

Self-powered floating capsule for decentralized water detection and disinfection

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A portable device capable of detecting and disinfecting water without power supplies or chemical additives can provide reliable and equitable access to safe drinking water. Here we develop an all-in-one floating capsule, requiring no external power or chemicals, which monitors chemical pollutants by detecting total dissolved solids (TDS) as surrogates and can disinfect microorganisms, guided by the measured TDS. The capsule converts manual shaking to electrical power for TDS detection and Bluetooth transmission through electromagnetic induction. When TDS levels indicate an acceptable level of chemical safety, the capsule autonomously initiates disinfection. Propelled by gentle movement, the capsule's dielectric outer shell generates electrostatic charges at the water–dielectric interface. These charges accumulate at the nanorod tips to create intense local electric fields, facilitating disinfection by electroporation. The cost-effective capsule (<US\$25) enables rapid detection (3-s shaking) and complete disinfection (>6.0-log removal) in containers over 120 cycles, demonstrating a scalable and energy-independent approach for decentralized water safety monitoring and treatment.

Access to safe and affordable drinking water is an essential human right. However, over two billion people globally suffer from water scarcity, and more than 400 million individuals rely solely on unprotected or untreated sources (for example, lakes, ponds and wells) for drinking water^{1,2}. Along the entire water supply chain from the source to the point of consumption, chemical pollutants including toxic ions and hazardous organics and pathogenic microorganisms, can compromise water quality^{3,4}. Even advanced centralized treatment systems cannot fully eliminate these contaminants or prevent secondary pollution during distribution. Consequently, communities in rural, remote or

disaster-affected regions, and those dependent on ageing urban infrastructure, remain vulnerable to unsafe water^{5,6}. One promising solution is to develop a portable, smart device that is able to rapidly detect existing chemical pollutants and effectively inactivate pathogens just before drinking, which does not rely on power or chemicals.

Current water detection methods to determine the pollution level (for example, electrochemical, optical and chemical) primarily rely on stable power sources and/or chemical supplies; transmitting the detection data to a user interface also requires additional energy^{7,8}. In addition, existing disinfection methods require an external energy source

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or chemicals to activate microbial inactivation^{9–11}. For example, chlorination relies on the continuous addition of chlorine or hypochlorite, which also results in the production of carcinogenic by-products^{12,13}. Alternative approaches, such as ultraviolet irradiation or membrane filtration, require a stable power supply and incur high operating costs^{14,15}. In addition, advanced oxidation processes primarily rely on energy or chemical inputs to produce antimicrobial reactive radicals in situ^{16,17}. As a promising candidate, the process of electroporation is a chemical-free disinfection route that uses strong local electric fields at the tips of one-dimensional (1D) nanomaterials¹⁸. This physics-based process can compress bacterial membranes or viral capsids to achieve lethal levels of damage with a minimal energy input ($\sim 10^{-4}$ kWh m⁻³) (refs. 19,20). Recently, we achieved electroporation in a bottle by collecting walking-induced electrostatic charges through contact electrification²¹. The work demonstrated the potential of using low-energy electrostatic charges to power energy-efficient electroporation. However, its reliance on external charge collection (for example, foils and wires) and the limitation of deploying in a bottle (volume less than 1 l) restricts its energy utilization and application potential. In addition, electrostatic charges primarily exhibit a low current output (nA to μ A). It is insufficient for powering common detection sensors and data transmission, which typically requires mA-level current levels²².

There are two common types of daily kinetic energy that are readily available for power generation. One is relatively intense but brief (for example, high-frequency manual shaking), and the other is of lower energy, but is continuous (for example, gentle winds). The exploitation of these various forms of kinetic energy to generate electricity at a mA-level for rapid transmission-integrated detection and prolonged low-power electroporation, respectively, could be a feasible way to perform water analysis and disinfection in a single device. In particular, mA-level currents for micropower detection sensors (for example, total dissolved solids (TDS)) and Bluetooth data transmission can be generated through electromagnetic induction when a magnet vibrates in a coil by hand at several Hz (refs. 23,24). Additionally, low-frequency movement (1–2 Hz) produced by walking or gentle winds can harvest low-power, continuous electrostatic charges through contact electrification when materials with a density of less than 1 g cm⁻³ float up and down in the water being treated^{25–27}. Although the energy density of electrostatic charges at the water–solid interface is relatively low, it may be a sufficient and reliable power source for in situ electroporation disinfection in containers because the 1D nanomaterial-assisted electroporation requires a relatively low-energy input²¹.

Here we present a portable, smart capsule that enables rapid water detection and effective disinfection, while requiring no power or chemical input. The capsule is able to convert manual shaking into a mA-level current output to establish a Bluetooth connection and allow the capsule to detect TDS and transmit data when placed into water. The detection data is used to determine whether disinfection is necessary. If a low TDS is detected, the floating acrylonitrile butadiene styrene (ABS) capsule will remain in the water and propel itself by low-frequency walking or gentle waves produced by winds. As the capsule floats up and down in the water, it generates electrostatic charges at the water–ABS interface. The in situ-generated charges accumulate at the conductive nanorod tips of the electrode, which is adhered to the capsule without the need for any external charge collection, and produce sufficient power density to achieve energy-efficient electroporation. After 52 min of gentle vibrations, >99.9999% of bacteria and viruses are inactivated in containers up to 4 l. This capsule exhibits a rapid response (3 s shaking for data detection and transmission) and high stability (120-cycle disinfection with negligible material release), making it feasible to provide safe drinking water in a broad range of application scenarios.

Concept and working principle

The prerequisite for rapid analysis of water quality using a floating capsule with limited power output is identifying a representative parameter

that can evaluate water quality with minimal energy input and no chemical dosage. Typical pollution sources, such as farm manure, agricultural runoff and sewage discharge, can introduce complex pollutants into water²⁸. Harmless ions, such as Na⁺, Mg²⁺ and Cl⁻, often become dominant and coexist with typical chemical contaminants in water, for example, heavy metals and toxic organics (Fig. 1a). This phenomenon occurs because activities related to livestock, agriculture and domestic life can simultaneously release ions and a wide variety of pollutants into water²⁹. Thus, the concentration of total ions in water, namely, the TDS, may approximately represent the chemical concentration³⁰.

Accordingly, we analyse the relationship between the TDS and typical chemical pollutants in surface water, including toxic ions (Pb²⁺, Cd²⁺ and As) and hazardous organics (polychlorinated biphenyls, organochlorine pesticides and endocrine-disrupting chemicals) based on recent research (Supplementary Tables 1 and 2). When the TDS is lower than 250 mg l⁻¹, harmful ions and organics generally pose a low normalized risk (<1.0), determined by dividing the pollutant concentration by the World Health Organization (WHO)-recommended drinking water standards. With a normalized risk <1.0, the water is potentially safe to drink (Fig. 1b). As the TDS is higher than 250 mg l⁻¹, the level of harmful chemicals increases notably with the TDS, posing a considerable threat to drinking water. Thus, 250 mg l⁻¹ represents a threshold for potentially safe drinking and water with a TDS level that is lower than this threshold can be considered to have a sufficiently low level of chemical pollutants. The WHO-recommended drinking water standard (TDS < 300 mg l⁻¹) is also consistent with our analysis³¹. Additionally, a micropower sensor can measure the electrical conductivity of water to evaluate TDS, eliminating the need for chemical additives, thereby making TDS detection possible using the floating capsule.

The process of using the floating-induced detection-guided disinfection (FDGD) capsule begins with the detection of the TDS to estimate the chemical pollutants. If the TDS is lower than 250 mg l⁻¹, the water has a relatively low potential to contain chemical pollutants. Disinfection can then be performed on this chemically safe water to inactivate all microorganisms that are present, thereby ensuring microbial safety and making the water safe to drink directly. Otherwise, the operator must discard the heavily polluted water because it is unsuitable for drinking (Fig. 1c). The FDGD capsule contains an internal electromagnetic generator (EMG), which consists of a permanent NdFeB magnet that is housed within a copper coil, along with two additional NdFeB magnets located at the top and bottom of the generator holder (Fig. 1d and Supplementary Fig. 1a). These two magnets repel the central magnet, suspending it in the middle of the coil. The coil connects to a TDS sensor and a Bluetooth module. A magnetic shielding layer separates the bottom magnet from the Bluetooth module, protecting the circuit from the strong magnetic field for stable data transmission. Additionally, a nanorod-modified polypyrrole (PPy) electrode is adhered to the ABS outer surface, which does not need any external connection wires and directly utilizes the electrostatic charges generated at the water–dielectric interface through contact electrification to achieve electroporation (Fig. 1d).

