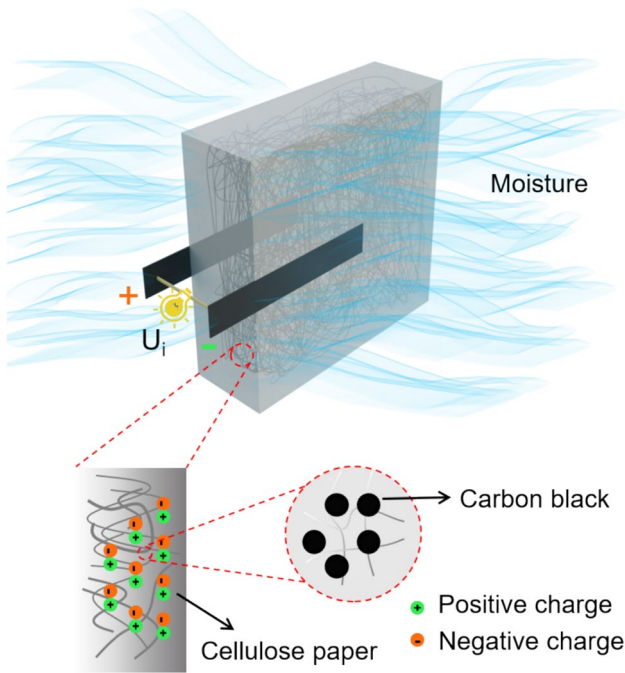
| Year | Main content                              | Innovation point  | Future research direction         | References |
|------|---|---|-----------------------------------|------------|
| 2018 | Basic properties of water–solid interface | Revealed the hydrovoltaic effect of carbon nano-materials directly interacting with water to generate electricity   | Material optimization             | [45]       |
|      | Nanostructured carbon materials           | A variety of nanostructured carbon materials, including graphene, carbon nanotubes and carbon black, have been studied in detail  | Deepening of theoretical research |            |
|      | Energy conversion of hydrovoltaic effect  | Various related mechanisms of the hydrovoltaic effect are discussed, including current potential, traction potential, fluctuation potential, electricity induced by natural water evaporation and electricity induced by humidity | Device performance improvement    |            |



**Fig. 1** Hydrovoltaic technologies in the self-powered sensor and pollutant treatment. Hydrovoltaic technology has a unique ability to generate electricity by using water changes. Therefore, hydrovoltaic technologies show great application potential in the field of strain sensors, pressure sensors, humidity sensors, gas sensors and liquid sensors. The hydrovoltaic technologies can transform pollutants into harmless substances or remove them from water through electrochemical reactions or photocatalytic degradation, while achieving energy recovery and utilization

the presence of hydrophilic, oxygen-containing chemical groups. When exposed to moisture, water units preferentially aggregate around the oxygen-rich regions, resulting in the release of hydrogen ions through local solvation effects (Fig. 2). This aggregation, whether caused by the spatial arrangement of the oxygen functional groups in the material or by uneven water infiltration, causes the establishment of a concentration gradient of  $H^+$ .

Driven by the concentration gradient, hydrogen ions diffuse, which in turn induces a potential difference in the external circuit [41]. To establish the desired hydrogen ion concentration gradient within the hydrovoltaic generator, two strategies are commonly employed. The first strategy is to enable oxygen-containing functional groups to exhibit a gradient distribution within the device through a specific treatment technique. When the hydrovoltaic generator is subjected to dampness, the internal oxygen-containing functional groups are ionized, leading to a directional migration of charged ions, which generates electrical energy. The second strategy is to introduce the asymmetrical distribution of water, where two sides of the device encounters different humidity conditions. A straightforward approach to achieve this purpose is by sealing one side of the hydrovoltaic materials so when exposed to humidity, the uncovered side



**Fig. 2** Hydrovoltaic effect induced by the ion gradient. As an example, carbon black is doped into cellulose paper to form an asymmetric distribution in the vertical direction. When exposed to moisture, oxygen-containing functional groups ionize, generating electrical energy through the directional movement of charged particles resulting from an ion gradient

absorbs water while the covered side is isolated from the moisture [48, 49]. The expression of voltage is as follows:

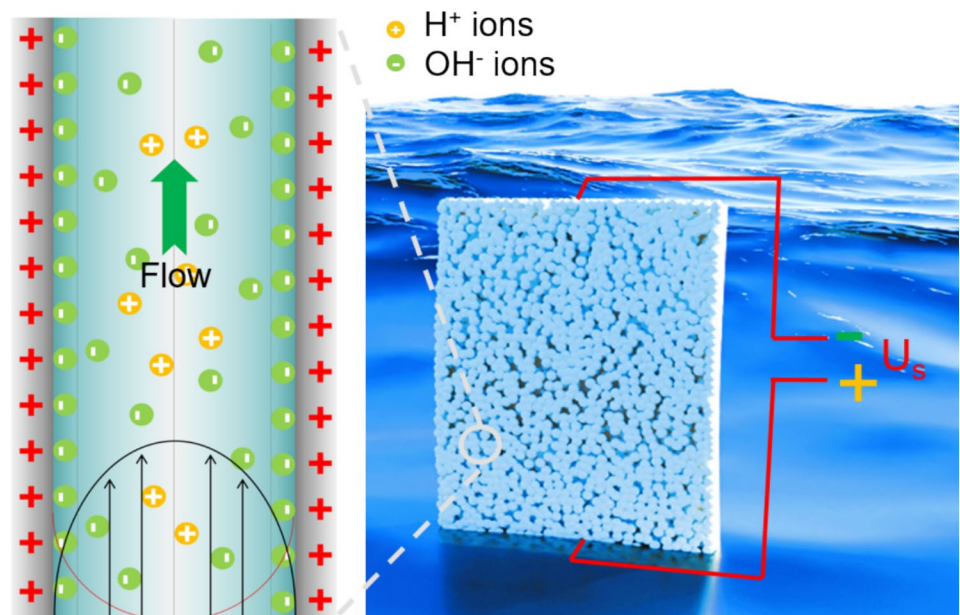
$$U_i = \frac{qD}{\sigma} \int \frac{dc}{dx} \quad (1)$$

where  $U_i$  is induced potential (V),  $q$  is the charge of the basic charge ( $1.602 \times 10^{-19}$  C),  $D$  is the diffusion coefficient of  $H^+$  ( $m^2/s$ ),  $\sigma$  is the ionic conductivity of water (S/m), and  $dc/dx$  is the concentration gradient of  $H^+$  along the X-axis perpendicular to the surface of the hydrovoltaic generator ( $mol/m^4$ ).

