Research Article

Muddasir, Irfan Qasim, Najeeb-ur-Rehman, Muhammad Waqar Ahmed*, Muhammad Ijaz Khan*, Habib Bukhari, Mohamed Ahmed Said Mohamed, Ahmed Osman Ibrahim, Faizah Mohammed Bashir, and Sayed M. Eldin

Degradation of *Vibrio cholerae* from drinking water by the underwater capillary discharge

https://doi.org/10.1515/phys-2022-0243
received December 27, 2022; accepted March 28, 2023

Abstract: Underwater plasma discharge is considered a nontoxic and effectual purification approach to control waterborne bacterial pathogens. In the present study, *Vibrio cholerae* contaminated drinking water was sterilized by using underwater capillary discharge generation *via* high voltage, oxygen (O_2) injection, and hydrogen peroxide (H_2O_2) addition. The effects of oxidant species generated by plasma discharge on *V. cholerae* disinfection have been studied and reported. The electrical and optical analysis of capillary discharge revealed the generation of reactive oxygen species ($OH^·$, H and O), which are highly useful for bacterial disinfection along with enhanced power and energy of discharge pulses. Complete elimination of *V. cholerae* (0 CFUs (colony forming units)) from the water after O_2 injected and H_2O_2 added plasma discharge was achieved, and 100% inactivation of *V. cholera* from drinking water was proven. The retardant effect of the initial *V. cholerae* colonies with time variation was reported through optical density ($OD_{600\ nm}$) measurements. The time course study of bactericidal activity of plasma treatment on *V. cholerae*, observed every 12 h up to 36 h, revealed a high retardant effect on *V. cholerae* CFUs. Underwater capillary discharge is an efficient approach for the inactivation of *V. cholerae* from drinking water.

Keywords: capillary discharge, *V. cholerae*, antibacterial activity, water-borne pathogens

1 Introduction

V. cholerae causes major health issues in more than 50 countries around the world. The presence of *V. cholerae* in water grows dynamically and in continuous recurring cycles [1,2]. The climate factors such as rainfall, floods, human exposure and sanitary conditions, population growth, and land development along river banks and near underwater reservoirs affect the *V. cholerae* concentrations in the environment, especially in drinking water [3,4]. Many common methods for regulating the above-mentioned bacteria from drinking water have been used in the past [5–8]. Sterilization of waterborne pathogens such as *V. cholera*, by low-temperature arc plasma, has proved to be very effective in the last few decades [9]. In the past, many pioneer works and industrial device developments including DC-powered plasma jets, RF-induced devices, dielectric barrier discharges, based on plasma generation, in the context of antibacterial applications, for mitigating agrochemical and pesticide residue in foods and water, plasma medicines, and hygiene and in health sciences, were investigated and reported [10–13]. Underwater capillary discharge is a novel technique for water purification and has been proven an effective approach in the last few decades [14]. The occurrence of arc discharge in capillary tubes containing flowing water leads to the

* **Corresponding author: Muhammad Waqar Ahmed,** Department of Physics, Riphah International University I-14, 44000, Islamabad, Pakistan, e-mail: mwaqar.ahmed@riphah.edu.pk
* **Corresponding author: Muhammad Ijaz Khan,** Department of Mechanical Engineering, Lebanese American University, Kraytem, Beirut 1102-2801, Lebanon; Department of Mathematics and Statistics, Riphah International University I-14, 44000, Islamabad, Pakistan, e-mail: scientificresearchglobe@gmail.com
Muddasir, Irfan Qasim: Department of Physics, Riphah International University I-14, 44000, Islamabad, Pakistan
Najeeb-ur-Rehman: Department of Physics, COMSATS University, 45550, Islamabad, Pakistan
Habib Bukhari: Department of Bioinformatics, Kohsar University, Murree, Pakistan
Mohamed Ahmed Said Mohamed: Department of Architectural Engineering, College of Engineering, University of Ha'il, Ha'il, Saudi Arabia
Ahmed Osman Ibrahim: Department of Architectural Engineering, Faculty of Engineering, University of Ha'il, Ha'il, Saudi Arabia
Faizah Mohammed Bashir: Department of Interior Design and Decoration, College of Engineering, University of Ha'il, Ha'il, Saudi Arabia
Sayed M. Eldin: Center of Research, Faculty of Engineering, Future University in Egypt, New Cairo 11835, Egypt

