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Smartphone-powered efficient water disinfection at the point of use

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Clean water free of bacteria is a precious resource in areas where no centralized water facilities are available. Conventional chlorine disinfection is limited by chemical transportation, storage, and the production of carcinogenic by-products. Here, a smartphone-powered disinfection system is developed for point-of-use (POU) bacterial inactivation. The integrated system uses the smartphone battery as a power source, and a customized on-the-go (OTG) hardware connected to the phone to realize the desired electrical output. Through a downloadable mobile application, the electrical output, either constant current (20–1000 μA) or voltage (0.7–2.1 V), can be configured easily through a user-friendly graphical interface on the screen. The disinfection device, a coaxial-electrode copper ionization cell (CECIC), inactivates bacteria by low levels of electrochemically generated copper with low energy consumption. The strategy of constant current control is applied in this study to solve the problem of uncontrollable copper release by previous constant voltage control. With the current control, a high inactivation efficiency of *E. coli* (~6 logs) is achieved with a low level of effluent Cu (~200 μg L^{-1}) in the water samples within a range of salt concentration (0.2–1 mmol L^{-1}). The smartphone-based power workstation provides a versatile and accurate electrical output with a simple graphical user interface. The disinfection device is robust, highly efficient, and does not require complex equipment. As smartphones are pervasive in modern life, the smartphone-powered CECIC system could provide an alternative decentralized water disinfection approach like rural areas and outdoor activities.

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INTRODUCTION

Clean water free of bacteria is precious for public health. The water treatment and supply in the United States (U.S.) are mostly conducted by centralized drinking water plants. Still, 14% of the total population access drinking water from self-supplied sources (e.g., wells), according to a 2017 report from U.S. Geological Survey[1,2]. Without proper water treatment, about 700,000 residents in California's Central Valley are currently being exposed to contaminated water at home or school. Even worse, American Community Survey data suggest that 1.6 million individuals in the U.S. lack the basic indoor plumbing[1]. Looking at the big picture, it is not economical to build treatment plants in rural areas because of their high capital and maintenance costs. Thus, the threat of unsafe drinking water becomes a pressing problem, especially from waterborne pathogens. Drinking undisinfected water may cause diarrhea, cholera, typhoid, or even death. According to the US Centers for Disease Control and Prevention (CDC) report in 2017, waterborne diseases cause about 7,000 death, 477,000 emergency department visits, and $3.8 billion for disease-associated treatment[3]. Therefore, access to clean water free of bacteria is the essential and basic need for public health.

The water treatment process to remove/inactivate bacteria is called disinfection[4]. The conventional disinfection in centralized facilities and distribution systems is usually not applicable to decentralized areas[5]. Consequently, it is critical to developing point-of-use (POU) disinfection methods. Chlorination kits are efficient, handy, and low-cost. However, the proper storage and transportation of chemicals are challenging in rural areas[6,7]. Rechargeable ultraviolet lamps have been developed and commercialized, but is confined by the high energy consumption and limited treatment volume per charge[8–10]. On-site ozone generators rely on standard voltage inputs (110 or 220 V), which are also hardly accessible after calamity or in underdeveloped areas[11]. POU disinfection techniques assisted by new materials arise quickly, including photocatalytic process[12–14], locally enhanced electric field treatment (LEEFT)[15,16], and filtration[17–21]. These techniques conquer some limitations of the previous methods (e.g., complex equipment, the formation of by-products, and/or demand of chemicals), but also suffer from different drawbacks, including long treatment time, short product lifespan, and/or fouling problems.

In such context, we are eagerly looking for an efficient disinfection method that is simple, robust, and energy-efficient. In recent years, electrochemical disinfection has become a more feasible approach because of its versatile reactions, high inactivation efficiency, and low cost[22]. Tremendous electrogenerated antimicrobial species have been developed and approved efficient, such as active chlorine (e.g., Cl_2 and HClO), reactive oxygen species (e.g., $^{\bullet}OH$ and $^{\bullet}O_{2-}$), and metal ions (e.g., Ag^{+} and Cu^{2+})[22–32]. A recently developed coaxial-electrode copper ionization cell (CECIC) achieved 6-log inactivation of *E. coli* with a low level of Cu concentration (~200 μg L^{-1}), low applied voltage (1.5 V), and low estimated cost (~$ 0.1 m^{-3})[33,34]. Notably, the effluent Cu concentration for efficient disinfection is far lower than the maximum contaminant level goal (MCLG) of 1300 μg L^{-1} by the U.S. Environmental Protection Agency. The CECIC utilized both electrochemically generated Cu ions and the non-uniform electric field brought by the coaxial-electrode design to provide a new method for POU water disinfection.

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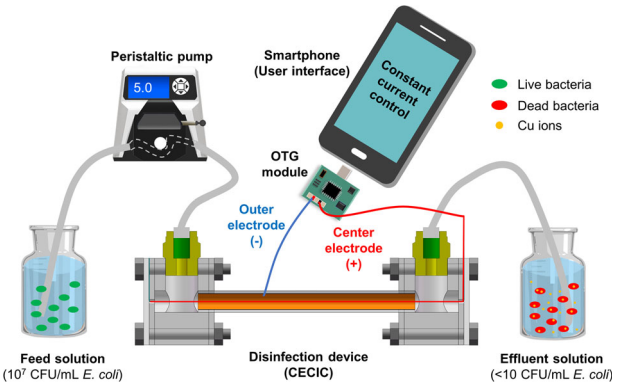

Fig. 1 Schematic showing the smartphone-based water disinfection using a coaxial-electrode copper ionization cell (CECIC).