### Water evaporation-induced hydrovoltaic generators

The evaporation of water, much like the omnipresent existence of moisture in nature, is a universal phenomenon that absorbs heat from the surrounding environment. Hydrovoltaic technologies, which harness the energy from the evaporation process to generate electricity, is considered another encouraging and cost-effective way for power generation. In the water evaporation-driven hydrovoltaic system, the primary mechanism relies on the streaming potential effect. For efficient power generation, two prerequisites are required: First, the material surface must possess either a positive or negative charge, and second, the material must feature a micro- and nano-scale pore structure [50]. When a hydrovoltaic generator is in touch with solution, the surface charge interacts with the counter-ions in the solution to form an electric double layer [51]. This process attracts ions contrary to the surface charge of the solid to its vicinity and repels ions with the same charge into the nanopores (Fig. 3). Under the combined drive of capillarity and vaporization, ions

**Fig. 3** Hydrovoltaic effect induced by the streaming potential. When water is in contact with a hydrovoltaic generator, the overlapped double electrical layers will spontaneously form at the solid-liquid boundary. The capillary action can drive the water flow through the poriferous passage. Taking the positive zeta potential of a porous channel as an example, the  $H^+$  in the solution are repelled accordingly, causing the  $OH^-$  carried in the solution migrating from the bottom to the top to form forming the streaming potential



relocate from the base to the top with the aqueous solution, forming the streaming potential, which continuously generates electricity [52]. The potential value can be expressed as:

$$U_s = \frac{\varepsilon_0 \varepsilon_r}{\sigma \eta} \Delta P \zeta \quad (2)$$

where  $U_s$  is streaming potential (V),  $\varepsilon_0$  is the dielectric constant of vacuum (F/m),  $\varepsilon_r$  is the dielectric constant of water,  $\sigma$  is the conductivity of the solution (S/m),  $\eta$  is the viscosity of the solution (Pa·s),  $\Delta P$  is the pressure difference (Pa), and  $\zeta$  is the zeta potential (V). It should be noted that the mechanism of electricity generation in hydrovoltaic technology remains controversial, with no unified explanation for the hydrovoltaic effect.

Currently, there is no unified theoretical model for the hydrovoltaic effect. The prevailing hypotheses include ion gradient diffusion and streaming potential effect, but these differ in their explanations of the dynamics of the electrical double layer within nanochannels. The ion gradient diffusion attributes the primary driving force to the asymmetric distribution of surface charges, whereas the streaming potential effect emphasizes the conversion of kinetic energy from capillary flow.

## Self-powered sensors driven by hydrovoltaic technologies

### Strain sensors

The strain sensor represents an apparatus employed to gauge the distortion and strain of an object. The operating principle of the strain sensor relies on alterations in the resistance, capacitance, or inductance properties of the material when

strain occurs [53]. The self-energized strain sensors driven by hydrovoltaic technologies that have been reported so far are all resistive type with characteristics of excellent sensitivity and fast response speed [54]. Table 2 compares different types of self-powered sensors based on hydrovoltaic technology.

Hydrogels can absorb moisture to generate electricity. Simultaneously, deformation-induced resistance changes alter the output voltage, making them ideal for manufacturing self-powered strain sensors. More impressively, hydrogels have good elasticity, flexibility and biocompatibility, and are able to come into direct contact with human tissues without causing inflammation or rejection, thereby highly suitable for use as human strain sensors. A multifunctional hydrogel-based hydrovoltaic generator was prepared using a deep eutectic solvent, pretreated lignin, aluminum ions, and polyacrylic acid [55]. The hydrovoltaic generator generated an open-circuit voltage ( $V_{oc}$ ) of 1.32 V and a short-circuit current ( $I_{sc}$ ) of 22.37  $\mu$ A in an environment at 26 °C with 55% relative humidity (RH), suitable to be used as a self-energized strain sensor for finger motion surveillance. As expected, the bending of the finger was accompanied by a decrease in the current signal, while the extension of the finger was accompanied by an increase in the current signal. A hydrovoltaic generator with 400% tensile capacity was prepared by combining hygroscopic ion hydrogel with carbon black-coated cotton knitwear, which achieved continuous high  $I_{sc}$  of 50  $\mu$ A and  $V_{oc}$  of 300 mV [56]. When the device was attached to the knuckles of the hand via commercial tape, the current output from the hydrovoltaic generator changed with the Angle of the finger bend, allowing the apparatus to act as a strain sensor.