generation of highly reactive oxidant species (ROS), including OH· radicals, reactive hydrogen (H), reactive oxygen (O), ozone (O_3), hydrogen peroxide (H_2O_2) (due to the dissociation of water molecules within the water medium), and the generation of intensive shockwaves was proven to be very effective for inactivating bacteria from water [15]. Some of the species like OH· radicals are very short-lived (10^{-8} s), but due to high redox potential they react efficiently and quickly for the treatment of contaminated water of large volume, while other oxidant species like ozone (O_3) and hydrogen peroxide (H_2O_2) remain active for a longer time in water and could act as a sterilization agent for a longer time [16]. The main reason for using oxygen as an injected gas is to generate a large amount of ROS, which is highly useful for water purification [17,18]. Other outcomes of the discharge include shockwaves intense electric fields and UV radiations that are also highly useful for water purification [19–21]. The intense electric field reacts with the cell membranes of bacteria, overcomes its tensile strength, and causes its rupture. The electric field accumulates electric charges in the discharge region, and the interaction of electric charges with the bacterial cell membrane causes cell stress and its rupturing, making it unable to reproduce [22–27]. Refs. [28–36] highlight different important studies on the material review and literature.

In the present research, underwater capillary discharge was performed to neutralize frequently occurring waterborne pathogens, *i.e., Vibrio cholera.*

2 Materials and methods

2.1 *Vibrio cholerae* strains and growth conditions

V. cholerae strains (O1) belonging to two unique subclades, *i.e.*, PSC1 and PSC2, were obtained from the Microbiology and Public Health Lab, COMSATS University, Islamabad, Pakistan. These strains were revived on thiosulfate–citrate–bile salts–sucrose (TCBS) (Sigma-Aldrich, Ireland Ltd.) agar plates. For each set of experiments, overnight cultures (16–18 h) of *V. cholerae* strains were grown in Luria broth (Lenox Invitrogen 22700025) at 37°C.

2.2 Bacterial cell survival assay

The effect of plasma treatment on bacterial growth and cell survival was determined under various experimental conditions. An overnight culture of *V. cholerae* strains (~10^7 CFUs) was used to prepare the inoculum of bacteria suspension (~10^3 CFU/mL) in 1 L of autoclaved distilled water. These suspensions were used to prepare different groups of experimental design (0.35 mL/L H_2O_2 and 0 mL/L H_2O_2) and were then exposed to plasma at a flow rate of 0.1 L/min through discharge containing a capillary tube. After plasma treatment of the water that contained bacteria, 100 μL of the water suspension was plated on TCBS agar plates using a spreader, and the plates were incubated at 37°C for 24 h.

3 Experimental setup

The flowing water plasma discharge was created in a quartz capillary tube (length, 12 cm; outer diameter, 4 mm; and inner diameter, 2 mm with a thickness of 2 mm) specifically designed with a water inlet and outlet segments, along with gas injection facility for creating bubbles. A high-frequency (758 kHz) alternating current (AC) plasma generator CTP-2000S was used for applying a voltage across pin-pin configured tungsten electrodes, each of diameter 1 mm. Figure 1(a) represents the schematic diagram of the experimental setup, and Figure 1(b) represents the visual view of the capillary discharge.