The working principle of the FDGD capsule consists of two steps (Fig. 1e). During step I, the capsule is shaken at a relatively high frequency (3–4 Hz) by hand to propel the suspended central magnet up and down within the middle of the coil to generate a mA-level current output. The generated power is able to activate the Bluetooth device, and once the Bluetooth is connected, the operator can place the capsule into the water. The generated mA-level current is then used to drive a commercial micropower sensor for TDS detection (Fig. 1f) and transmit data to a user interface (that is, a phone, watch or screen) (Fig. 1e, top). If the detected TDS is below the threshold (that is, <250 mg l⁻¹), the FDGD capsule performs step II, namely self-powered disinfection. Electrostatic charges are generated on the water–ABS interface through contact electrification as the capsule floats up and down in water when it is driven by gentle (~1 Hz) vibrations. The conductive PPy

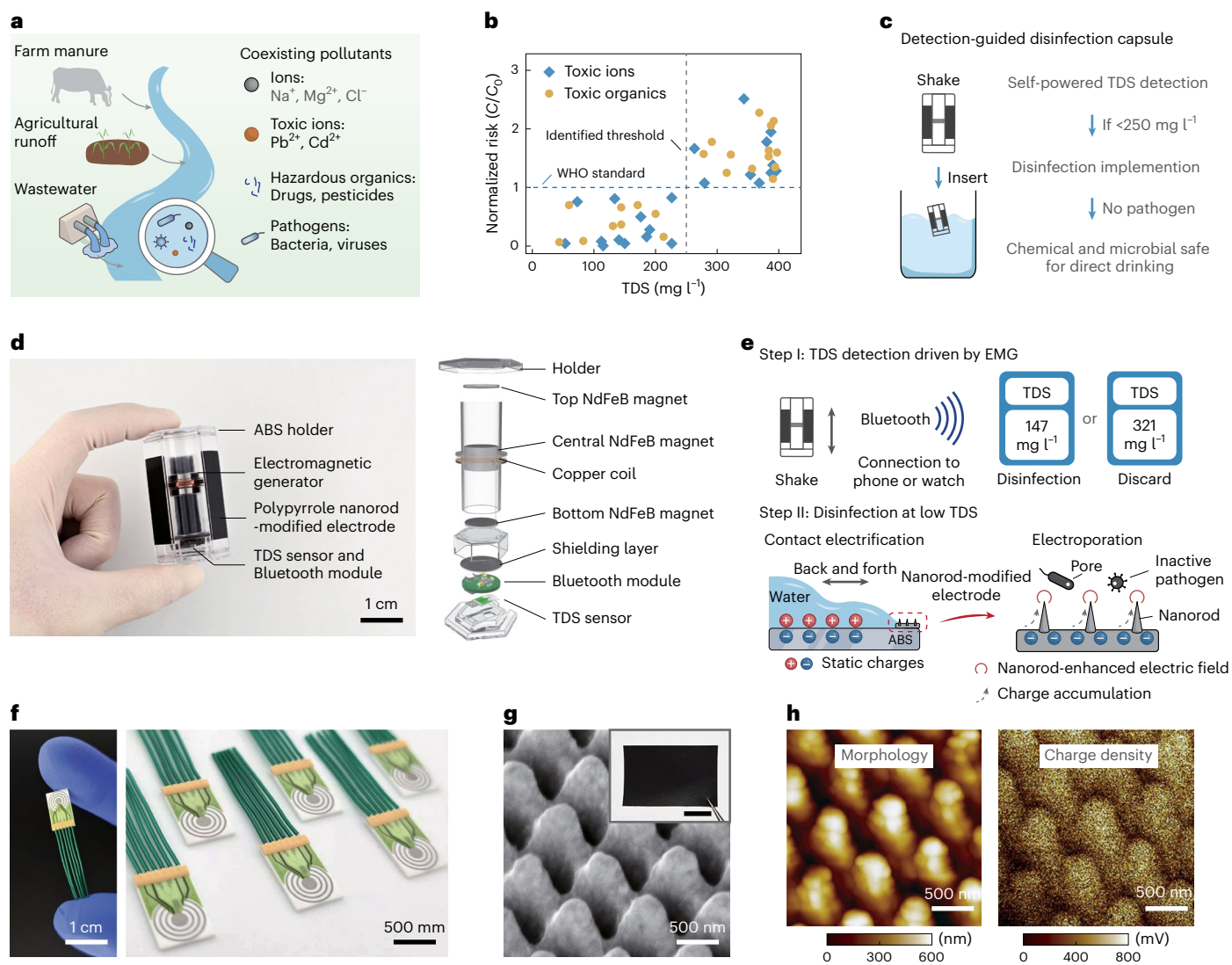


Fig. 1 | Working principle of the FDGD capsule. **a**, Schematic of the complex contaminations coexisting in water matrices. **b**, Analysis of the relationship between TDS and typical chemical contaminations in surface water, including toxic ions (Pb^{2+} , Cd^{2+} and As) and hazardous organics (polychlorinated biphenyls, organochlorine pesticides and endocrine-disrupting chemicals). Normalized risk is determined by dividing pollutant concentrations (C) by the WHO-recommended drinking water standards (C_0). **c**, Application of the FDGD capsule, including TDS detection for approximate evaluation of chemical pollutants and the decision to begin disinfection, if needed ($\text{TDS} < 250 \text{ mg l}^{-1}$). **d**, Photographs showing the construction of an FDGD capsule, including an internal EMG and a

TDS sensor with the Bluetooth module and an outside ABS dielectric shell taped with PPY nanorod-modified electrodes on its surface. **e**, Working principle of the FDGD capsule. Step I: the mA-level current required for TDS detection and Bluetooth transmission is generated by manually shaking the capsule. Step II: electrostatic charges are generated at the water–ABS interface through gentle vibrations, which accumulate at the tips of nanorods to create strong local electric fields for disinfection. **f**, Photographs showing the TDS sensor. **g**, SEM image of the PPY nanorods. Inset: the electrode with a scale bar of 5 mm. Experiments are repeated independently for three times. **h**, AFM and KPFM images describing the surface morphology and the corresponding surface charge of the PPY nanorods.

nanorod-modified electrode on the ABS holder induces charges on its surface. These charges accumulate at the tips of the high-aspect-ratio PPY nanorods, generating strong local electric fields for electroporation disinfection in the water container (Fig. 1e, bottom).

We prepare the PPY nanorod-modified electrodes ($1 \text{ cm} \times 3 \text{ cm}$ for each) through a nanopatterning fabrication method²¹. The PPY nanorods are distributed in an orientation that is perpendicular to the electrode substrate by accurately replicating a nanoimprint mould structure with uniform lengths of $\sim 700 \text{ nm}$ and diameters of $\sim 40 \text{ nm}$ (Fig. 1g). Due to the integrated structure of the nanorods and substrate, and the strong covalent bonds of the PPY materials, the as-prepared electrode prevents material release and detachment, thereby eliminating potential contamination and enabling safe drinking. These nanorods exhibit high electrical conductivity ($\sim 10^3 \text{ S cm}^{-1}$; Supplementary Fig. 1b), which facilitates charge accumulation at the

nanorod tips and generates strong local electric fields for electroporation. An investigation of the nanorod morphology and surface charge distribution through atomic force microscopy (AFM) and Kelvin probe force microscopy (KPFM) also indicates that the nanorods can successfully accumulate free charges at the tip regions (Fig. 1h).