In rural areas, the power grid is much more accessible for household[35]. However, electrochemical disinfection usually requires adjustable and accurate electrical output, and thus expensive and complex equipment (e.g., electrochemical workstations)[36]. Smartphones are potentially an excellent alternative of power sources because of their pervasive existence in the modern life[37]. Smartphones can provide a user-friendly graphical interface, high-class energy storage and output (the lithium ion battery), and a highly programable platform. Smartphone-dependent applications have been developed for water monitoring and sensing[38–40]. The rapid detection of bacterial density, heavy metal, and salinity using smartphones has been reported with the advantages of compact size, low cost, and user friendly. However, to the best of our knowledge, smartphones have never been used as a mobile power bank to conduct water disinfection.

Herein, we report an integrated smartphone-powered CECIC disinfection system with high pathogen inactivation efficiency and capacity (Fig. 1). The electrical output from the smartphone is realized by using a rationally designed Universal Serial Bus (USB) on-the-go (OTG) module and a downloadable mobile app. Through the mobile app, a constant current or voltage can be configured and delivered via the OTG module with high accuracy, even when the battery is running low (>5%). Powered by the proposed system, the CECIC device achieves >6-log bacterial inactivation with a constant current operation. Unlike the previous voltage control, the constant current provides a controllable rate of copper ion release to diverse water matrixes within the range that poses little toxicity to humans. Such an integrated disinfection system along with its high performance in different water matrixes demonstrates its feasibility to be applied in real-world cases to provide bacteria-free drinking water.

RESULTS

Design of the smartphone-based power workstation

The smartphone has been modified to function as a power workstation and consists of two parts: a software that can be downloaded from the application market (Fig. 2a), and an OTG module, as the hardware, to be connected with the smartphone (Fig. 2b). The software has a simple graphical user interface for the control of the electrical output. The output value can be adjusted either by the +/− bottom or by entering numerically from the virtual keyboard (Fig. 2c). The voltage output has a range of 0.7–2.1 V with an increment of 0.1 V, while the current has a range of 20–1000 μA with an increment of 10 μA. For each practice, the source output can be either voltage or current, but not both at the same time. The circuit of the OTG module consists of a microcontroller (MCU) (STM32) and two sets of electrical output systems (Fig. 2d). The constant voltage output is realized by the voltage source chip RT8008 coupled with a variable resistor MAX5484 to adjust the output range. Similarly, the constant current is realized by a current source chip LM334MX coupled with the other variable resistor MAX5483.

For practical use, the OTG module should be inserted into the smartphone as the first step. After the chip is recognized by the phone, the software is then opened, followed by the adjustment of source output. After the connection to the electrical appliance (the disinfection device in this case) is established, the energy can be delivered by clicking the “SEND” bottom. Notably, the current and voltage output have their specific wiring cord. Thus, when the source is switched from one to the other, the electrical connection should be changed accordingly.

Characterization of the smartphone-based power workstation

The electrical output of the smartphone-based power workstation has been characterized in three domains: the output range, the performance under low battery level, and the output accuracy.

Figure 3a, b shows the output current range when resistors of different values (from 1 to 220 kΩ) are installed in the circuit. The minimum current is 20 μA in the tested resistance range with a minimum increment of 10 μA. When the external resistor is ≤1 kΩ, a maximum of 1000 μA can be realized. With the increase of the resistance, the maximum current output decreases, since the resulted voltage cannot exceed the open-circuit voltage of the lithium ion battery in the smartphone. For example, the measured current plateaus at 800, 400, 81, or 40 μA when the external resistance is 4.7, 10, 47, or 100 kΩ, respectively. For the constant voltage operation, the output range is from 0.7 to 2.1 V with an increment of 0.1 V, no matter what external resistor is used (Fig. 3c).

When the battery drains out, the energy workstation is able to maintain high output performance. Within the range of 50–250 μA, the measured current is equal to or slightly higher than the set current, even when the battery level is 5% left (Fig. 3d). Such results indicate that the smartphone-based energy workstation is capable of providing sufficient output even when the battery level is low, i.e., the reliability and durability of the system are high.

The accuracy of the electrical output has been evaluated by linear regression between the applied and measured current/voltage with the calculation of the coefficient of determination (R^2) (Fig. 3a–c). The Y-intercept of the trendline was set to 0 since the ideal regression equation should be $y = x$ (where y and x are the measured and applied values, and the constant of variation is 1). In all experimental results, the constant of variation ranges from 0.9982 to 1.0187, while the R^2 ranges from 0.9992 to 1 (Supplementary Tables 1, 2). The above statistical measurements indicate high accuracy of the electrical output from the smartphone-based workstation.

Adopting current control in CECIC operation

The CECIC functions to inactivate bacteria by a low level of electrochemically generated copper (~200 μg L^{-1}), which posts little toxicity to human health. The CECIC consists of two coaxial electrodes. The center electrode is a thin copper wire (76-μm diameter), which is connected to the positive end of the electrical output. The outer electrode is a copper cylinder (0.95-cm diameter) connecting to the negative end. Attributed to this layout, the copper ions are released in situ from the center electrode as the disinfectant with a concentration gradient that is higher near the center. Meanwhile, the electric field is stronger near the center electrode, where the strength is up to 27 times higher than that in the conventional parallel-plate configuration[33]. Such a strong electric field can alter the permeability of the bacterial cells, promote the uptake of copper ions into the cells, and thus lead to an enhanced inactivation[41,42]. Last, when