However, hydrogels generally display feeble mechanical characteristics and isotropy, which restricts their prospective

**Table 2** Performance comparison of self-powered sensors

| Type of Sensor  | Potential (V) | Current ( $\mu$ A) | Detection limit        | Sensitivity      | Stability (cycles/time) | Physical limitation  | References |
|-----------------|---------------|--------------------|------------------------|------------------|-------------------------|--|------------|
| Strain sensor   | 1.32          | 22.37              | Not mentioned          | Not mentioned    | 14                      | Low mechanical strength<br>The performance decreases after long-term deformation | [55]       |
| Pressure sensor | 0.3           | 50                 | 10 g                   | Not mentioned    | 50                      | Easily affected by environmental humidity  | [56]       |
| Humidity sensor | 1             | 15.5               | 15% RH                 | 6.4 mV/RH        | 7 days                  | Unstable performance in extreme humidity   | [57]       |
| Gas sensor      | 1.2           | 0.5                | 50 ppm                 | 0.65 mV/ppm      | 4                       | High cross-sensitivity and insufficient selectivity                              | [58]       |
| Liquid sensors  | 0.4           | 13.9               | $5.2 \times 10^{-9}$ M | 17.2 mV/ $\mu$ M | Not mentioned           | Significant signal interference in complex liquid matrices                       | [59]       |

applications. A conductive wood-based hydrogel hydrovoltaic generator with good anisotropy and mechanical properties was prepared by using hydrophilic lignin wood as a scaffold, polyvinyl alcohol, chitosan and 2-acrylamide-2-methyl-1-propyl sulfonic acid as a precursor solution [60]. When exposed to humid air, the hydrogel outputted an  $V_{oc}$  of 66.1 mV. The hydrogel generator was capable of monitoring body joint flexion and capturing facial smiles. In addition to hydrogels, one-dimensional fibers have unique advantages such as flexibility, strong weaving ability and easy integration, and are also excellent materials for the preparation of wearable devices and strain sensors. Using waste mask and carbon oxide nano-materials, a hydrovoltaic generator based on fiber was constructed, which generated electricity efficiently under deformation conditions, with a maximum voltage of 430 mV and a maximum current of 29.5  $\mu$ A [51]. Since the stable electromechanical response of the generator was closely related to tensile deformation, the generator acted as a wearable self-energized strain sensor for monitoring body physiological activity and motor behavior applications such as swallowing and capturing human facial movement.

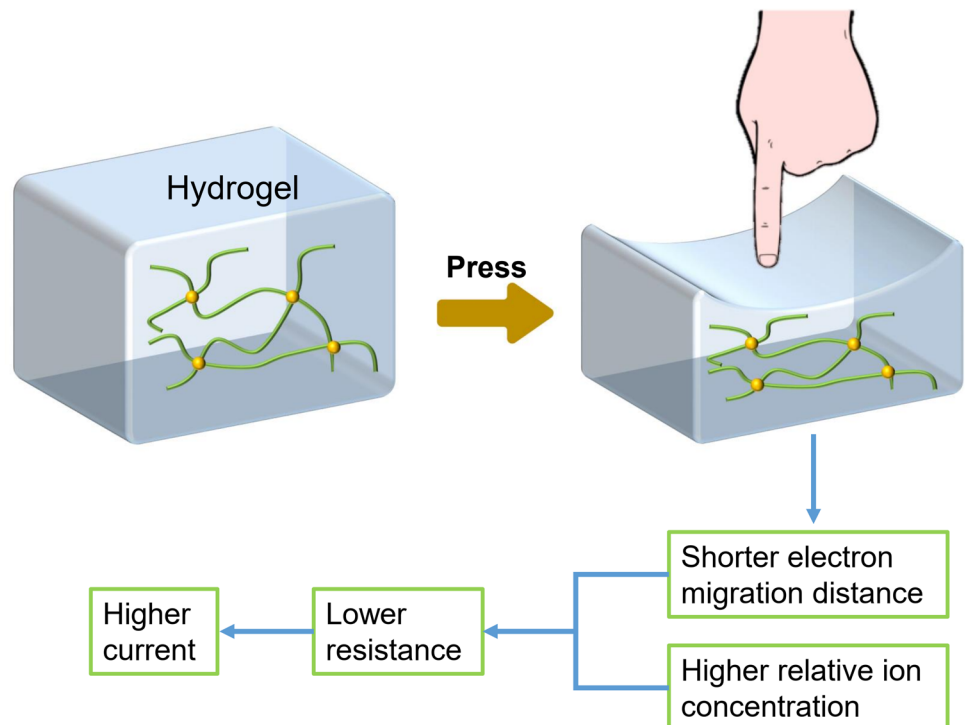
In summary, the hydrovoltaic technology has shown extensive application potentials in the realm of self-supplying energy sensors. By preparing a multifunctional hydrogel-based hydrovoltaic generator, a conductive wood-based hydrovoltaic sensor, and a fiber-type hydrovoltaic generator, researchers have made remarkable progress in improving energy conversion efficiency and enhancing mechanical

properties. These achievements provide strong support for the application of hydrovoltaic technology in intelligent wearable apparatuses, object motion monitoring gadgets, human-computer interaction equipment and other fields, and are anticipated to fuel the further progress of related technologies in the future.

### Pressure sensors

Pressure sensors primarily serve to measure the pressure of media such as liquids or solids and convert this pressure signal into a measurable electrical output (Fig. 4). An aerogel-based hydrovoltaic generator was developed using polyvinyl alcohol and graphene oxide (GO), achieving an exceptionally high  $V_{oc}$  (1.9 V) and  $I_{sc}$  (82.5  $\mu$ A) [61]. When encapsulated with polydimethylsiloxane, the aerogel, in the presence of water, functions as a self-powered pressure sensing device. When compression was exerted on the aerogel, the water molecules within the aerogel were expelled to achieve unidirectional flow, hence generating the corresponding output voltage. A sandwich-like flexible nanofiber pressure sensor with excellent flexibility and rapid reaction was also developed for the instantaneous detection of body movements, including finger motions, sound waves, and neck pulses [62]. Furthermore, a graphene oxide-based single-component multimode sensor has been developed that can spontaneously adsorb moisture in the air to produce electricity [63]. With the help of machine learning, a single sensor had the capacity to concurrently monitor and separate

**Fig. 4** Diagram of a hydrogel-based hydrovoltaic generator-based pressure sensor. The compressed hydrogel-based hydrovoltaic generator reduces the electron migration distance and increases the ion concentration, thereby reducing the resistance between the two ends of the hydrovoltaic generator, so that when the hydrovoltaic generator is compressed, the output current increases



alterations in temperature, humidity, and light intensity in addition to monitoring changes in pressure. This sensor shows great application potential in the domains of health monitoring, artificial electronic epidermis and the Internet of Things. In practical applications, pressure sensors based on hydrovoltaic technology need to be well responsive to pressure and be able to recover after multiple deformations.