TDS measurement and data transmission

We select a micro-sized TDS sensor ($0.5 \text{ cm} \times 1 \text{ cm}$) to integrate into the FDGD capsule (Fig. 2a). The TDS sensor, which consists of a four-concentric-circle electrode structure, requires an input current (0.3 mA) applied to the middle and outer electrodes (Supplementary Fig. 2a). The output voltage between the other two measurement electrodes is linearly related to the water TDS within the range of $10\text{--}600 \text{ mg l}^{-1}$ ($R^2 = 0.99$) (Fig. 2b and Supplementary Fig. 2b). This range fully covers the TDS of typical surface water. In particular,

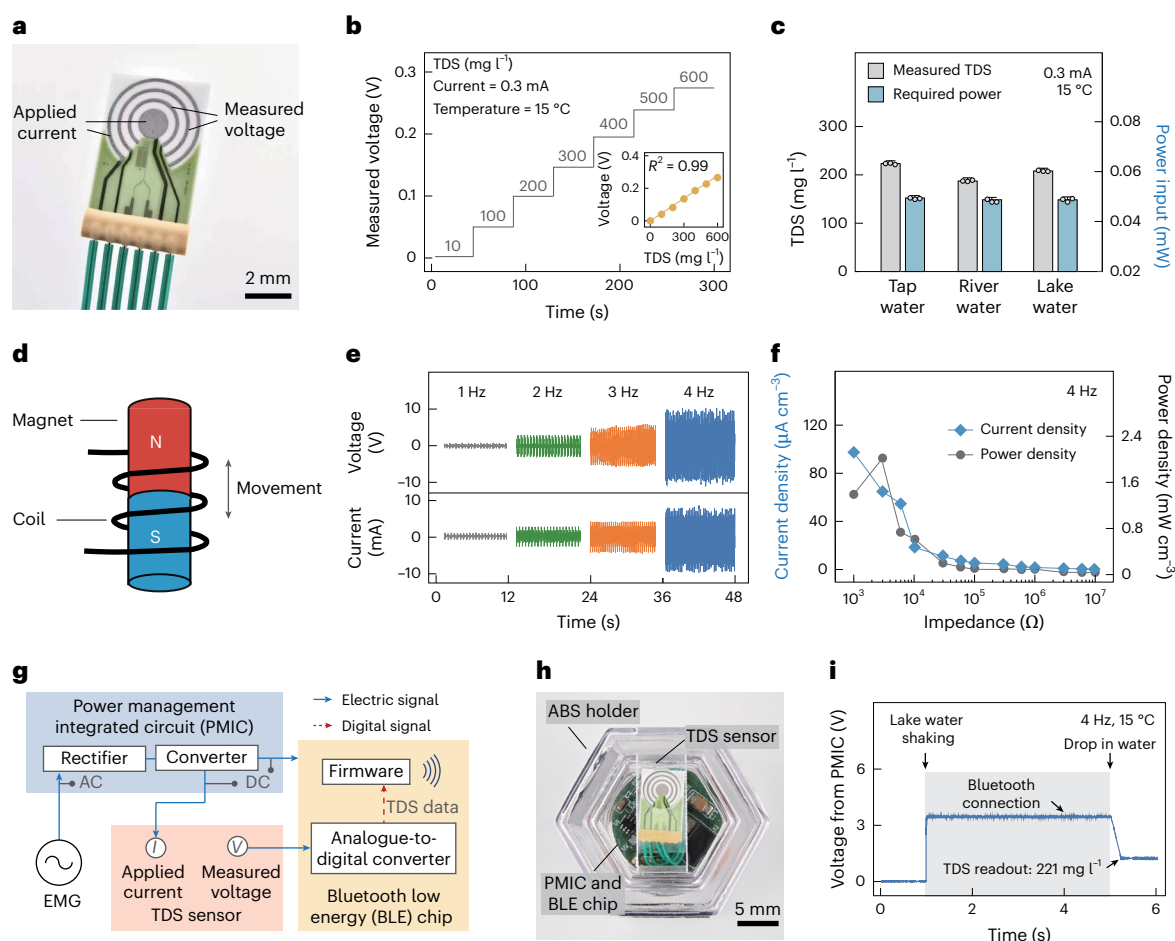


Fig. 2 | TDS measurement and data transmission. **a**, Photographs showing the construction of the TDS sensor, including the electrodes that apply the input current and those that measure the corresponding output voltage. **b**, Measured voltage responses of the water TDS using the sensor with a fixed input current of 0.3 mA. Inset: the linear trendline fit between TDS (10–600 mg l⁻¹) and measured voltage. **c**, TDS measurements of real water samples and the required power. **d**, Schematic of the EMG showing the magnet moving in the middle of the coil. **e**, Effect of vibration frequency (1–4 Hz) on the output voltage (top) and current (bottom) of the EMG. **f**, Effect of load resistance (10³–10⁷ Ω) on the output current

density and power of the EMG at a fixed vibration frequency (4 Hz). **g**, Schematic of the designed circuit, including the PMIC, the TDS sensor and the BLE chip. **h**, Photographs showing the bottom view of the FDGD capsule, including the ABS exterior holder, the TDS sensor, the PMIC and the BLE chip. **i**, TDS measurement of the lake water using the FDGD capsule powered by the EMG with manual shaking at 4 Hz. In **b**, **c** and **i**, temperatures are 15 °C. Error bars represent the standard deviations (s.d.), and data are presented as mean values ± s.d. from three independent biological replicates (*n* = 3).

the TDS sensor obtains accurate data when measuring tap, river and lake water while requiring minimal energy input (<0.06 mW) (Fig. 2c).

We optimize the EMG to generate the required energy of the TDS sensor by investigating the effects of the EMG operating conditions (vibration frequency and external load) on the electrical output. When a magnet moves through the middle of a 1,500-turn coil at a frequency of 4 Hz (Fig. 2d), the EMG generates a peak-to-peak output voltage of 22 V_{p-p} and a peak-to-peak output current of 16 mA_{p-p} (Fig. 2e). The EMG output reduces as the vibration frequency decreases with an output voltage of 1.5 V_{p-p} and current of 1.8 mA_{p-p} generated at 1 Hz vibration (Fig. 2e). Additionally, the EMG achieves its maximum power output (2.1 mW cm⁻³) when the external load is between 10³ and 10⁴ Ω (Fig. 2f).

The mA-level current generated by the EMG is an alternating current (AC), which requires a power management integrated circuit (PMIC) to convert it to direct current (DC) power for TDS detection and data transmission (Fig. 2g). The AC output from the EMG first passes through a rectifier, which converts it to DC power. A converter can then tune the DC power into a stable output with a target current (0.3 mA) to drive the TDS sensor (Extended Data Fig. 1a). In addition to powering the TDS sensor, the converted stable DC power from the

EMG is also used to drive the Bluetooth low-energy (BLE) chip for data transmission. Within the BLE chip, an analogue-to-digital converter transforms the measured voltage from the TDS sensor into a digital signal, enabling data transmission to a user interface (for example, a phone, watch or other screen) via Bluetooth firmware. The PMIC and BLE chip are on the 18-mm-diameter integrated PCB plate and encapsulated by the ABS exterior holder of the FDGD capsule (Fig. 2h and Extended Data Fig. 1b,c).

During practical application of the device, manually shaking the FDGD capsule at 4 Hz yields a stable output voltage of ~3.3 V from the PMIC, which enables the Bluetooth connection in 3 s (Fig. 2i and Supplementary Fig. 3). Next, the FDGD capsule is placed in a container with the water sample (for example, lake water). The device successfully detects and transmits TDS data to a user interface within one second (Fig. 2i and Supplementary Video 1), where the detected data will then determine whether subsequent disinfection is necessary.

Gentle-vibration-induced electroporation disinfection

An FDGD capsule, including an exterior holder manufactured using a dielectric material and nanorod-modified PPy electrodes taped