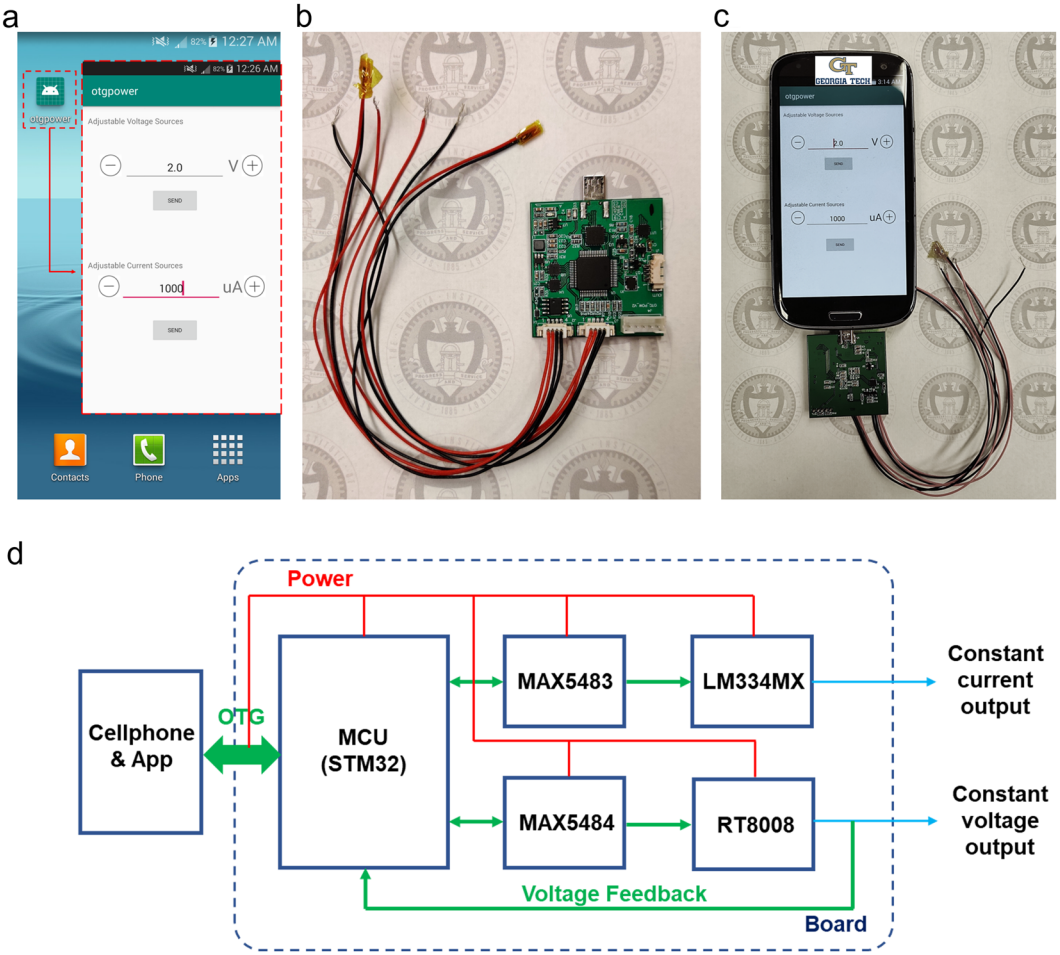

Fig. 2 Components of the smartphone-based power workstation. a Downloadable Android Application "otgpower" for power output management. Insertion is the user interface of "otgpower" for output value setup and deliver. **b** Photograph of the OTG module. **c** Photograph of the smartphone workstation system. **d** Circuit design showing the dual power output of constant current and voltage.

exposing to the non-uniform electric field, the bacterial cells are subjected to electrophoretic and dielectrophoretic forces, both of which drag the cells toward the center electrode[43,44]. The results of the previous control experiment using a Pt center electrode indicate that the copper ions play a major role for the disinfection while the electric field assists the CECIC to outcompete the conventional planar electrode CICs[33]. All the above mechanisms function synergistically to achieve a high bacterial inactivation in the CECIC (Supplementary Fig. 1).

The level of copper concentration in the effluent is a key factor in the disinfection by CECIC. A low level of copper may not be sufficient for inactivation. On the other hand, a high copper concentration in the effluent leads to the secondary contamination and toxicity to the human and environment[45]. Therefore, it is critical to control the level of copper in the effluent. In the previous practices, a constant voltage was applied between the outer and center electrodes for copper oxidation[33]. The overall resistance of the device changed with flow rate, water conductivity, and device geometry. It was thus difficult to control the effluent copper concentration precisely in different conditions.

A strategy of current control of CECIC is therefore applied, which is not common for typical municipal and industrial electric users. The release rate of copper, i.e., the transfer of ions is determined by both the electron transfer (i.e., the applied current) and the columbic efficiency, which describes the efficiency of electron transfer to facilitate the Cu ionization in the CECIC. The columbic efficiency of the CECIC remains stable (27.67% ± 2.84% in the DI water matrix, Supplementary Table 3) in different experimental conditions, which indicates that the effluent copper concentration can be controlled by the constant current. Experimentally, when the applied current is fixed, the release rate (release rate = effluent Cu concentration × flow rate) is similar at different flow rates (Fig. 4).

The disinfection performance of the smartphone-powered CECIC was evaluated by the standard plating technique. When the bacterial samples (~10^7 colony-forming units (CFU) mL^{-1} *E. coli*) were pumped through the device, a constant current was applied by the smartphone set. The battery level of the phone was kept higher than 80% along with the disinfection experiments. As shown in Fig. 5a–c, the effluent copper concentration is proportional to the applied current no matter what the flow rate is. For example, when the flow rate is 2 mL min^{-1}, the effluent copper concentrations are 96.3, 201.9, and 290.9 μg L^{-1} with the applied currents of 40, 80, and 120 μA, respectively.