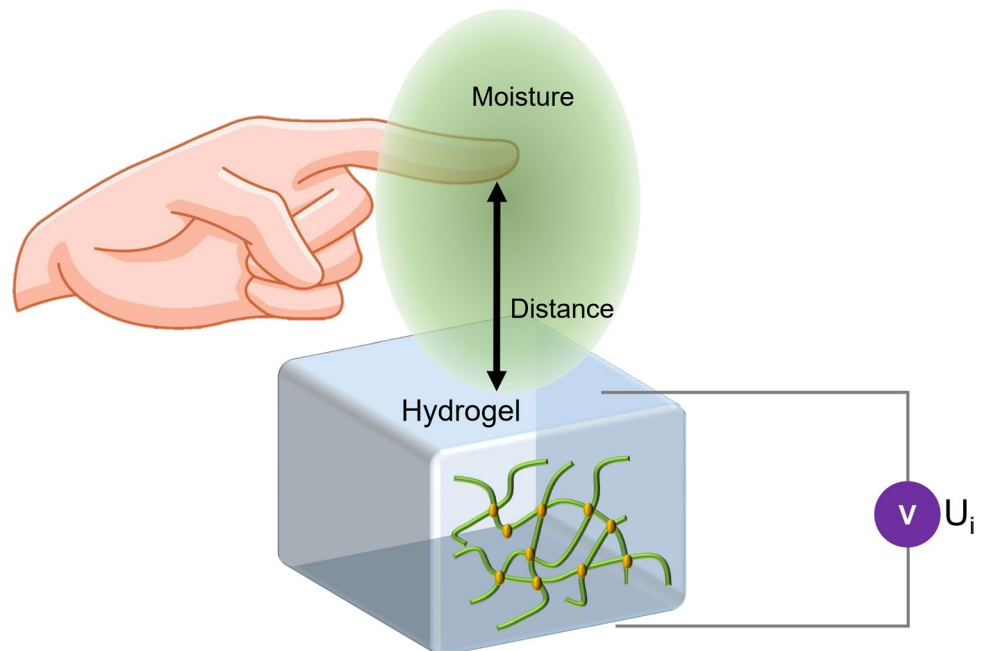
## Humidity sensors

A humidity sensor is an electronic device designed to measure the water vapor content in the surrounding atmosphere, enabling the determination of relative humidity and the conversion of this information into an electrical output [64]. A novel tree-shaped cellulose acetate nanofiber film was fabricated using a one-step electrospinning method to build a low-cost, high-efficiency, and wearable hydrovoltaic generator [65]. The hydrovoltaic generator exhibited excellent power generation performance due to its increased hydrophilicity, higher specific surface area, and decreased pore dimensions, thereby producing a voltage of approximately 0.7 V for a single generator. When integrated into a commercial face mask, this generator provided highly sensitive monitoring of respiratory rate and intensity, highlighting its potential for use in portable health monitoring devices. Additionally, a high-performance wood-based hydrovoltaic generator with superior mechanical properties was developed by chemically modifying natural wood to create a double-layer wood film [66]. At 85% relative humidity, the generator generated an  $V_{oc}$  of 0.57 V, demonstrating its

potential as a self-energized sensor or power supply. This wood-based hydrovoltaic generator is applicable in diverse domains, including monitoring human finger movements, tracking respiratory characteristics, quantifying plant transpiration, and sensing humidity changes related to gas leaks, weather fluctuations, and forest fires.

To meet the continuous power supply demands of wearable microsensors, a flexible hydrovoltaic generator was developed with conductive polymer modification [67]. It is capable of outputting 1000 mV voltage and over 12  $\mu\text{A}$  current along with excellent durability and humidity sensitivity. The device's rapid electrical response to humidity made it suitable for use in wearable technology to monitor breathing patterns. Through the testing of different breathing rates, the device was able to clearly reflect the characteristics of breathing signals, including normal breathing, slow breathing and wheezing. A wearable hydrovoltaic generator with excellent power generation, air permeability, and fire resistance was designed using asymmetric nanofiber components [57]. A single 1  $\text{cm}^2$  hydrovoltaic generator can continuously produce high direct current power, with a voltage of 1.0 V, a current of 15.5  $\mu\text{A}$ , and a power density of 3.0  $\mu\text{W}/\text{cm}^2$ . This hydrovoltaic generator exhibits excellent bending durability, maintaining stable output voltage after hundreds of bending cycles. The internal water circulation mechanism ensures that the voltage output remains stable for up to 7 days without degradation. When integrated into a fire glove, this generator accurately responded to humidity changes during fire simulation tests. The generator's stable voltage signal confirmed its potential as a reliable fire sensing device.

**Fig. 5** A hydrovoltaic generator being used as a self-powered sensor to track the movement of the human finger through non-contact control based on the moisture distribution determined by the distance near the human skin. As the distance between the finger and the hydrovoltaic generator approaches, the humidity increases and the hydrovoltaic generator produces a higher open-circuit voltage  $U_i$



Depending on the sensitivity of the hydrovoltaic generator to humidity changes, the hydrovoltaic generator can also be used in non-touch sensing. As shown in Fig. 5, the hydrovoltaic generator outputs a voltage corresponding to the moisture distribution determined by the distance near the human skin. A flexible thin film hydrovoltaic generator was prepared using GO. When the finger was close to the film, moisture was diffused from the finger to the film to generate electricity. So it can be used as a finger position signal and smart artificial skin [68, 69]. To address the issue of slow humidity response in traditional hydrovoltaic generators, an ultra-fast electrical response ( $972.4 \text{ mV s}^{-1}$ ) was achieved through Grotthuss proton hopping [70]. Based on this generator, a diagnostic mechanism for obstructive sleep apnea hypopnea syndrome was developed, capable of stably monitoring complex and variable breathing states, such as normal breathing, hypoventilation, and apnea. In addition to water, hydrovoltaic generators are also capable of detecting various liquids. A hydrovoltaic generator based on carbon nanoparticles and  $\text{TiO}_2$  nanowires was exposed to  $6 \mu\text{L}$  of water, ethanol, acetone, and methanol, respectively, producing an output voltage of  $0.3 \text{ V}$  after 244, 876, 931, and  $184 \mu\text{s}$ . The rapid response time and high sensitivity to liquids indicate that this device holds great potential for detecting small quantities of liquid [71].