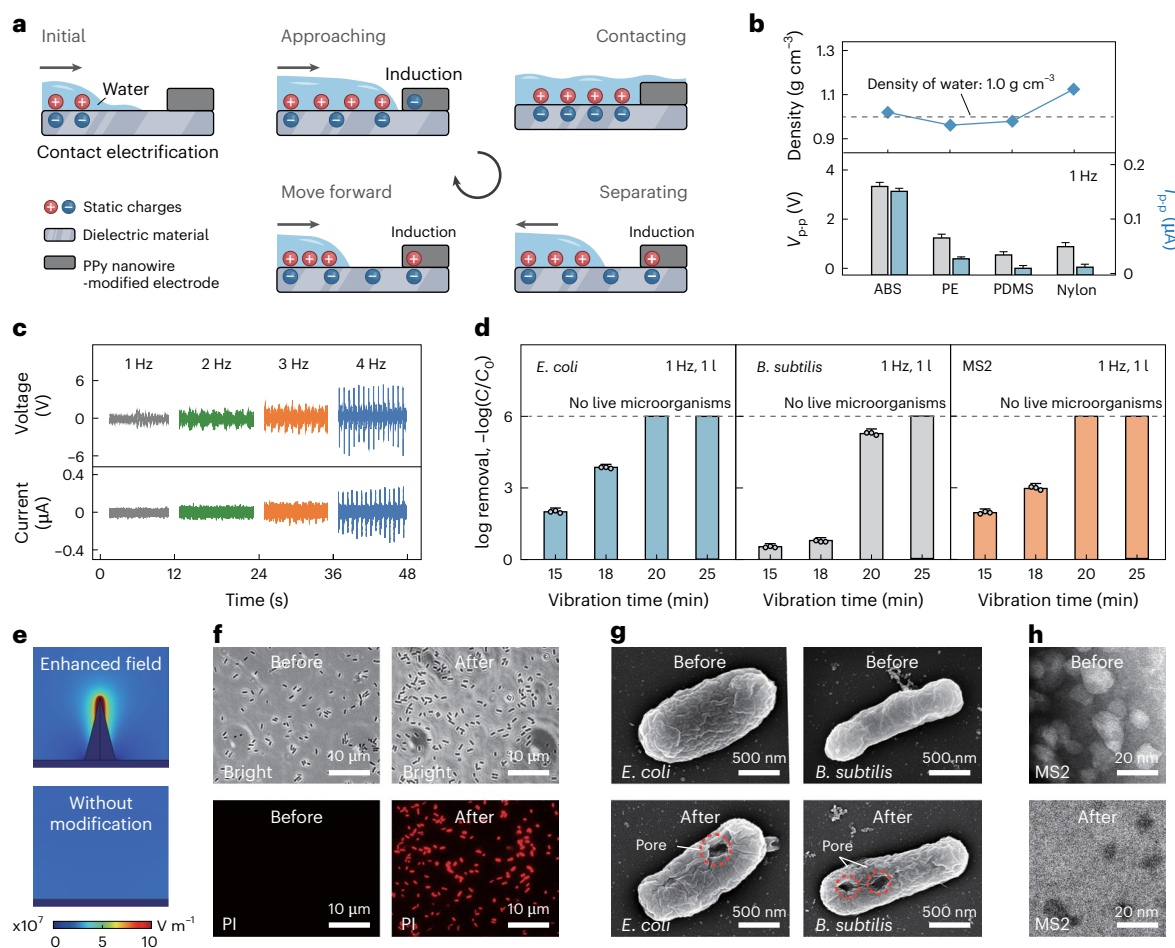


Fig. 3 | Gentle-vibration-induced electroporation disinfection. **a**, Schematic of electrostatic charge generation at the water–dielectric interface and induction for charge production on the PPy nanorod-modified electrode taped to the dielectric outer surface when vibrating the FDGD capsule in water. **b**, Density of the common lightweight dielectric materials and the electrical output of the PPy electrode when using these materials and vibrating in water at 1 Hz. **c**, Effect of vibration frequency (1–4 Hz) on the output voltage (top) and current (bottom) of the PPy electrode when using the ABS exterior holder and vibrating in water. **d**, Effect of vibration time (15–25 min) on the disinfection efficiency for *E. coli* (gram-negative bacterium), *B. subtilis* (gram-positive bacterium) and MS2 bacteriophage (virus) when vibrating the FDGD capsule in 1 l of water at

1 Hz. **e**, Simulated electric fields near the PPy nanorod, representing enhanced local electric fields. **f**, Bright-field (total bacteria) and fluorescence (inactivated bacteria) microscopy images of *E. coli* before and after treatment using the FDGD capsule. **g**, SEM images of *E. coli* (left) and *B. subtilis* (right) before and after treatment using the FDGD capsule. Dashed lines indicate that all microorganisms are inactivated (that is, live microorganisms are not detected). Experiments are conducted in PBS buffer (10 mM) at pH 7.0. In **e–h**, the FDGD capsule is vibrated in 1 l of water at 1 Hz for 25 min. In **f–h**, experiments are repeated independently for three times. Error bars represent s.d., and data are presented as mean values $\pm$ s.d. from three independent biological replicates ($n = 3$).

to its surface, can achieve disinfection when floating on the water surface and subject to gentle vibration. The working principle of the FDGD capsule, enabling disinfection without the need for external power or chemicals, is shown in Fig. 3a. The FDGD capsule floats up and down on the water surface, propelled by gentle vibration due to walking or gentle winds. This movement can generate positive electrostatic charges on the water surface and negative electrostatic charges on the dielectric material surface through contact electrification. The conductive nanorod-modified PPy electrode becomes negatively charged when positively charged water approaches it through electrostatic induction. As the water moves away from the PPy electrode, the electrostatic impact of the dielectric material becomes dominant, further inducing positive charges in the PPy electrode from the negatively charged dielectric surface. During this periodic water movement, the PPy electrode continuously induces electrostatic charges on its surface. The high-aspect-ratio nanorods on the electrode surface can accumulate these induced charges, producing strong local electric fields to enable in situ electroporation for microbial inactivation.

We measure the electrostatic charges induced on the PPy electrode using a metal electrode taped to its surface to collect the charges (Supplementary Fig. 4). To meet the requirement of being able to float on water, we select lightweight dielectric materials with a density of less than 1.2 g cm^{-3} as potential materials to fabricate the FDGD capsule. These materials include ABS, polyethylene (PE), polydimethylsiloxane (PDMS) and nylon; material selection details in Methods. ABS generates high-power electrostatic charges on the PPy electrode (Fig. 3b) in terms of peak-to-peak voltage ($3.7 V_{pp}$) and peak-to-peak current ($0.16 \mu\text{A}_{pp}$), due to its high triboelectric charge density ($108.07 \mu\text{C m}^{-2}$) (ref. 32). By comparison, materials with triboelectric charge densities below $100 \mu\text{C m}^{-2}$, such as PE, PDMS and nylon³², can only produce limited charges (voltage $<1.2 V_{pp}$ and current $<0.05 \mu\text{A}_{pp}$) when vibrated in water at 1 Hz (Fig. 3b). Increasing the vibration frequency of the ABS from 1 to 4 Hz further improves the electrical output (for example, $13.5 V_{pp}$ and $0.72 \mu\text{A}_{pp}$), possibly due to induction charges being separated faster at higher vibration frequencies (Fig. 3c).

We investigate the disinfection performance of the FDGD capsule using three model microorganisms: *Escherichia coli* (*E. coli*;

a gram-negative bacterium), *Bacillus subtilis* (*B. subtilis*; a gram-positive bacterium) and MS2 bacteriophage (a common model virus indicating faecal contamination)²⁰. A high concentration of microorganisms was added to 10 mM phosphate-buffered saline (PBS), resulting in a final concentration of 10^7 colony-forming units per ml (CFU ml⁻¹ for bacteria) or 10^7 plaque-forming units per ml (PFU ml⁻¹ for viruses). The 10 mM PBS can simulate the typical conductivity and pH-buffering capacity of surface water²⁰.

An FDGD capsule was placed in a container with 1 l of water and vibrated at frequencies ranging from 1 to 4 Hz. The FDGD capsule with an ABS exterior holder achieves complete disinfection (6.0-log removal, with no live microorganisms detected in water) of the gram-negative *E. coli* and MS2 after 20 min of vibration at 1 Hz (Fig. 3d). It can also inactivate all the tested gram-positive *B. subtilis* after 25 min of vibration at 1 Hz (Fig. 3d). The slightly reduced disinfection efficiency of *B. subtilis* after 20 min of vibration (5.3-log removal corresponding to >99.999% inactivation) is probably due to the thick peptidoglycan layer in the cell membrane³³. In contrast, PE, PDMS and nylon with lower triboelectric charge densities (<100 $\mu\text{C m}^{-2}$) can produce limited charges when used as the exterior holder of the capsule, rendering them ineffective for microbial inactivation (<0.5-log removal) under the same operating conditions (Extended Data Fig. 2a). Additionally, the FDGD capsule exhibits improved disinfection efficiency with increased vibration frequency and can inactivate all microorganisms after 18 min of vibration at a higher frequency of 4 Hz (Extended Data Fig. 2b). Furthermore, the FDGD capsule achieves complete disinfection over a broad range of microbial concentrations (10^2 – 10^6 CFU ml⁻¹ or PFU ml⁻¹), which represent typical microbial levels in surface water (Extended Data Fig. 2c). The FDGD capsule enables complete disinfection of water samples with a high organic content, such as secondary effluent from a wastewater plant, without conventional disinfection, by slightly extending the treatment time (Supplementary Fig. 5). This indicates its feasibility for treating a broad range of natural water sources.