The voltage resulted from the applied current is also critical because it provides the enhanced electric field near the center electrode to promote disinfection. As shown in Fig. 5d–f, the measured voltage increases linearly with the applied current. When the same current is applied, the voltage decreases at lower flow rates. This is because more copper ions accumulate along with the device when a lower flow rate is applied. The accumulation increases media conductivity, lowers the overall resistance, and leads to a lower applied voltage.

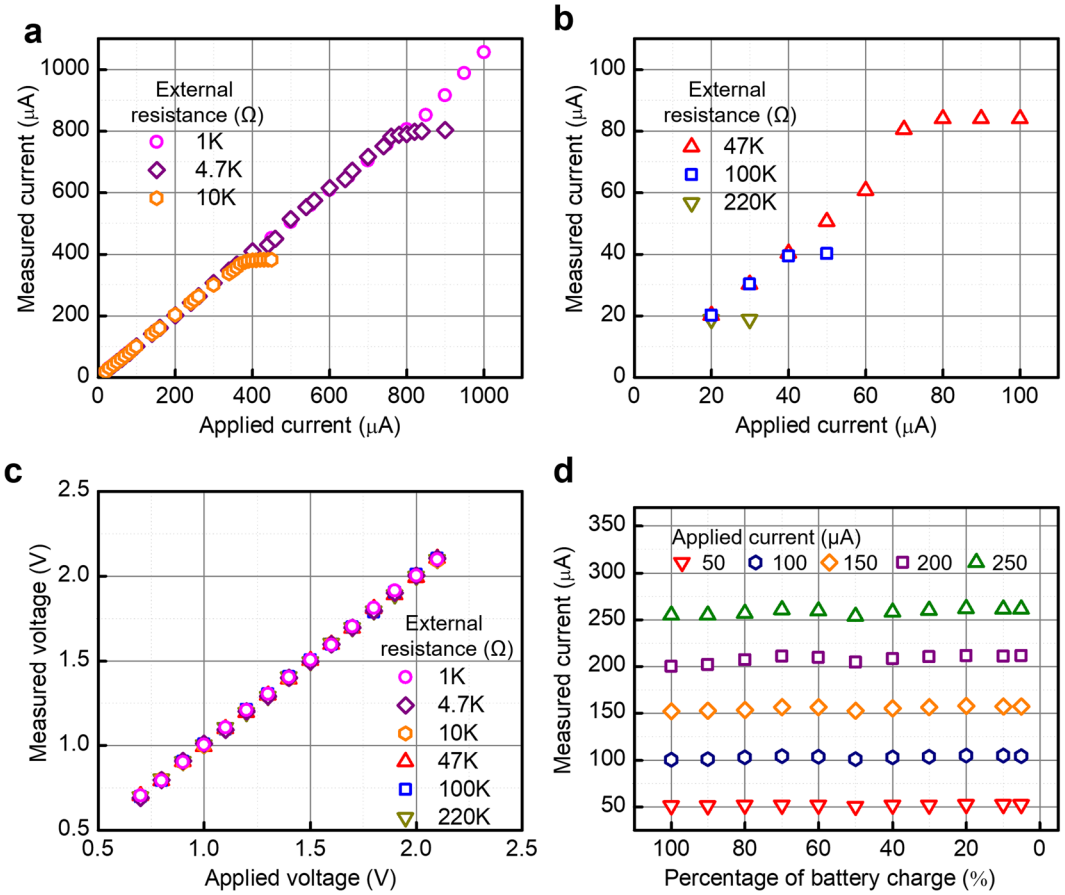

Fig. 3 Performance evaluation of the smartphone-based power workstation. a, **b** The current output range at different values of external resistor (**a**: 1, 4.7, and 10 kΩ; **b**: 47, 100, and 220 kΩ). **c** The voltage output range at different values of external resistance. **d** The current output value at different smartphone battery levels.

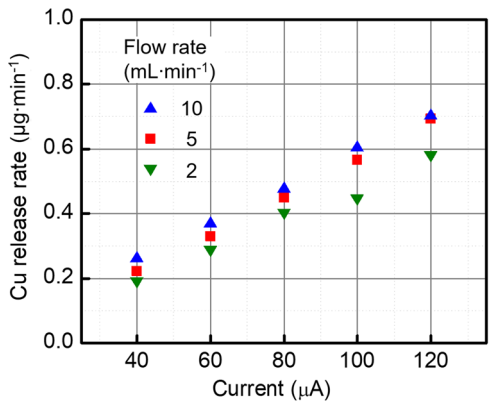

Fig. 4 The copper release rate of the CECIC at different flow rates and applied currents.

The log inactivation efficiency of *E. coli* (Fig. 5d–f) increases with the increase of current. Specifically, when the flow rate is 2 mL min^{-1} and the current is higher than 100 μA, >6 logs of inactivation can be achieved, wherein there is no bacterial colony growing on the agar plate. The effluent copper concentration is only 201.9 μg L^{-1}, far less than the MCLG of 1300 μg L^{-1}. Both the inactivation efficiency and effluent copper concentration are positively correlated with the applied current. Thus, when put into practical use, the smartphone-powered CECIC can be customized to achieve certain levels of pathogen inactivation with desired copper concentrations.