Hydrophilic materials, such as graphene oxide and cellulose, exhibit optimal response speeds due to their high specific surface areas and rapid moisture adsorption capabilities. However, carbon-based materials are prone to ion contamination, which limits their long-term stability. Compared with traditional sensors, humidity sensors based on hydrovoltaic technology do not require an external power source, making them suitable for remote monitoring applications, such as early warning systems for forest fires. Nevertheless, their detection range (20–90% RH) is narrower than that of commercial capacitive sensors (0–100% RH), and they have longer response times. In future research, composite materials should be developed to balance sensitivity and durability, while multimodal sensing approaches, such as coupling temperature and humidity sensing, should be explored to enhance environmental adaptability. In all, hydrovoltaic technology generates electricity by absorbing moisture and detecting changes in electrical signals caused due to variations in humidity, hence enabling environmental moisture monitoring.

### Gas sensors

A gas sensor is an apparatus that transforms the volume fraction of a gas into a corresponding electrical signal. The operating principle of gas sensors relies on the physical or chemical interactions between gas molecules and gas-sensitive materials, which cause changes in physical or chemical

properties. These changes are then converted into measurable electrical, optical, or acoustic signals [72]. In maritime and coastal settings, salt aerosol laden with significant amounts of salt ( $\text{NaCl}$ ,  $\text{MgCl}_2$ ,  $\text{KCl}$ ,  $\text{CaSO}_4$ ) can corrode metals, degrade the insulation of electrical components, and impair the performance of electronic devices. Keeping track of the salt concentration in the air can assist in reducing such losses. A fibroin-regulated nanofiber thin film hydrovoltaic generator with excellent ion sensing capabilities was developed, achieving an  $V_{oc}$  of close to  $5 \text{ V}$  in deionized water [73]. The generator's voltage response to varying sea salt concentrations was studied, establishing an immediate quantitative correlation between salt concentration in the air and the generated voltage sign. When the salt concentration changed from  $5 \times 10^{-5}$  to  $7 \times 10^{-4} \text{ g kg}^{-1}$ , the voltage decreased from  $4.37$  to  $3.29 \text{ V}$ . Carbon's surface functional moieties are capable of binding to gas molecules, altering its zeta potential. Based on this principle, a new self-energized gas monitoring system was proposed [58]. The system was powered by a hydrovoltaic generator that harvested electricity from evaporating rainwater, and the generated power of the generator increased as the oxygen concentration increases. In addition to oxygen, the self-energized gas sensor also showed a good response to ammonia, methane, argon, carbon monoxide and nitrogen. The stability, environmental adaptability, signal accuracy and anti-interference of gas sensors based on hydrovoltaic technology still need further exploration.

### Liquid sensors

Hydrovoltaic technologies can use water evaporation to generate electricity. The properties of aqueous solution have a great relationship with the electricity generation performance of hydrovoltaic generator, so the hydrovoltaic equipment is expected to serve as a liquid sensor. Sweat contains a lot of electrolytes, which are a key indicator of health. A hydrovoltaic generator made from an array of silicon nanowires has been developed [74]. The generator was utilized as a self-driven sensor to detect electrolyte in sweat, showing high responsiveness and good discrimination. In another example, a high current density of more than  $400 \mu\text{A}\cdot\text{cm}^{-2}$  was achieved by fabricating a concentration gradient in the direction of ion migration in a hydrogel to prepare a hydrovoltaic generator [75]. This generator was used in wearable device to assess the loss of electrolytes in sweat by monitoring human sweat to generate electricity. The experiment showed that when the output current was  $71.8 \mu\text{A}$ , the sweat salinity was inferred to be about  $0.35 \text{ wt}\%$ , which showed the unique advantage of the hydrovoltaic technology in body fluid monitoring.

Sensors need to be repeatable, field applicable and anti-interference. A self-powered sensor for high sensitivity

salinity detection in aqueous solution was prepared by vacuum filtration of single-walled carbon nanotubes onto cellulose paper [76]. This generator output a voltage of 0.55 V, with a repeatability of more than seven detection cycles, demonstrating comparable sensitivity, stability, and anti-interference capabilities. A hydrovoltaic generator was fabricated by modifying MOF-801 with UIO-66 to synthesize composite MOF (Metal–Organic Framework) nanomaterials, which were then loaded onto filter paper [77]. The produced voltage of the generator was proportional to the NaCl concentration in the solution. By exploiting the proportional connection between the produced voltage and salinity, a wireless salinity sensing system was developed, powered by evaporation-driven hydrovoltaic energy. A self-energized desalting monitoring system founded on hydrovoltaic technology was also designed [78]. The system specifically included a hydrovoltaic generator and a capacitive deion battery, in which the hydrovoltaic generator supplied power to the capacitive deion battery and acted as a monitoring apparatus to detect the desalination process of the salt solution.