We simulate the electric field near the tip area of the PPy nanorod while the FDGD capsule floats on water to clarify the electrostatic charge accumulation process (Supplementary Fig. 6). For a 1 Hz vibration, electrostatic charges initially generate at the water–ABS interface, which can further induce charges on the PPy electrode. These induced charges can accumulate at the tip of the 40-nm-diameter PPy nanorod, corresponding to the area with a small radius of curvature, and therefore produce strong local electric fields ($>10^7$ V m⁻¹) (Fig. 3e). The local electric field generated by the floating capsule exceeds the electroporation threshold (10^6 V m⁻¹) (refs. 34,35), indicating the feasibility of disinfection by electroporation.

We examine the contribution of electroporation to compromising the bacterial membrane using a propidium iodide (PI) staining test, where the PI stain penetrates damaged cell membranes. Before disinfection, bacteria are intact with negligible PI staining, whereas after electroporation treatment using an FDGD capsule, over 95% of the bacteria are stained and show red fluorescence (Fig. 3f and Supplementary Fig. 7). Scanning electron microscopy (SEM) reveals that electroporation occurred after the FDGD capsule treatment. The bacterial membrane has small pores (<200 nm) on its surface that do not shrink or collapse, which is clear evidence of electroporation (Fig. 3g). We evaluate viral integrity using a transmission electron microscopy (TEM) method that incorporates phosphotungstic acid staining. Phosphotungstic acid can diffuse through damaged viral capsids and appear as dark contrast under TEM. Compared to the initial viruses with a bright structure before treatment, the viruses exhibit a dark contrast after treatment with the FDGD capsule, indicating compromised capsids due to electroporation (Fig. 3h). Additionally, we confirm that contributions from other potential disinfection mechanisms, such as oxidative stress (Extended Data Fig. 3a), nanomaterial toxicity (Extended Data Fig. 3b,c) and reactive antimicrobial species (Extended Data Fig. 3d), are negligible.

Operation under environmentally realistic conditions

We evaluate the feasibility of using the FDGD capsule to estimate chemical contamination and enable microbial inactivation under realistic conditions (Fig. 4a). After shaking the FDGD capsule at 4 Hz for 3 s to establish the Bluetooth connection, we place it in a water container (0.5–4 L) for TDS detection and data transmission (Fig. 4b; step I). The FDGD capsule enables accurate detection of typical natural water samples, and the resulting data are similar to those obtained using the commercial HANNA sensor (Fig. 4c). When the detected TDS level is lower than 250 mg l⁻¹, we will further leave the FDGD capsule in the water container to perform electroporation disinfection (Fig. 4b; step II). If the untreated water is in the range of 0.5–1 l, we are able to collect it in a bottle and place the bottle in a backpack (Supplementary Video 2). The FDGD capsule achieves disinfection through low-frequency walking. Additionally, the FDGD capsule can enable water disinfection in a larger 2–4 l open container (for example, a water tank) through movement driven solely by gentle winds.

We investigate the disinfection efficiency of the FDGD capsule by treating real water samples from various sources, including tap, river and lake water. We dose these samples with high concentrations of microorganisms (for example, 10^7 CFU ml⁻¹ of *E. coli* and *B. subtilis* or 10^7 PFU ml⁻¹ of MS2). The FDGD capsule can disinfect all tested microorganisms in 1 l of water by placing the bottle in a backpack and walking at a rate of 1 Hz for 30 min (Fig. 4d). This indicates the maximum microbial level the device can achieve in real water is at least up to 10^7 CFU ml⁻¹ or PFU ml⁻¹. The FDGD capsule can also enable complete disinfection of 4 l of water in a tank through gentle up-and-down motion from the action of gentle winds (1 Hz) for 52 min (Fig. 4e and Supplementary Fig. 8). Compared with a low vibration frequency of 1 Hz, increasing the vibration rate enhances disinfection efficiency. The time required for complete disinfection of 4 l of water was 52, 44 and 40 min at vibration frequencies of 1, 2 and 4 Hz, respectively (Supplementary Fig. 9).

The FDGD capsule enables complete (>6.0-log) and long-term disinfection throughout 120 continuous cycles when treating water samples with high concentrations of microorganisms at both low (1 Hz) and high (4 Hz) frequencies (Fig. 4f and Supplementary Figs. 10 and 11). In each cycle, a 4 l water sample containing bacteria (10^7 CFU ml⁻¹ of *E. coli* and *B. subtilis*) or viruses (10^7 PFU ml⁻¹ of MS2) is treated for 60 min. The PPy electrode fully utilizes the reaction-free electroporation mechanism to achieve long-term disinfection. Its inert properties, which stem from the integrated structure of the nanorods and substrate and strong covalent bonds of the PPy material, result in a negligible release of the pyrrole (not detected) (Fig. 4g and Supplementary Fig. 12) and a slight morphological change of PPy nanorods (Fig. 4h) after 120 cycles of operation. Therefore, the FDGD capsule achieves robust and effective disinfection (Fig. 4i) with negligible material release or by-product formation (Supplementary Fig. 13). This feature makes it a notable improvement over chlorination, ensuring the safety of drinking water in point-of-use applications.

Discussion

An all-in-one device that swiftly detects chemical pollutants and effectively disinfects pathogens without requiring external power or chemicals can provide versatile access to safe and reliable drinking water. This study has developed a portable capsule that generates electricity through electromagnetic induction and contact electrification using kinetic energy to enable simultaneous, on-demand water detection and disinfection, which does not rely on external power or chemicals. Our FDGD capsule converts manual shaking into a mA-level output for TDS detection and Bluetooth data transmission. The detected TDS, if lower than 250 mg l⁻¹, can determine the following necessary disinfection. Propelled by low-frequency walking or gentle winds, the FDGD capsule can generate electrostatic charges to facilitate electroporation,