A series of disinfection efficiency contours are shown in Fig. 6a, b, which provide guidance about choosing the operating parameters in the disinfection applications. The current and flow rate are parameters to be adjusted during the operation. For example, when an inactivation efficiency goal of >5 logs is set, the combination of either condition I (60 μA and 2 mL min^{-1}), II (80 μA and 4 mL min^{-1}), or III (100 μA and 6 mL min^{-1}) can be selected to achieve the goal. Next, the capacity (flow rate) and effluent copper concentration are considered to select which of the above conditions is more favorable. Conditions I and II show a copper concentration of 125~150 μg L^{-1}, while condition III indicates 100~125 μg L^{-1}. Thus, condition III is optimum to achieve 5-log inactivation of *E. coli*.

Operating current control in a high-salt-concentration media

The natural drinking water sources, unlike DI water, have a much higher conductivity because of various inorganic ions. Thus, the disinfection performance of the smartphone-powered CECIC system has been studied in an artificial surface water matrix. The artificial water samples contain *E. coli* (~1×10^7 CFU mL^{-1}) and Na_2SO_4 as the electrolyte with a final salt concentration of 0.2–10 mmol L^{-1} (conductivity: 65–2450 μs cm^{-1}, pH: ~5.5, Supplementary Fig. 2). For water samples with higher salt concentration, i.e., higher conductivity, the system resistance of the CECIC decreases (Supplementary Fig. 3). The system resistance is ~800 Ω when the salt concentration is 0.2 mmol L^{-1}, and further decrease

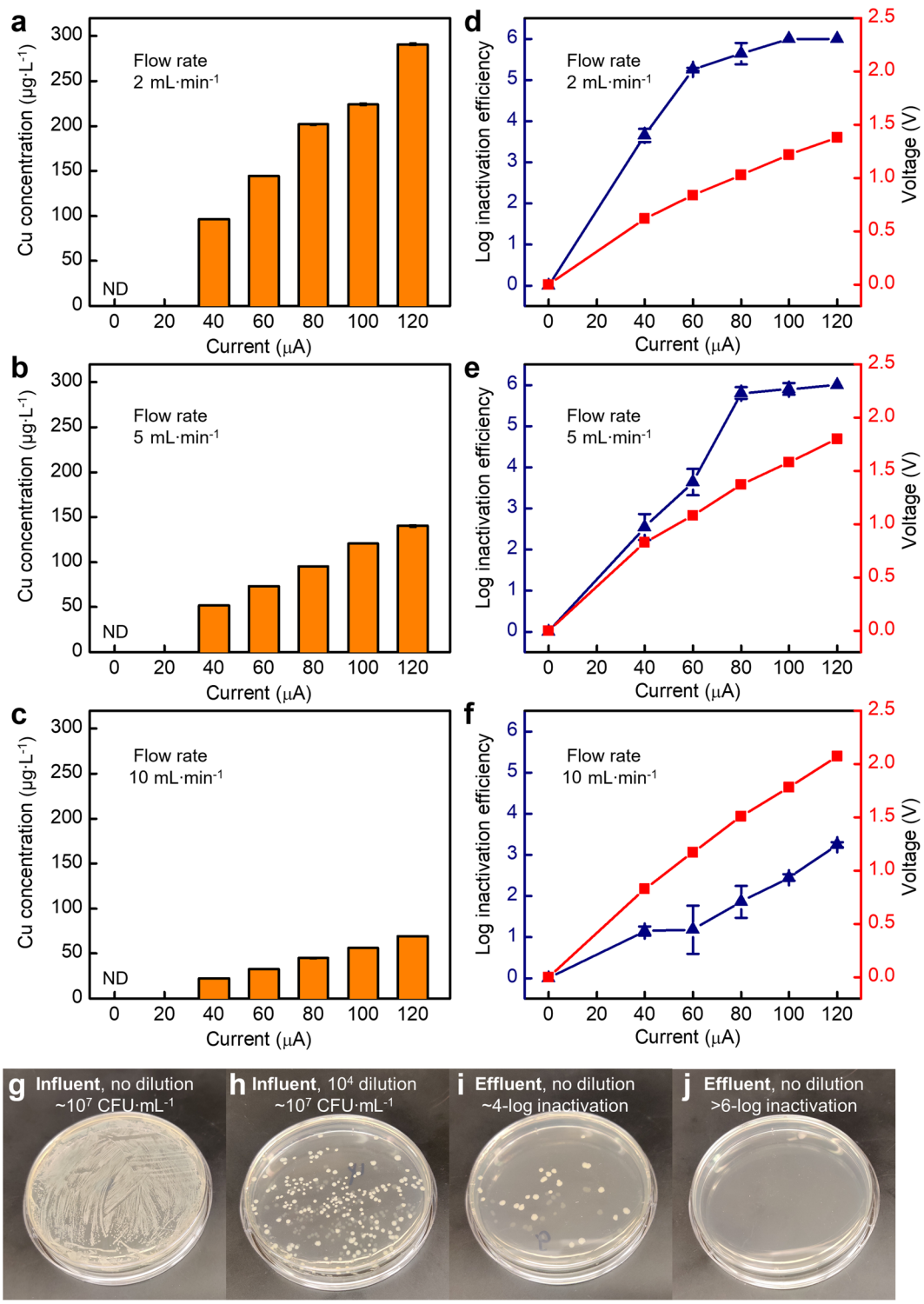

Fig. 5 Disinfection performance of the smartphone-based disinfection system. a–c Effluent copper concentration at different flow rates (2, 5, and 10 mL min^{-1}, respectively). **d–f** Log inactivation efficiency and measured applied voltage at different flow rates (2, 5, and 10 mL min^{-1}, respectively). **g–j** Images of *E. coli* colonies cultured on agar plates. Influent with no dilution (**g**) and 10^4 dilution (**i**). Effluent of a ~4-log (**i**) and a >6-log inactivation efficiency (**j**). Error bars present standard deviations.

with the conductivity. When the CECIC system is powered by the smartphone-based workstation, the maximum applied current is limited by the external resistance (Fig. 3a, b). Thus, when the artificial samples are used (system resistance < 1 KΩ), the smartphone-based workstation can provide a constant current of up to 1 mA across the CECIC.