Table 3 summarizes the various hydrovoltaic technologies designed for sensing different targets in liquid media. A novel self-energized electrochemical sensor was created by coupling hydrovoltaic effect with capacitance amplification. The sensor was fabricated by two-dimensional transition metal carbides and nitrides (MXene) -polyaniline (PANI), which obtained electrical energy from water evaporation [79]. The self-actuated electrochemical sensor detected enrofloxacin in the range of 1 fM to  $1 \times 10^6$  fM with a detection limit of 0.585 fM. This sensor is environmentally friendly, user-friendly, and ideal for accurate detection of enrofloxacin in real water samples. Neonatal jaundice needs to be monitored in real time, and the current routine blood collection method is inconvenient and unpopular, so a new wearable percutaneous bilirubin measurement device is expected to achieve real-time dynamic monitoring. A self-energized wearable biosensor based on ZnO nanoarray was designed for instantaneous monitoring of neonatal jaundice [80]. The sensor did not need to rely on an outer electricity source to work independently, and the resulting hydrovoltaic output

was both an energy supply and a signal source for biosensing. Many techniques have been devised for selective chirality detection, yet they frequently demand costly device and exterior power source, so creating self-energized detection equipment has become an urgent need. A power-free sensing platform using bovine serum albumin as chiral discriminator was proposed. The sensor directly measured the difference in enantioselectivity of arginine enantiomers on porous carbon substrates modified with bovine serum albumin, with detection limits as low as 76.0 nM [81]. This self-energized chiral recognition chip is flexible and portable, providing a novel way to detect chiral molecules anytime, anywhere, and showing great potential in flexible wearable technology.

The inherent limitations of the interrelation between solid–liquid interface limit the number of carriers generated inside solid materials and only produce weak electrical signal output, which directly leads to the narrow detection linear range and insufficient measurement sensitivity. In order to solve the problem, a new hydrovoltaic-photothermal coupling self-energized electrochemical sensing platform was devised for detection of microcystin [82]. Polyaniline and bismuth oxybromide (BiOBr) nanosheets were synthesized by direct ultrasonic method and then integrated into a hydrovoltaic generator as active components. The photothermal properties of PANI convert light energy into heat, enhancing water evaporation and improving current output. This system achieves a detection limit of 0.31 fM with a concentration range from 1 to  $1 \times 10^6$  fM. Another way to improve the performance of hydrovoltaic generator was to deploy NH<sub>2</sub>-MIL-125-modified TiO<sub>2</sub> nanotube arrays on hydrovoltaic chips, which achieved collaborative enhancement of the photoelectrochemical effect. Under the light-emitting diode lamp irradiation, the  $V_{oc}$  of the hydrovoltaic chip was significantly increased by 90.3%, and the peak value reached 400.2 mV [59]. In addition, the Schiff-based reaction between the active layer and CH<sub>2</sub>O has been cleverly exploited to develop a device specifically designed for CH<sub>2</sub>O monitoring with a detection sensitivity as low as  $5.2 \times 10^{-9}$  M. This innovative approach not only optimizes the performance of hydrovoltaic generator, but also opens up

**Table 3** Hydrovoltaic technologies for liquid sensing

| Type of material  | Potential (V) | Current ( $\mu$ A) | Type of target       | Concentration range      | Detection limit           | References |
|---|---------------|--------------------|----------------------|--------------------------|---------------------------|------------|
| Silicon nanowire  | 0.45          | 10.2               | NaCl                 | $10^{-5} \sim 10^{-1}$ M | $10^{-5}$ M               | [74]       |
| Ti <sub>3</sub> C <sub>2</sub> -polyaniline               | Not mentioned | 2                  | Enrofloxacin         | 1 fM ~ 1 nM              | $0.585 \times 10^{-15}$ M | [79]       |
| ZnO nanoarray   | 0.039         | Not mentioned      | Bilirubin            | 13.68 ~ 85.5 $\mu$ M     | $1.368 \times 10^{-5}$ M  | [80]       |
| Toluene soot  | 0.9           | 0.18               | Arginine enantiomers | 1.0 ~ 100.0 $\mu$ M      | $76.0 \times 10^{-9}$ M   | [81]       |
| BiOBr-polyaniline   | Not mentioned | 1.81               | Microcystin          | 1 fM ~ 1 nM              | $0.31 \times 10^{-15}$ M  | [82]       |
| NH <sub>2</sub> -MIL-125/TiO <sub>2</sub> nanotube arrays | 0.4           | 13.9               | HCHO                 | $10^{-6} \sim 10^{-8}$ M | $5.2 \times 10^{-9}$ M    | [59]       |

a novel general way for the construction of instant-sensing self-energized device.

In summary, the liquid sensor driven by hydrovoltaic technology has exhibited extensive application prospects in the areas of water quality monitoring, body fluid analysis, biosensing and chiral recognition. Through innovative design and optimization strategies, the hydrovoltaic sensor not only achieves real-time monitoring of various parameters in the liquid, but also demonstrates high sensitivity, high specificity and good stability.

## Hydrovoltaic technologies for water pollutant treatment

Traditional pollutant treatment methods often have high energy consumption and low efficiency. Therefore, the development of efficient and environmentally friendly pollutant treatment technology has become a hot spot in contemporary research. Hydrovoltaic technology, as a new energy conversion technology, provides a new way to solve this problem. As shown in Table 4, through clever design, the hydrovoltaic generator is able to recover energy while treating wastewater, achieving maximum utilization of resources [15, 83].

In order to verify the effectiveness of hydrovoltaic technology in pollutant treatment, a hydrovoltaic generator based on alkalinity gradient was designed. The generator generated an ultra-high  $V_{oc}$  of about 1.1 V and a  $I_{sc}$  of up to 320  $\mu A$  in a high alkalinity sewage environment, which effectively realized wastewater power generation [84]. Beyond energy generation, hydrovoltaic technology has also proven effective in pollutant removal. A rechargeable hydrovoltaic generator was developed, which consisted of a polymer functional layer containing  $Fe^{3+}$  and an Fe electrode. The oxidation–reduction reaction between the active metal electrode Fe and  $Fe^{3+}$  significantly improved the output of the hydrovoltaic generator. When the  $Fe^{3+}$  were depleted and the

hydrovoltaic was exposed to a solution containing oxides, the  $Fe^{2+}$  re-oxidized to  $Fe^{3+}$ . Therefore, this hydrovoltaic generator not only produced electricity in contact with industrial wastewater containing oxidants, but also degraded oxidizing toxic substances in wastewater and contributed to the recycling of hazardous waste [85].