The inter-electrode gap where the plasma was generated was 5 mm and the water flow rate was kept at 0.1 L/min. A mass flow controller (TELEDYNE-500P) was used for controlling the flow of oxygen (100-800 sccm, with 100 sccm trail). The emission spectrum of capillary discharge was recorded on an Avantes Avaspec-NIR256 miniature fiber-optic spectrometer. The spectrum shows the concentration of highly oxidant reactive species generated by underwater capillary discharge. The *V. cholerae* containing water was treated by plasma discharge under specific experimental conditions including various oxygen injected rates and with and without hydrogen peroxide (H_2O_2) addition. A standard amount of H_2O_2 (0.35 mL/L) was added for generating immense consolidation of the oxidant species. One liter of water reservoir containing 10^5 CFUs of *V. cholerae* was introduced through the discharge tube along with oxygen injection by using an injecting syringe for spawning oxygen bubbles in flowing water. A digital oscilloscope (GWINS-TEK) having high voltage (peak-peak, 39 kV, DC/AC, rms, 27 kV) and large current probes (1 mA to 40 A with an effective frequency bandwidth range up to 50 MHz) and data storage facility was used for recording volt–ampere characteristics of flowing water capillary discharge. Sterilized water was tested directly after plasma treatment and examined every 12 h, up to 36 h to detect the growth of *V. cholerae* in water.