When water samples with higher conductivity are used, low inactivation efficiency (<2.5 logs) is achieved when the flow rate is 5 mL min^{-1} and the applied current is 100 μA (Supplementary Fig. 4). A lower current (50 μA) results in a worse result (1.6-log inactivation under the same condition) (Supplementary Fig. 4). The increase of conductivity reduces the overall resistance, and

thus with the same constant current, the applied voltage is reduced significantly (<0.5 V) (Supplementary Fig. 5). Within such a low applied voltage, the change of cell permeability by the electric field and the dragging forces of the bacterial cells to the center electrodes are all weakened, thus resulting in a poor disinfection performance.

To solve the problem of low applied voltage, a higher flow rate (50 mL min^{-1}) and higher constant current (1 mA), which are both 10 times higher than the previous case, are used for CECIC disinfection. The effluent copper concentration is in the range of 155–290 μg L^{-1}, which is similar to the previous situations (Fig. 7a). As shown in Fig. 7b, a much higher disinfection efficiency is observed compared with the low-flow-rate groups. For example, when the ionic strength is lower than 0.5 mmol L^{-1}, 6-log inactivation is achieved with no live bacteria grown on the agar plate. The inactivation efficiency decreases with the increase of the media conductivity, but shows a more controllable trend through the conductivity range. Notably, in the case of 6-log inactivation, the applied voltage increases to 1.9 and 1.2 V at the media conductivity of 0.2 and 0.5 mmol L^{-1}, respectively (Fig. 7b), which is consistent with the disinfection contour (Fig. 6). When the salt concentration of the water sample further increases (higher than 1 mmol L^{-1}), the applied voltage decreases to <1 V. Such low voltage is too low to induce the change of cell membrane permeability and drive the bacterial cells near to the center electrode within the retention time, and thus leads to a decrease of inactivation efficiency. Thus, the strategy of constant current demonstrated at this point can only partially solve the problem of low applied voltage causing by the high conductivity of the media: The effluent copper concentration can be controlled while the disinfection efficiency still drops. A potential solution is to apply an alternative current, whereas controlling the peak applied voltage by the current amplitude and controlling the effluent copper concentration by the total energy consumption.

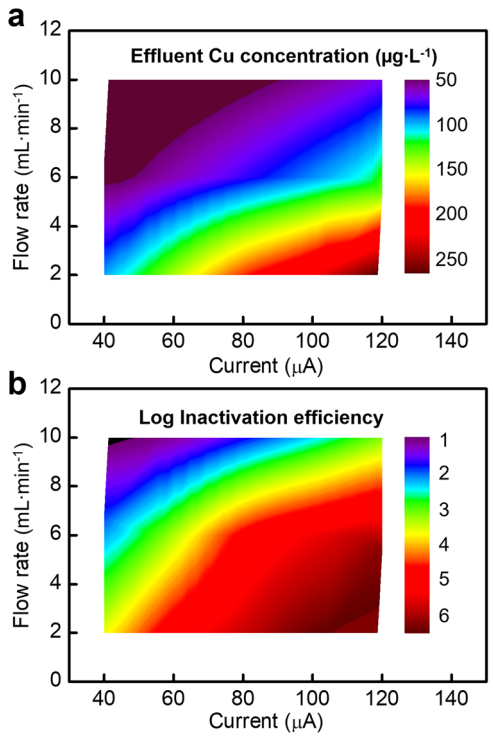

Fig. 6 Disinfection performance contour. a The effluent copper concentration under different flow rates and applied currents. **b** The disinfection efficiency under different flow rates and applied currents.

DISCUSSION

The technology of copper ionization has been studied and applied to aquatic disinfection for more than 20 years[46,47]. The outstanding antimicrobial effect, low cost, and little human toxicity make copper an excellent disinfectant with no concerns of carcinogenic byproducts[45,48]. The copper ionization controls the copper ion dosage precisely, relieving the problem of material storage and transportation. Thus, copper ionization systems have been used for disinfection in drinking water, wastewater, hospitals, cooling towers, etc[22,33,46,49,50]. The major obstacle of the conventional copper disinfection is that the dosage for efficient disinfection (>1500 μg L^{-1}) brings secondary contamination that is toxic to both the human and the environment[51,52]. The coaxial-electrode configuration of the CECIC brings additional mechanisms to assist water disinfection[33]. Copper ions are released in situ from the center electrode, making the copper ion concentration near the center electrode highly concentrated. The electric field, which is stronger near the center electrode, increases the permeability of bacterial cell membranes, enhances the uptake of copper into bacteria, and thus leads to a higher disinfection efficiency. Moreover, the electrophoretic and dielectrophoretic forces in the system can transport bacterial cells to regions near the center electrode, where there are higher copper concentration and electric field strength. The simple but superior coaxial-electrode design is promising to replace the traditional parallel-plate-electrode design.