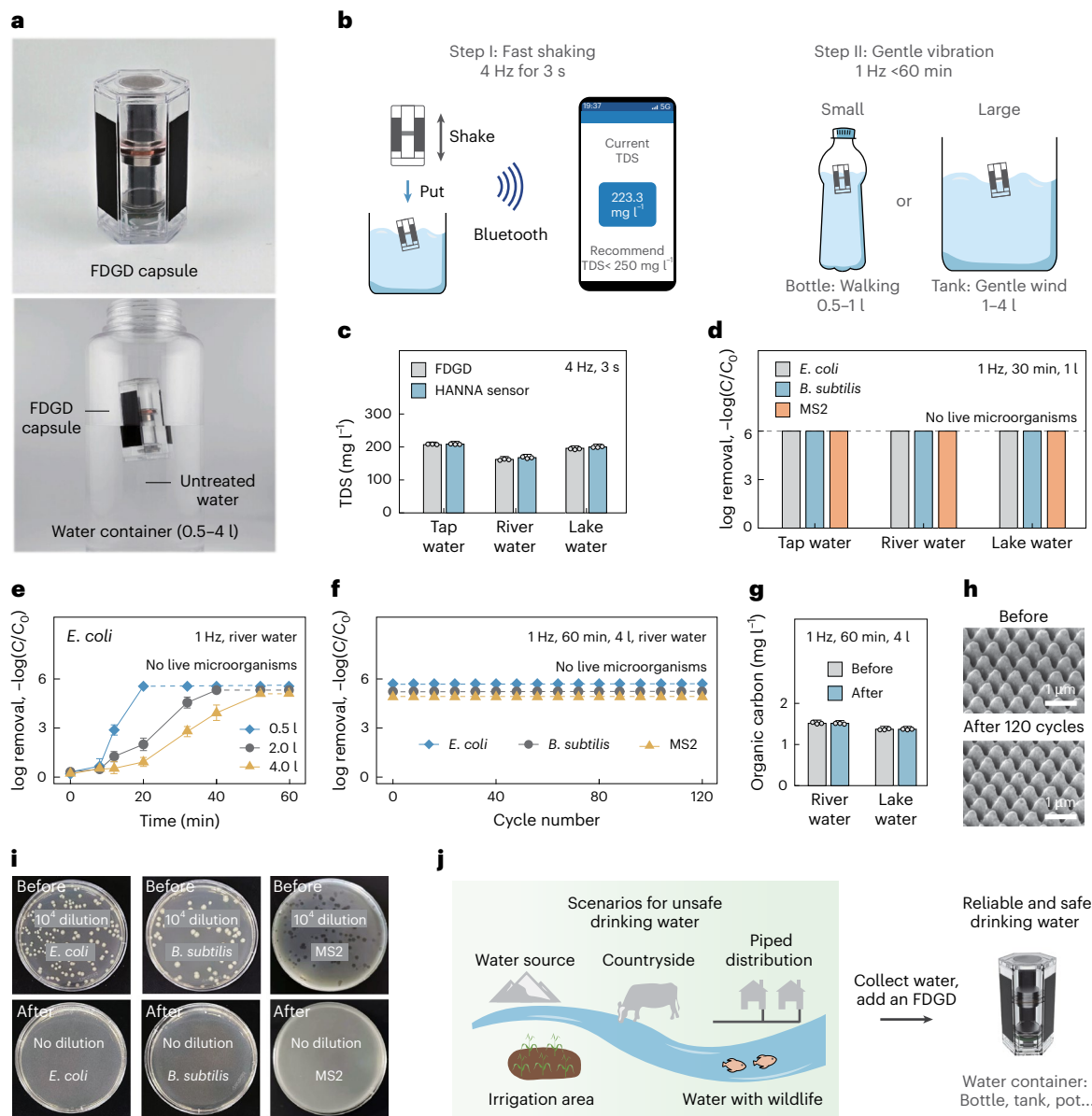


Fig. 4 | Application process and disinfection performance of the FDGD capsule.

a, Photographs of an FDGD capsule that can float on water. **b**, Application process of the FDGD capsule. Step I: shake the capsule manually at ~4 Hz to establish the Bluetooth connection. Drop the FDGD capsule into untreated water to detect the TDS level and transmit the data. Step II: if a low TDS level (<250 mg l⁻¹) is detected, the FDGD capsule is left in the water. Gentle movement (for example, walking or gentle wind) can generate electrostatic charges on the ABS surface for electroporation disinfection. **c**, TDS measurement of different water sources using an FDGD capsule and a commercial HANNA sensor. The FDGD capsule is shaken at 4 Hz for 3 s and then dropped into the water. **d**, Disinfection efficiency of the FDGD capsule to treat water samples (1 l) containing 10⁷ CFU ml⁻¹ (or PFU ml⁻¹) of *E. coli*, *B. subtilis* or MS2 from different sources at a fixed frequency of 1 Hz. **e**, Effect of volume (0.5–4 l) on the disinfection efficiency for treating river water using an FDGD capsule at a fixed frequency of 1 Hz. The necessary time for complete disinfection of 0.5, 2 and 4 l of water is 20, 40 and 52 min, respectively. **f**, Long-term disinfection stability of the FDGD capsule. River water (4 l)

containing microorganisms is treated for 60 min in each cycle, and a total of 120 cycles is performed. **g**, Evaluation of electrode stability during long-term disinfection. Organic carbon concentrations in the river water before and after continuous operation for 60 and 120 cycles without microorganism dosing. **h**, SEM images showing the morphology of PPY nanorods before and after a 120-cycle operation. Experiments are repeated independently for three times. **i**, Plating photographs showing the concentrations of live microorganisms before and after treatment using the FDGD capsule. **j**, Schematic illustrating the potential application of the FDGD capsule for providing reliable access to safe drinking water. In **f–i**, the FDGD capsule floats up and down in 4 l of the water sample at an approximate frequency of 1 Hz. In **h** and **i**, experiments are conducted in river water. Dashed lines indicate that all microorganisms are inactivated (that is, live microorganisms are not detected). Error bars represent s.d., and data are presented as mean values ± s.d. from three independent biological replicates (*n* = 3).

enabling complete disinfection (>6.0-log removal) in 0.5 to 4 l containers over a continuous long-term operation of 120 cycles with negligible material release.

The proposed FDGD capsule is able to rapidly detect the TDS level and effectively disinfect a broad spectrum of microorganisms in typical natural water. When the TDS levels indicate an acceptable

chemical safety by transmitting the data to a phone, watch or other screens, or triggering an LED light, the user can initiate disinfection, creating a detection-informed disinfection approach. The manual-shaking-enabled electromagnetic induction and gentle-vibrating-induced contact electrification processes eliminate the need for an external power input, such as grid electricity or solar panels.

When water is needed, people can collect potentially unsafe water and use a cost-effective FDGD capsule (<US\$25) to test for chemical pollution and inactivate microorganisms, thereby making the water safe to drink (Supplementary Table 3). The chemical-free electroporation disinfection inhibits chemical reactions, leading to negligible material release and by-product formation.

The FDGD monitors chemical pollutants by detecting TDS as surrogates. The limitation of this method is that the measured TDS cannot accurately indicate the concentration of each chemical pollutant, especially for water contaminated by industrial discharge, such as those containing trace heavy metals or persistent organic pollutants. In this case, water contaminated by nearby industrial pollution is unsuitable as a source of drinking water, regardless of the TDS level in the water. As for common water bodies with no industrial point-source discharges, typical pollution sources (for example, farm manure, agricultural runoff and sewage discharge) can introduce harmless ions and chemical contaminants simultaneously. Thus, the TDS level may be employed to approximately represent the chemical risk. In some cases, water sources can be impacted by harmless salts, where the concentration of toxic ions or organic pollutants may remain low. Nevertheless, if the TDS exceeds the 250 mg l⁻¹ threshold, the water is still unsuitable for drinking since a high TDS level can also increase the health risk. Additionally, the versatile FDGD capsule has a broad treatment capacity, meeting various application scenarios: immediate personal use in a small bottle or for approximately one hour in a larger water tank for batch treatment for family use. In the future, the disinfection device also holds promise for applications in lakes and reservoirs. Multiple floating units can be assembled into a network with each device serving as a node, enabling effective disinfection of the covered shallow water surfaces. Therefore, this study presents a flexible approach for reliable and affordable water detection and disinfection in various containers without any constraints of power or chemical inputs, thereby ensuring drinking safety for the vast majority of application scenarios.

Methods

PPy nanorod-modified electrode fabrication

A toluene solution of methyl methacrylate (MMA) (MMA: toluene = 8: 3) was spin-coated at 1,000 rpm for 20 s onto a commercial nickel nanoimprint mould (area of 25 × 25 cm, HT-AR-02C, Temicon) with periodic nanorod structures²¹. After drying at 80 °C for 4 h, the MMA layer was converted into a 100-μm-thick polystyrene-isobutyl methacrylate (PMMA) film exhibiting the negative structure of the nickel mould. The PMMA template was then immersed in a 10 mM PEDOT:PSS solution for 20 min to increase the surface electrical conductivity. After drying at 15 °C, the PEDOT:PSS-PMMA template can be used as a working electrode to deposit PPy on its surface via electropolymerization in a 100 mM pyrrole solution with an applied current of 0.1 mA cm⁻². The morphology of the PPy nanorods was characterized by SEM (SU8230, Hitachi) and AFM (Dimension Icon, Bruker). The surface charge was measured in air using AFM with the KPFM module.

Development of the floating-induced detection-guided disinfection capsule

The FDGD capsule included an internal EMG and an ABS outer shell. The EMG consisted of a permanent NdFeB magnet (thickness of 1.0 cm) located within a 1,500-turn copper coil. Two additional NdFeB magnets (each with a thickness of 0.1 cm) were placed at the top and bottom of the generator holder to repel the central magnet and suspend it in the middle of the coil. Wires from the coil connected to a PMIC, which consisted of a rectifier and a converter (LTC3331, Linear Technology) that tuned the AC output into a stable DC power supply with a target output of 0.3 mA and 3.3 V. This power supply is able to drive the TDS sensor (LFS1107, Innovative Sensor Technology) and the Bluetooth module (BLE chip [RSL10, Onsemi]). The PMIC and BLE chip were arranged on an integrated 18-mm-diameter PCB plate. A 0.1-cm-thick shielding layer

separated the bottom magnet from the BLE chip. The EMG, PMIC, BLE chip and TDS sensor were encapsulated by a hexagonal prism-shaped (height of 4 cm and side length of 1.4 cm) ABS exterior holder (thickness of 0.1 cm). Three PPy nanorod-modified electrodes (each area of 1 × 3 cm) were adhered to the outer surface of the ABS holder without external connection wires.