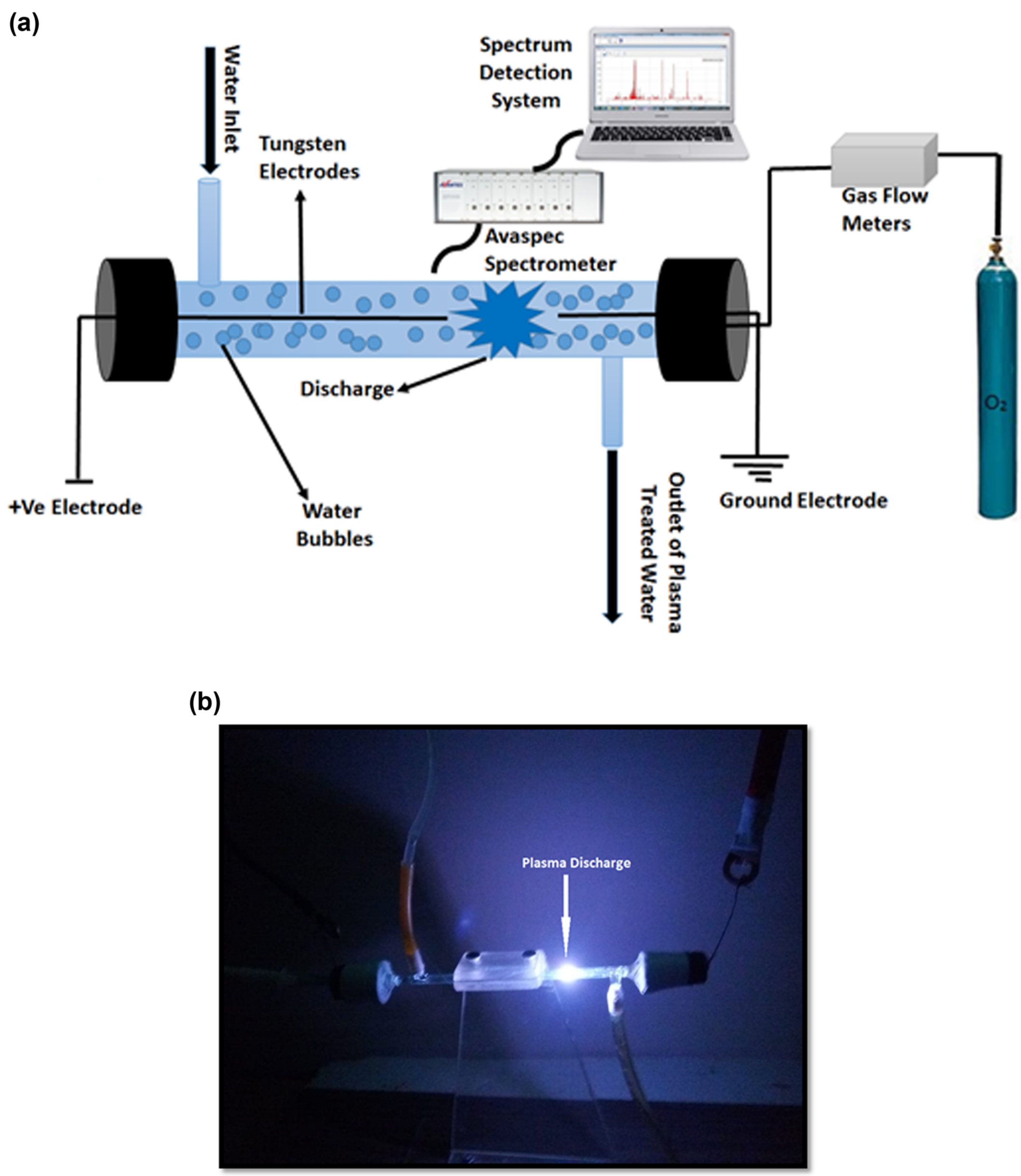

Figure 1: (a) Schematic diagram of the experimental setup. (b) A visual view of capillary discharge.

4 Results and discussion

The electrical, optical, and biological diagnostics techniques were adopted to study and report the inactivation of water-borne pathogens, *V. cholerae*, from drinking water.

4.1 Electrical results

The volt–ampere characteristics of capillary discharge were measured by a digital oscilloscope (GDS-3504). A high-voltage probe (TT-HCP 2739) having a 1,000 attenuation factor, a high input impedance (900 MΩ), and a large current probe (GCP-530) with a current range of 1 mA to 40 A and an effective frequency bandwidth up to 50 MHz were used for determining the breakdown voltages, discharge currents, and power and energy of discharge pulses at various experimental schemes. Typical *I*–*V* curves are presented in Figure 2, after discharge occurrence. Since the dielectric strength of the tap water used in this experiment is quite high, enormous power is required to create a breakdown in the flowing water. In order to overcome this challenge, gas bubbles were introduced inside the capillary tube that induced elongated gas channels and bubbles inside the capillary tube and caused a reduction in the required breakdown voltage. In this experiment, oxygen

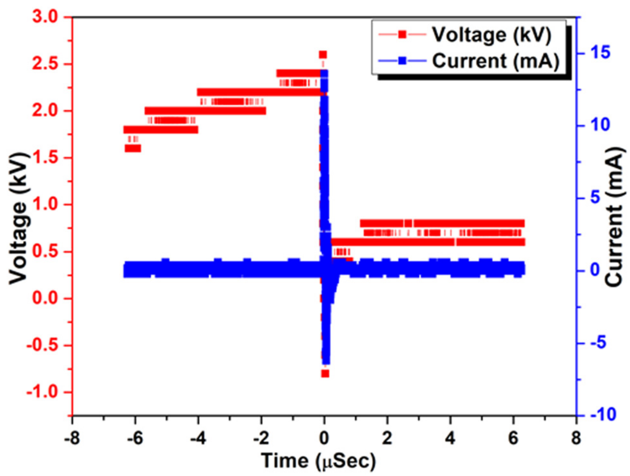

Figure 2: Typical volt–ampere characteristics curve.

was chosen as the preferred gas for creating flowing water discharge because oxygen has the ability to generate a high concentration of oxidant species (OH·, H_α,H_β, O_3, H_2O_2). At various higher oxygen injection rates (100–800 sccm), the energy and power of discharge pulses have shown an incremental increase. Figure 3(a and b) represents the variations in energy and power of discharge pulses with and without H_2O_2 addition and for different oxygen injection rates.

The increase in oxygen injection rates caused an increase in the size and elongation of gas bubbles and gas channels inside the capillary tube, which drastically enhanced the power and energy of discharge pulses by limiting the required breakdown voltage. Such an increase in the power and energy of discharge pulses not only enhanced the yield rate of oxidant species by dissociating water molecules but also played a critical role in disinfecting *V. cholerae*. The results showed that the addition of hydrogen peroxide (H_2O_2) does not cause a remarkable increase in water conductivity; therefore, electrical characteristics were not influenced by the addition of hydrogen peroxide (H_2O_2). But the addition of hydrogen peroxide (H_2O_2) along with the occurrence of discharge caused a remarkable increase in the concentration of the oxidant species (Figure 5).