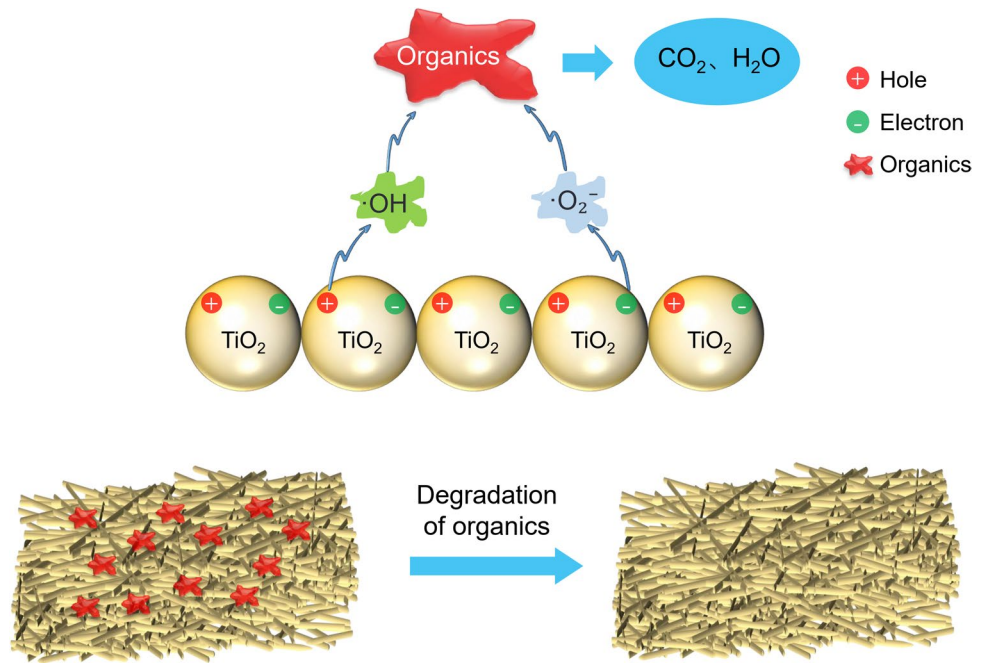
Furthermore, a hydrovoltaic generator capable of simultaneously generating electricity and desalinating seawater was constructed using a commercial polyvinylidene fluoride (PVDF) membrane coated with a hybrid MXene-GO-MXene system [83]. The electric energy generated by the hydrovoltaic effect was loaded at both ends of the membrane, the motion of electrons in the membrane was inhibited, and the electric energy was converted into heat energy. Therefore, coupling the hydrovoltaic effect and Joule thermal effect is expected to improve the performance of seawater desalination in cloudy and dark environments. In addition, the membrane acted as a molecular sieve, adsorbing dye molecules through collisions with its surface, thereby achieving both separation and removal of impurities from the sewage. In another study, a co-material hydrovoltaic generator was designed based on polypyrrole-coated titanium dioxide nanotubes [86]. This generator produced a high current of 40  $\mu A$  and demonstrated an effective pollutant capture capability, achieving a degradation rate of over 90% for methylene blue. The degradation mechanism of  $TiO_2$  nano-materials on organic pollutants is shown in Fig. 6. This innovative design improves the efficiency of the hydrovoltaic generator and significantly enhances its ability to deal with pollutants.

In addition to degrading pollutants, hydrovoltaic technology also shows promise in disinfection of pathogens. A nanofiber film hydrovoltaic generator was prepared by using fibroin and sericin [87]. The hydrovoltaic generator achieved a maximum  $V_{oc}$  and  $I_{sc}$  of 276 mV and 70 nA, respectively, at 95% relative humidity. This generator had a bacteriostatic rate of more than 80% against *Staphylococcus aureus* and *Escherichia coli*, and was used as a wearable smart device,

**Table 4** Hydrovoltaic technologies for water pollutant removal

| Type of material  | Dimension (cm)      | Potential (V) | Current ( $\mu A$ )  | Power ( $\mu W \cdot cm^{-2}$ ) | Pollutant   | References |
|---|---------------------|---------------|----------------------|---------------------------------|---|------------|
| MXene-graphene oxide-MXene  | Not mentioned       | 0.2           | $8.5 \times 10^{-4}$ | Not mentioned                   | Dye wastewater<br>Metal ions                            | [83]       |
| Wood  | 2×2                 | 1.1           | 320                  | 6.75                            | Alkaline wastewater                                     | [84]       |
| Poly styrene sulfonic acid/ $Fe^{3+}$ /<br>poly diallyl dimethyl ammonium<br>chloride | 2×2                 | 1.08          | 72                   | 5.83                            | Wastewater containing<br>$HNO_3$ and $KMnO_4$           | [85]       |
| Polypyrrole@ $TiO_2$ nanotube   | $\Phi 1.5 \times 1$ | 0.13          | 40                   | Not mentioned                   | Dye wastewater  | [86]       |
| Silk fibroin nanofiber  | 2×2                 | 0.28          | 0.07                 | $1.3 \times 10^{-3}$            | <i>Staphylococcus aureus</i><br><i>Escherichia coli</i> | [87]       |
| Titanium oxide nanowire   | 2×1                 | 0.18          | 2                    | Not mentioned                   | High salt organic sewage                                | [88]       |
| $TiO_2/ZrO_2$   | 1×1                 | 0.8           | $5 \times 10^{-3}$   | Not mentioned                   | Dye wastewater  | [89]       |

**Fig. 6** Photocatalytic activity of the TiO<sub>2</sub> nanofiber membrane under light. When TiO<sub>2</sub> is illuminated by light with an energy greater than or equal to its bandgap energy, electrons in the valence band are excited to transition to the conduction band, forming photogenic electrons while leaving holes in the valence band. The holes react with water molecules to form hydroxyl radicals ( $\cdot\text{OH}$ ). Electrons react with dissolved oxygen to form superoxide radicals ( $\cdot\text{O}_2^-$ ).  $\cdot\text{OH}$  and  $\cdot\text{O}_2^-$  have strong oxidizing properties, which can degrade organic pollutants and eventually mineralize them into harmless substances such as CO<sub>2</sub> and H<sub>2</sub>O



which made hydrovoltaic technology applied and expanded in the field of healthcare and preventive health care.