Total dissolved solids measurement

A fixed input current of 0.3 mA was applied to the middle and outer electrodes of the TDS sensor using a DC power supply (2220, Keithley). The output voltage between the two measurement electrodes of the TDS sensor was measured using a potentiostat (Interface 1010E, Gamry). The TDS of the water sample was controlled by adding various amounts of sodium chloride to deionized water, ranging from 10 to 600 mg l⁻¹. The output voltage and measured TDS values were collected to create a standard curve for detecting the TDS of natural water samples. The measured output voltage was also used to calculate the required power of the TDS sensor. The temperature of the water sample was kept at 15.0 °C.

Characterization of the electrical output

To measure the electrical properties of the EMG, wires from the EMG coil were connected to an oscilloscope (Tektronix, DPO3052) to measure the output voltage. The output current was recorded with a low-noise current amplifier (FEMTO, DLPCA-200) connected to the oscilloscope. Various external load resistors ranging from 10³ to 10⁷ Ω were applied to the circuit, and the power was determined using the applied resistance and measured current. The power density was then obtained by normalizing the calculated power to the device volume. The output voltage from the PMIC was also measured using the multimeter (34470 A, Keysight). To measure the electrical output of the PPy electrode, a metal electrode was adhered to its surface to collect the charges induced by the electrostatic charges generated at the water-dielectric interface. Liquid silver glue was used to fill the junction between the PPy electrode and the measurement metal electrode to reduce the contact resistance. This metal electrode was then connected to an oscilloscope (Tektronix, DPO3052) to measure the output voltage and current. Other lightweight dielectric substrates with a density of less than 1.2 g cm⁻³ and a thickness of 0.1 cm were also used as the exterior holder of the FDGD capsule. These substrates included PE, PDMS and nylon. The output voltage and current of the PPy electrode when using these materials were measured to evaluate the impact of the triboelectric properties on the electrical output. A capsule made from other common but heavyweight dielectric materials, such as polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF), were also tested. However, due to their high density (2.1 g cm⁻³ of PTFE and 1.8 g cm⁻³ of PVDF), the prepared capsule cannot float on water, making these materials unsuitable for capsule fabrication. For the electrical output measurements of both the EMG and the PPy electrodes, the capsule's vibration rate was controlled between 1 and 4 Hz. The experiment was performed in a 10 mM PBS buffer at pH 7.0 to simulate the typical conductivity and pH-buffering capacity of surface water.

Disinfection performance evaluation

Bacteria (*E. coli* [ATCC 15597] and *B. subtilis* [ATCC 23857]) were cultured in nutrient broth at 37 °C and 250 rpm for 12 h. Viruses (bacteriophage MS2 [ATCC 15597-B1]) were cultured by growing them with the host (that is, *E. coli*) at 37 °C and 150 rpm for 4 h. After culturing, bacteria and viruses were washed three times with deionized water using centrifugation at 4,000 g. High concentrations of microorganisms, dosed in PBS (10 mM) with an approximate concentration of 10⁷ CFU ml⁻¹ for bacteria or 10⁷ PFU ml⁻¹ for viruses, can serve as the untreated water sample. After vibrating the FDGD capsule in 1 l of untreated water for 15 to 25 min, 0.1 ml of water was collected to evaluate the concentration of live bacteria or viruses using the spread plating or the double agar

layer cultivation method, respectively²¹. The microbial log-inactivation efficiency (E) was calculated as follows:

$$E = -\log(N/N_0)$$

where N and N_0 are the amount of live microorganisms with and without disinfection.

Disinfection mechanisms investigation

The electric field near the tip area of the PPy nanorod while the FDGD capsule vibrated in water was evaluated using COMSOL Multiphysics. A 3D model consisting of two 1.0×3.0 cm electrodes separated by 100 μm was established. The nanorod, with a length of 700 nm and a diameter of 40 nm, was positioned vertically on each electrode. A total charge of 10 nC was applied to the electrodes to simulate the induced charges on the PPy electrode when the FDGD capsule vibrated in water at 1 Hz (detailed in Supplementary Fig. 6 and Supplementary Table 5).

To investigate bacterial membrane permeability, *E. coli* were immersed in a PI stain (2 mM) before or after treatment, where PI can penetrate damaged cell membranes. Then, bright-field images of total bacteria and fluorescence images of membrane-compromised bacteria (excitation at 535 nm) were captured using a fluorescence microscope (ECLIPSE Ts2, Nikon). Bacterial oxidative stress was evaluated using the reactive oxygen species assay, where a 0.5 μM DCFH-DA probe was added to a water sample containing bacteria (10^7 CFU ml^{-1}) for measurement using a microplate photometer (excitation at 495 nm; Multiskan FC, Thermo Scientific). The positive control group includes the addition of H_2O_2 (0.2 mM) to the water sample containing bacteria.

The bacterial morphology was investigated using SEM (SU8230, Hitachi). The bacteria (*E. coli* and *B. subtilis*), both before and after treatment, were collected by centrifugation at 4,000 g and fixed in a 2.0% glutaraldehyde solution at 4 °C overnight. After dehydration using a series of increasing concentrations of ethanol solutions (50, 70, 80, 90 and 100%), the bacterial samples underwent a critical point drying process (EM CPD300, Leica) and a gold coating process (EM ACE200, Leica) for SEM observation. The viral integrity was investigated using TEM. A carbon-supported copper TEM grid was immersed in a water sample containing MS2, both before and after treatment. After staining with a 2.0% phosphotungstic acid solution, the sample was examined using TEM (Tecnai F20, FEI).

FDGD capsule operation under realistic conditions

To evaluate the performance of water detection and disinfection under realistic conditions, an FDGD capsule was manually shaken at approximately 4 Hz for 3 s and placed in water containers with volumes ranging from 0.5 to 4 l to measure the TDS. The TDS of each water sample was also measured using a commercial, portable TDS meter (HI98199, HANNA).

Various natural water samples, including tap, river and lake water, were dosed with high concentrations of bacteria (*E. coli* and *B. subtilis*) and viruses (MS2), up to 10^7 CFU ml^{-1} or PFU ml^{-1} . Detailed water quality parameters are shown in the Supplementary Table 4. Containers with untreated water samples and an FDGD capsule were subjected to gentle vibration. If the volume of the untreated water is between 0.5 and 1 l, it can be collected in a bottle and placed in a backpack. Low-frequency walking can serve as a vibration source (approximately 1 Hz). If the volume of untreated water is between 2 and 4 l, it can be collected in an open water tank. A fan positioned above the water tank generates a light breeze at a speed of 2 m s^{-1} , thereby creating small ripples on the water surface. In this case, the device floats up and down with a period of ~1 Hz. The disinfection performance was then investigated after vibrating for 8 to 60 min.

For continuous operation, the FDGD capsule was used to treat river water for 120 cycles (60 h total). During each cycle, 4 l of river water containing bacteria (10^7 CFU ml^{-1} of *E. coli* and *B. subtilis*) or

viruses (10^7 PFU ml^{-1} of MS2) was treated with 1 Hz vibration for 60 min. The concentration of live microorganisms in the water was examined at the end of each cycle. The morphology of the PPy nanorod was examined before and after the 120 cycles using SEM (SU8230, Hitachi).

Toxicity evaluation

The concentrations of total organic carbon (TOC), pyrrole, trihalomethanes and haloacetic acids in the water sample were investigated before and after 60 and 120 cycles of treatment using the FDGD capsule. TOC and pyrrole were evaluated using a total organic carbon analyser (TOC-L, Shimadzu) and a liquid–liquid extraction integrated high-performance liquid chromatography (HPLC 1260, Agilent), respectively. Trihalomethanes and haloacetic acids in the water were measured using liquid–liquid extraction integrated gas chromatography (7890B, Agilent).

Data availability

The data supporting the findings of this study are available within the paper. Other relevant data are available from the corresponding authors on reasonable request. Source data are provided with this paper.

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Author contributions

Conceptualization: Z.-Y.H. and D.-M.L. Methodology: D.-M.L., M.J.P., S.C. and Y.-J.K. Investigation: Z.-Y.H. and S.-W.K. Visualization: Z.-Y.H., D.-M.L., M.J.P., F.P. and S.S.K. Supervision: Z.-Y.H. and S.-W.K. Writing—original draft: Z.-Y.H., M.X. and C.R.B. Writing—review and editing: Z.-Y.H., S.-W.K., M.X. and C.R.B.

Competing interests

M.J.P., D.-M.L., S.C. and S.-W.K. are inventors on the filed patent application KR/10-2025-0060609 (filed in the Republic of Korea). The other authors declare no competing interests.