4.2 Optical diagnostics

An optical emission spectrum was used to examine the ROS generated by plasma discharge in capillary tubes [37]. The short reactive species such as OH· radicals were present. Optical emission spectrometry has been frequently studied (10^{-8} s) as well as long-lived reactive species (H_2O_2 and O_3) along with reactive hydrogen (Hα, H_β) and atomic oxygen (O_2). Different types of spectral lines represent the concentration of specific oxidant species in different spectral regions (visible, UV, and IR).

An Ava-Spec spectrometer (AVS-RACKMOUNT-USH2) with a resolution of 0.06–13 nm and a wavelength of 200–900 nm was used to determine the concentration of ROS produced by capillary discharge. Figure 4 shows the emission spectrum of effective reactive oxidizing species under various experiential conditions, showing the dominant spectral lines produced by the highly reactive oxidizing species resulting from the dissociation of water molecules through electrical energy. In the IR region, most descriptive lines were expected due to atomic oxygen, and the dominant peaks of hydrogen lines (Balmer α = 656 nm and Balmer β = 484 nm) are present.

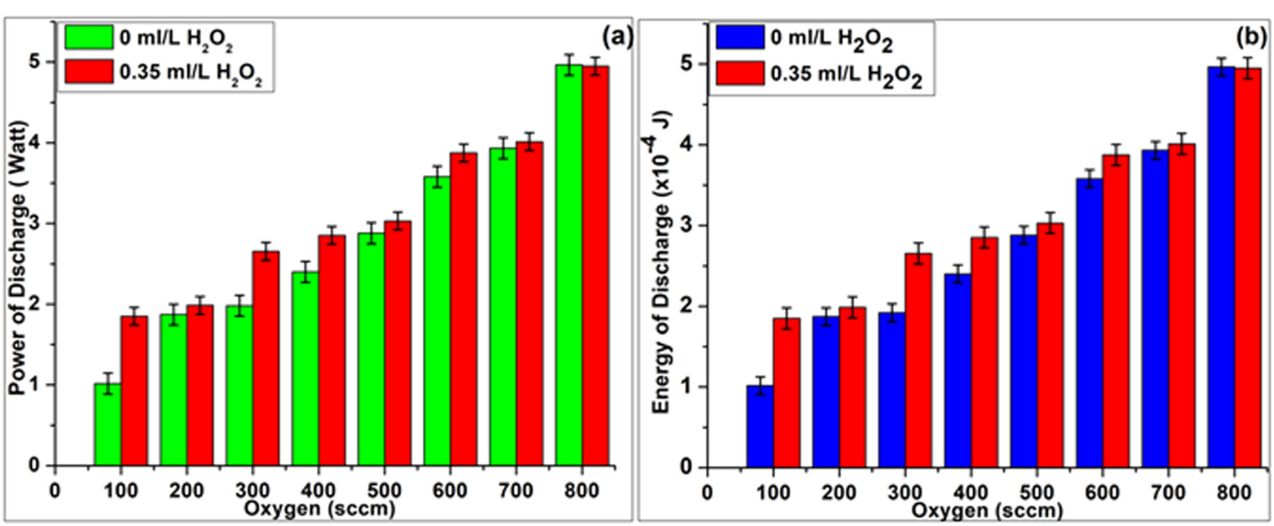

Figure 3: (a) Power and (b) energy of discharge pulses under various experimental conditions.