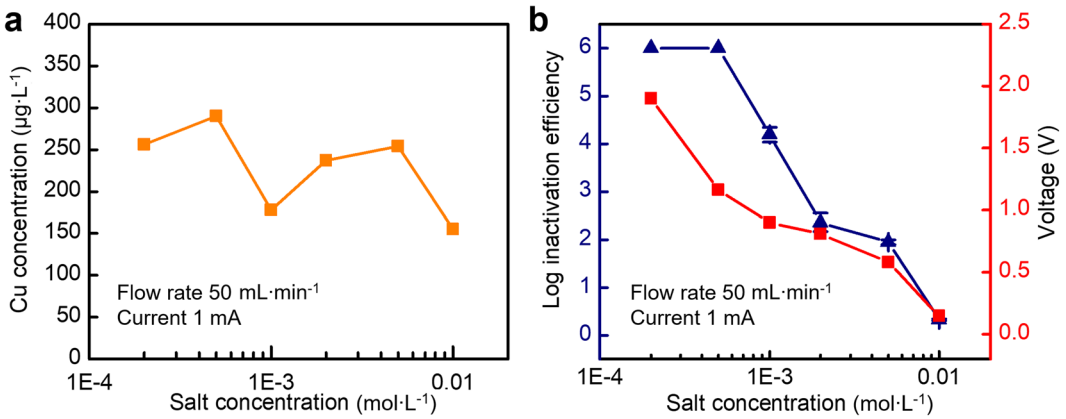

Fig. 7 Disinfection efficiency in artificial water samples of different salt concentrations. a Effluent copper concentration. **b** Log inactivation efficiency and applied voltage. The flow rate and applied current are fixed to 50 mL/min and 1 mA. Error bars present standard deviations.

The smartphone-powered disinfection system provides a convenient alternative for the POU disinfection. The smartphone brings strong enough batteries and friendly user interfaces, while the OTG system realizes a controllable and precise electrical output with a compact design. As smartphones are more and more prevalent, the smartphone-powered CECIC system can particularly benefit some remote regions where the construction of water grid is not cost-efficient. For example, 17% of people in rural areas in the U.S. reported having issues with safe drinking water[1]. In such case, an affordable and effective decentralized water disinfection system is critical. Meanwhile, the smartphone-based workstation can be applied to power various appliances, such as electrochemical disinfection or desalination by electrodialysis. If the grid electricity is not available, renewable energy from solar, water, wind, or human motions can also be used to charge the smartphone. Another key scenario of the smartphone-powered disinfection system is for outdoor activities like hiking or camping. Conventional filter-based disinfection tools are relatively expensive and are hindered by several problems[17]. For example, the filters are clogged rapidly if the turbidity of the raw water is high[4,19]. Some filters do not have an indicator to show the rest lifetime and remind replacement[27]. Other filtration methods may have the issue that pathogens can grow on the filter and cause secondary contamination[4]. Iodine tablets, another disinfectant designed for outdoor users, have been popular because of the low cost, fast-acting, and high portability. However, the water treated by iodine may develop a brown color and mildly astringent taste, which does not occur in copper disinfection[53]. Meanwhile, iodine tablets are in general suitable for small-scale and short-term applications. Long-term uptake of iodine may cause side effects such as nausea, stomach pain, headache, and diarrhea[53]. For the smartphone-based system, a set of the OTG module and CECIC disinfection device can be left near the water bodies. When campers need disinfected water, she/he can connect the system to her/his own electronic devices (e.g., smartphones or tablets).

Nevertheless, there are still significant challenges to be overcome before the application of the smartphone-based CECIC disinfection system in the field. A critical issue related to the CECIC is the compromised performance in complex water matrices. Water conductivity directly affects the ionization with a fixed voltage, which can be partially solved by current control. The decrease of disinfection performance still exists when treating water samples with higher conductivities. The effect of inorganic ions, organic matters, and particles on the disinfection should also be considered for future research. In terms of other waterborne pathogens, such as viruses and protozoa, the use of copper ions has shown an outstanding disinfection effect in other studies.[54,55] Nevertheless, future research should examine if the CECIC also inactivates viruses and protozoa more efficiently than the conventional Cu ions. Another problem that should be addressed is the scaling-up of the CECIC device. The current treatment capacity (10 mL min^{-1}) is still low and has great room to be improved. As the specific features of CECIC (i.e., centralized electric field strength and copper ion concentration) only exist near the center electrode, increasing the diameter of the system will result in a longer transportation time of bacteria to those regions. Thus, refined strategies should be investigated rather than simply increasing the electrode diameter by ratio. Lastly, circuit design can be optimized to enhance the efficiency of the smartphone energy workstation. Lower energy will be consumed by reducing the internal resistance of the OTG module, which results in higher overall efficiency.

With more research efforts, the smartphone-based CECIC disinfection system has the potential to be widely used in real life because of its low cost and versatile working modes. The cost of the non-consumable OTG module and disinfection device can be as low as $5 each and $10 each, respectively, after large-scale commercialization. The copper wire (center electrode) is consumable and should be replaced periodically. Theoretically, one unit of the copper wire (76-μm diameter, 12.7-cm length) can be used to treat ~100 L of water (Supplementary Table 4). However, in the practical situation, the copper wire is usually non-uniformly consumed and breaks at one point, which causes short-circuit and disinfection failure. A previous study has demonstrated that the copper wire lasts for more than 12 h continuously before breaking down, which results in a low material cost of ~$0.1 m^{-3} water treated[33]. Notably, even after the short-circuit, the copper wire is not completely consumed and can be recovered, which could further reduce the material cost. In terms of electric energy consumption, it only takes 0.2–0.4% of the total battery charge to disinfect 3 L water, a sufficient amount for an adult to drink for a day (Supplementary Table 5). Meanwhile, the adjustable current output provides options for customers to select the different degree of disinfection. When higher disinfection efficiency is to be achieved, the level of copper in the water will be higher and the copper wire will be consumed faster.