Additional information

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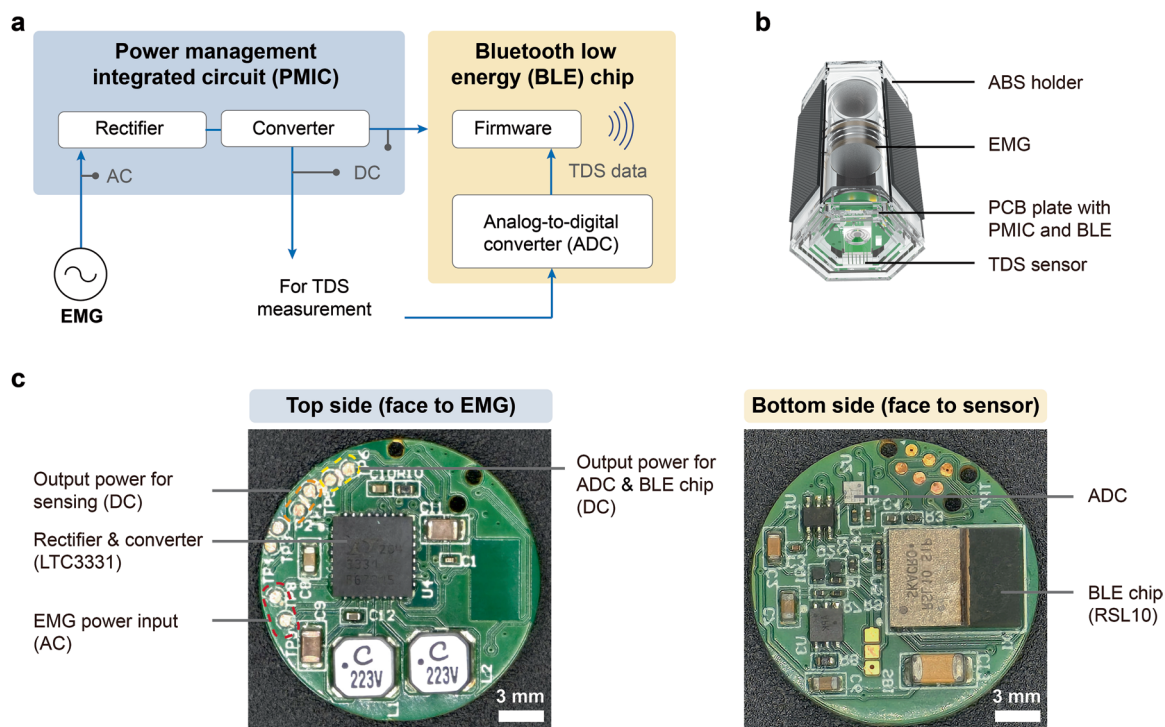
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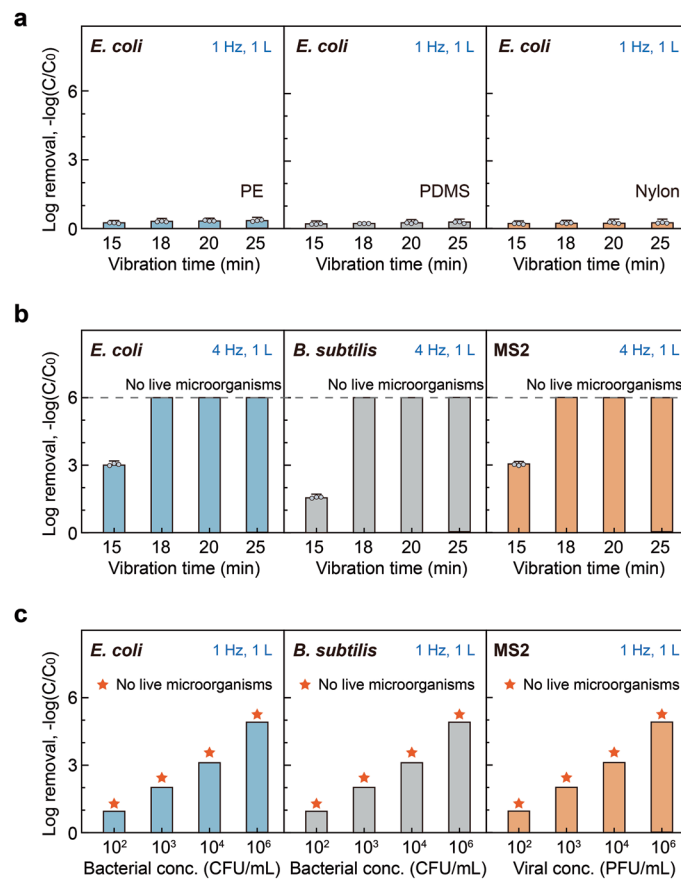
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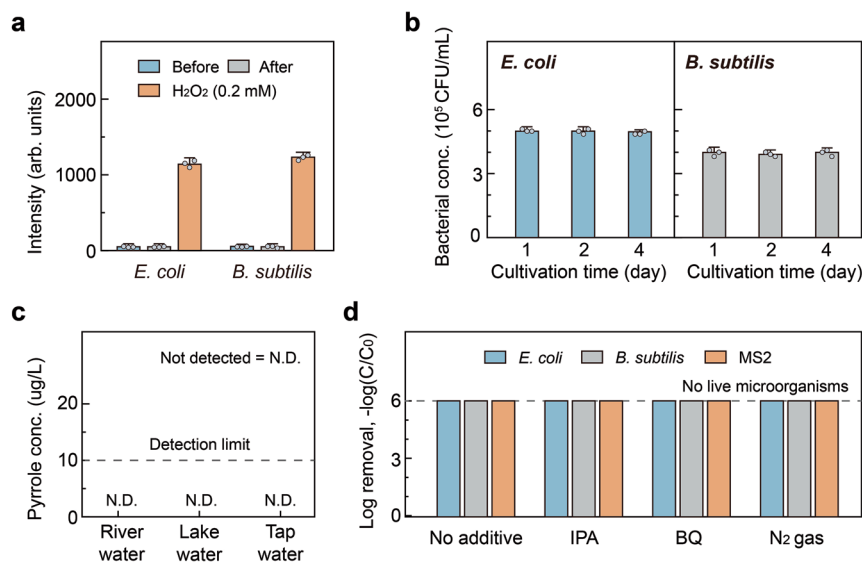


Extended Data Fig. 1 | Structure of the PMIC and Bluetooth module. **a** Circuit diagram of the PMIC and BLE chip. **b** A schematic showing a bottom view of the FDGD capsule, including the EMG, the PCB plate with PMIC and BLE chip, and the TDS sensor. **c** Photographs showing the top and bottom views of the PCB plate with the PMIC and the BLE chip.



Extended Data Fig. 2 | Disinfection Performance Investigation. **a** Effect of exterior holders made of PE, PDMS, and nylon on disinfection efficiency. The vibration rate is 1 Hz. **b** Effect of an increased vibration rate (4 Hz) on disinfection efficiency. **c** Effect of microbial concentration in the water sample on disinfection efficiency. The FDGD capsule is vibrated at 1 Hz for 30 min. Experiments are

conducted in 1 L PBS buffer (10 mM) at pH 7.0. Dashed lines indicate that all microorganisms are inactivated (that is, live microorganisms are not detected). Error bars represent s.d., and data are presented as mean values $\pm$ s.d. from three independent biological replicates ($n = 3$).



Extended Data Fig. 3 | Disinfection mechanism of the treatment using an FDGD capsule. **a** Change in oxidative stress within bacteria due to the potential charge transfer during treatment. The positive control group includes the addition of H₂O₂ (0.2 mM) to the water sample containing bacteria. **b** Evaluation of nanomaterial toxicity caused by the potential electrode release. Bacteria are added to the treated water and cultivated for 4 days. **c** Potential pyrrole release from the PPy electrode during disinfection. **d** Effect of the potential generated reactive species on the disinfection performance. Adding isopropanol (IPA),

benzoquinone (BQ), and bubbling nitrogen (N₂) gas to evaluate the effects of ·OH, ·O₂⁻, and the total oxygen reactive species, respectively. Experiments are conducted in 1 L PBS buffer (10 mM) at pH 7.0. The FDGD capsule is vibrated at 1 Hz for 30 min. Dashed lines indicate that all microorganisms are inactivated (that is, live microorganisms are not detected). Error bars represent s.d., and data are presented as mean values ± s.d. from three independent biological replicates (n = 3).