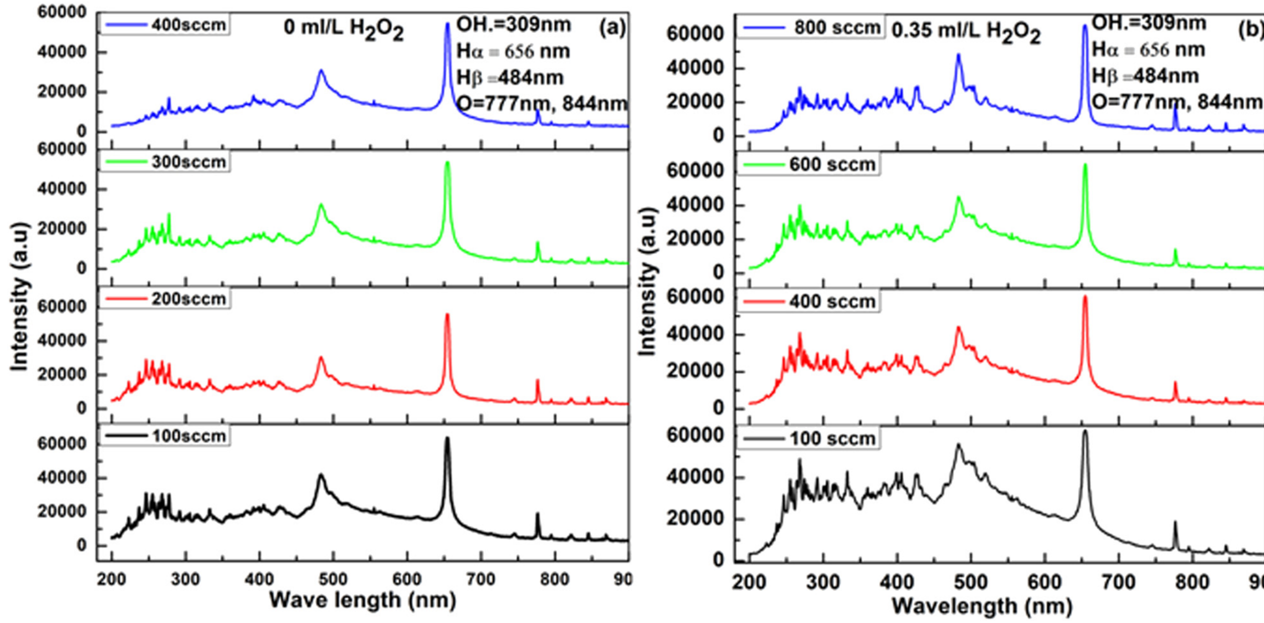

Figure 4: (Color online) A typical optical emission spectrum for the identification of ROS for (a) O_2 injection and 0 mL/L H_2O_2 addition; (b) O_2 injection and 0.35 mL/L H_2O_2 addition in water.

Powerful OH· radical peaks have been examined in the UV spectrum at 309 nm. No distinctive lines are examined in the spectral line due to metal ablation from electrodes. Other dominant oxidizing species like H_2O_2 and O_3 can be generated due to possible chemical reactions that take place when discharged into water [38,39]. The addition of H_2O_2 together with oxygen-injected discharge increased the oxidant species concentration. Each oxidant