Hydrovoltaic technology does not require an external power source and can directly harness environmental humidity or the natural evaporation of wastewater for operation, making it suitable for use in remote areas or decentralized wastewater treatment scenarios. When integrated with Internet of Things technology, hydrovoltaic systems can enable real-time water quality monitoring and treatment feedback, providing possibilities for large-scale intelligent management. Compared to traditional wastewater treatment technologies such as electrochemical oxidation and photocatalysis, hydrovoltaic technology offers significant advantages. Traditional electrochemical oxidation methods typically rely on external power to drive the electrolysis process, resulting in high energy consumption and operational costs. Photocatalytic technology requires intense light sources to activate catalysts, leading to lower efficiency under low-light conditions. The core advantage of hydrovoltaic technology lies in its ability to generate electricity from wastewater, enabling resource recovery. Despite its promising prospects, the large-scale application of hydrovoltaic technology still faces several key challenges. First is chemical corrosion, where acidic or alkaline substances and oxidative pollutants in wastewater may degrade the surface charge characteristics of the materials. Second is biofouling, where microbial attachments (such as bacteria or algae) on material surfaces can clog microporous structures, reducing evaporation efficiency. Finally, there are issues related to cost and scalable production. The synthesis of high-performance materials is costly, and scalable manufacturing processes are not yet fully developed.

There is a need to develop low-cost alternative materials (such as biomass-based carbon materials) and standardized production protocols to lower industrialization barriers.

Overall, hydrovoltaic technologies demonstrate significant potential for both water pollutant removal and energy recovery by incorporating various materials and design strategies [88]. These research results provide strong support for the application of hydrovoltaic technology in the field of environmental protection and sustainable development. In the times ahead, as technology keeps advancing and costs keep declining, hydrovoltaic technology is projected to assume a more crucial role within the domain of pollutant treatment.

## Conclusion

We reviewed the power generation mechanism of hydrovoltaic effect, as well as the possible uses of hydrovoltaic systems in self-driven sensing and water pollutant treatment. A synthesis of existing studies reveals that the surface charge characteristics and micropore structure of hydrovoltaic power generation materials are the key factors affecting the improvement of power generation efficiency. Although hydrovoltaic technologies has attained remarkable advances in the areas of self-driven sensors and pollutant treatment, current research still faces several challenges.

Firstly, improving material stability for long-term use. Current hydrovoltaic materials, such as carbon-based materials, hydrogels, and metal oxides, are susceptible to performance degradation during long-term operation due to

environmental humidity, mechanical stress, and chemical corrosion. In future research, their mechanical strength and chemical stability can be improved through composite modification, such as the introduction of nano-scale reinforcements and cross-linked structural design, as well as surface functionalization, such as gradient coatings with hydrophobic or hydrophilic properties. Furthermore, the development of biomimetic materials, like natural cellulose-based composites, or self-healing material systems could further extend the service life of devices, ensuring stable and reliable operation in complex environments over extended periods.

Secondly, enhancing power output for practical applications. The power density of existing hydrovoltaic generators is limited by issues such as non-uniform charge distribution in materials, insufficient design of micro–nano structures, and low efficiency of interfacial ion transport. Future research should focus on: (1) optimizing the charge characteristics of materials (e.g., regulating surface potential through doping); (2) designing multi-scale channel structures to enhance ion gradients and evaporation-driven effects; (3) coupling synergistic effects such as hydrovoltaic thermoelectric and hydrovoltaic triboelectric conversions to improve energy conversion efficiency. At the same time, developing modular integration technologies (such as series/parallel circuit designs) can effectively amplify output power, meeting the energy consumption requirements of practical sensors or wastewater treatment systems.

Lastly, scaling up hydrovoltaic systems for industrial wastewater treatment. Industrial wastewater is complex in composition (e.g., high salinity, high organic content, heavy metal pollutants), posing higher compatibility requirements for hydrovoltaic power generation systems. Future strategies to expand application scenarios should include: (1) developing membrane materials with broad pH adaptability and anti-fouling properties (such as MXene/GO composite membranes and MOF-functionalized materials); (2) coupling multi-mechanism synergistic treatment technologies, such as electrochemical oxidation and photocatalytic degradation, to achieve efficient pollutant removal while simultaneously recovering energy; (3) constructing intelligent systems (e.g., Internet of Things monitoring and feedback control) to enhance the automation level of large-scale wastewater treatment. Additionally, there is a need to explore low-cost, large-scale manufacturing processes for hydrovoltaic generators (such as 3D printing) to reduce the threshold for industrial applications and promote the transition of the technology from laboratory research to practical engineering scenarios.

Top priority should be given to the advancement of new materials that improve the stability and efficiency of hydrovoltaic systems. Interdisciplinary collaborations, particularly between materials science, nanotechnology, and biochemistry, will be crucial in advancing this field. Moreover, exploring the application of this technology in

remote areas, such as for power generation, environmental monitoring, and pollutant treatment, will contribute to the global energy transition and the achievement of Sustainable Development Goals. In addition to ground-based applications, the potential of hydrovoltaic power generation technology for use in extreme environments is worth exploring. For example, in space missions, the moisture exhaled by astronauts or the limited water vapor present in the spacecraft environment could potentially be utilized not only to generate electricity but also to monitor the air quality inside the cabin, providing new ideas for self-powered systems in space stations.

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## Declarations

**Conflict of interest** The writers state that they possess no recognized competing financial concerns or private connections that might seem to impact the research presented in this article. EL and XZ declare that they are Editors of Environmental Chemistry Letters.

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