Herein, we have demonstrated a smartphone-powered water disinfection system for POU. The electrical output of the smartphone, realized by an OTG module, can be either constant current or voltage. The functional output range is determined by the type of the smartphone (0.7–2.1 V and 20–1000 μA in our case). With a constant current applied, the disinfection device, a CECIC, efficiently inactivates *E. coli* (6 logs) with a low level of copper (~200 μg L^{-1}) in the effluent. The utilization of current control, instead of voltage control, leads to an even copper release rate in water with different quality. This design provides an energy-efficient and easily accessible method for POU water disinfection, especially in remote regions without centralized water treatment facilities.

METHODS

Design of the smartphone-based energy workstation

The hardware part is a customized OTG module that is powered and controlled by a connected smartphone. The OTG module is based on the embedded system design and integrated on the printed circuit board. In this module, a microcontroller unit (MCU) (STM32, STMicroelectronics) is used to manage the circuit, which mainly receives the command signal from the smartphone as well as to execute the command to the subsequent functional units. The functional units consist of a current source chip (LM334MX, Texas Instruments, Supplementary Fig. 6) and a voltage source chip (RT8008, Richtek Technology Corporation, Supplementary Fig. 7). To realize the adjustable energy output, two variable resistors, MAX5483 and MAX5484, are installed in the current and voltage circuit, respectively. Detailed circuit design and description can be found in Supplementary note 1. The software part is an Android application package (APK), a graphical interface for the user to input the desired current or voltage value. The APK is realized under the Eclipse environment and written by Java Script.

Characterization of the smartphone-based power workstation

The characterization of the smartphone-based power workstation was conducted by connecting the smartphone set with a constant resistor ranging from 1 to 220 kΩ. The output current/voltage was measured by a Keithley 2400 SourceMeter. The measured output values (either current or voltage) were recorded on the sourcemeter when the corresponding applied values were sent across the resistor. Except for the battery life experiment, the battery level of the smartphone was kept >80% during the experiments. For the accuracy of the output, the coefficient of determination (R^2) of the linear regression was calculated by Eq. (1), where n, x, y are the number of the total applied-measured output points, applied output values (independent variables), and measured output values (dependent variables).

$$R^2 = \frac{[n(\sum xy) - (\sum x)(\sum y)]^2}{\left[n\sum x^2 - (\sum x)^2\right]\left[n\sum y^2 - (\sum y)^2\right]^2} \quad (1)$$

Bacteria culturing and preparation

The model bacterium, *Escherichia coli* (*E. coli*, 10798^{TM}), was purchase from the American Type Culture Collection and used as the disinfection target. The bacterial cells were cultured aerobically in LB broth (BD Difco^{TM}) at 35 °C to the stationary phase (12–18 h) in a shaker (200 rpm). Next, the bacterial culture was centrifuged at 1677 × *g* for 5 min (HITACHI RX2 series). The supernatant was dumped, and the settled bacteria pellet was washed and resuspended with deionized (DI) water. The washing was repeated three times to remove the background substances from the bacterial suspension. Subsequently, the bacteria pellet was resuspended to a concentration of ~1×10^7 CFU mL^{-1}. The water matrixes used to suspend the bacteria pellet were either DI water (pH = ~5.5) or Na_2SO_4 solution. The reason for choosing Na_2SO_4 instead of NaCl as the electrolyte is to avoid the formation of Cl_2, a disinfectant, when a voltage is applied. The range of salt concentration of the Na_2SO_4 solution was 0.2–10 mmol L^{-1} to mimic the fresh drinking water sources. Notably, the suspension of *E. coli* in DI water did not cause a significant reduction of *E. coli* within the period of the disinfection experiments (3 h, Supplementary Fig. 8).

Disinfection experiments

An efficient disinfection device, the CECIC, was used for the disinfection experiment. A detailed description of the construction and configuration can be found in a previous study. In short, the disinfection device consisted of a thin copper wire (76-μm diameter) served as the positive center electrode, and a coaxial metal cylinder (0.95-cm diameter) as the negative outer electrode. The length of the device was 12.7 cm, which resulted in an effective volume of 10 mL. During the disinfection experiment, the prepared bacterial suspension was pumped into the disinfection cell with a flow rate of 2–50 mL min^{-1} (Cole Parmer Masterflex L/S Peristaltic Pump). After the bacterial suspension was filled in the device, a constant current of 20–1000 μA was applied between the two electrodes by the smartphone to enable disinfection. The effluent samples were collected after 40 mL of water flow through the cell so that the samples were collected under a steady-state condition. The operating voltage was recorded by a Keithley 2400 Sourcemeter at the sampling point. The concentration of bacterial cells was evaluated by the standard microbial plating technique between 2 and 3 h after disinfection experiments. The inactivation efficiency was calculated by Eq. (2), where c_{in} and c_{eff} were the bacterial concentration in the influent and effluent, respectively.

$$\text{Log inactivation efficiency} = -\log_{10}(c_{eff}/c_{in}) \quad (2)$$

Copper concentration measurement

The total copper concentration dissolved in the influent and effluent samples was measured by a copper test kit (HACH, porphyrin method 8143) and the steps are stated as follows: (1) collect a water sample (influent/effluent) of 5 mL; (2) acidify with 2% w/w HNO_3 solution; and (3) analyze the water sample using the copper test kit by a Hach DR6000 UV/VIS Spectrophotometer. The porphyrin method had an effective test range of copper from 1 to 210 μg L^{-1} and a sensitivity of 1 μg L^{-1}.

DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

CODE AVAILABILITY

The code used in the current study are available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

X.X., W.D., and J.Z. conceive the research idea. J.Z. conducted the water disinfection experiments and the performance analysis of the smartphone-powered workstation. F.Y. designed and fabricated the energy workstation. J.Z., X.X., W.D., and Y.H. discussed the results, and all authors reviewed the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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