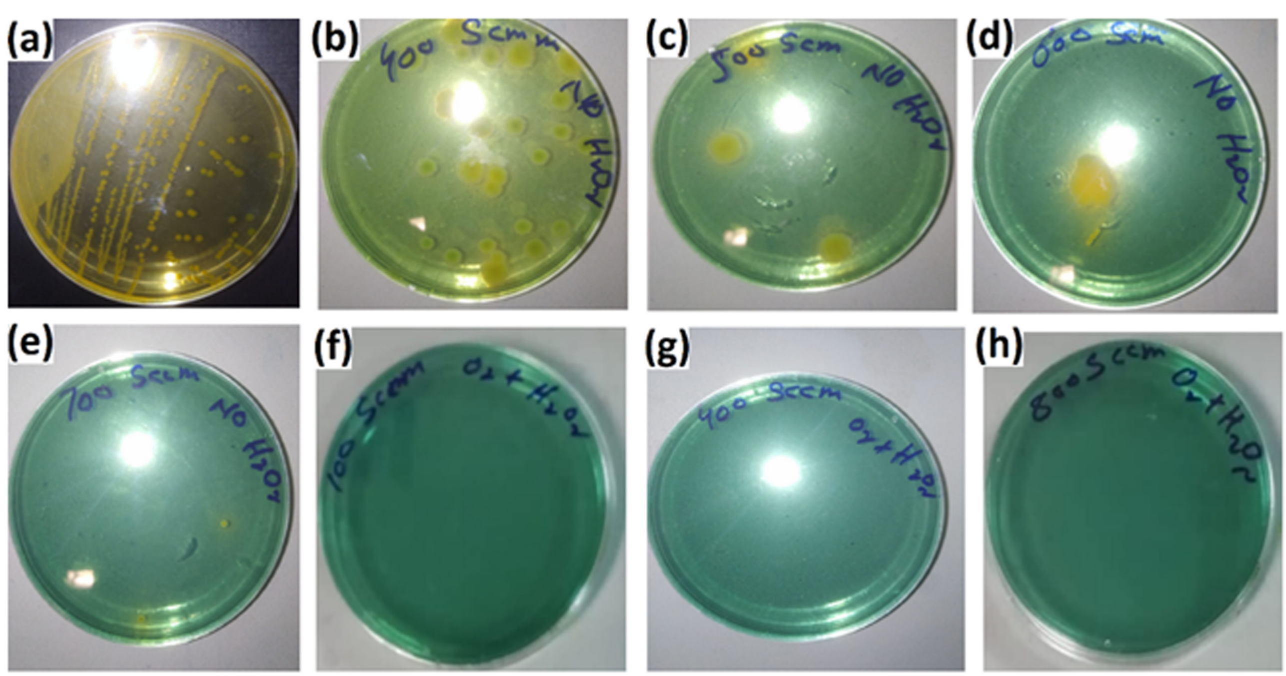

Figure 5: (Color online) Typical images of *Vibrio cholera* CFUs: (a) pure *V. cholerae* strain. CFUs obtained after (b) 400 sccm oxygen injection and 0 mL/L H_2O_2 addition, (c) 500 sccm oxygen injection and 0 mL/L H_2O_2 addition, (d) 600 sccm oxygen injection and 0 mL/L H_2O_2 addition, (e) 700 sccm oxygen injection and 0 mL/L H_2O_2 addition, (f) 100 sccm oxygen injection and 0.35 mL/L H_2O_2 addition, (g) 400 sccm oxygen injection and 0.35 mL/L H_2O_2 addition, and (h) 800 sccm oxygen injection and 0.35 mL/L H_2O_2 addition.

species ($OH^{\cdot}$, H_2O_2, O_3, Hα, $H_{\beta,}$ and O) have the potential for redox and water sterilization, but their individual effects are not very effective compared to their cumulative effects influencing *V. cholera* sterilization [40]. The concentration of these oxidant species was weak in the absence of the addition of hydrogen peroxide (H_2O_2); however, in the case of added hydrogen peroxide (H_2O_2) together with oxygen (O_2) injected in a capillary discharge, a remarkable increase was observed. More increased concentration was observed at higher oxygen injection rates. Although short-lived, OH radicals are effectively massacred by *V. cholerae* due to high redox potential (270 V). The discharge-generated, water dissolved H_2O_2, and O_3 also have exceptional antibacterial properties, so *V. cholerae* disinfection was also effectively of concern.

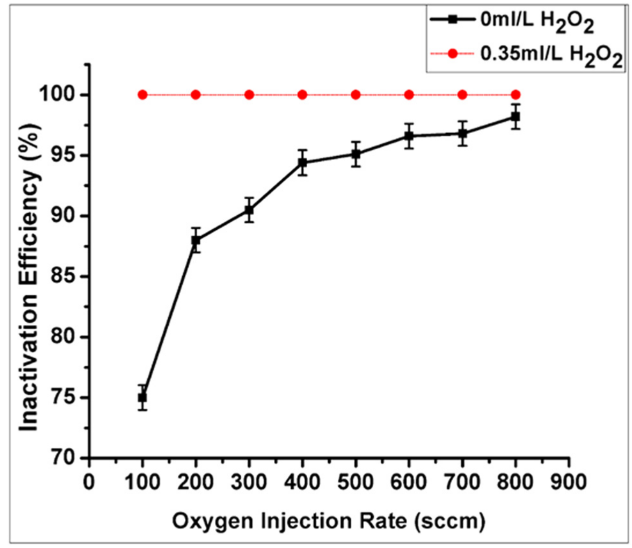

Figure 6: (Color online) Reliance of *V. cholerae* inactivation efficiency 'η' on various oxygen injection rates and with the addition of H_2O_2 in underwater plasma discharges.

4.3 Plasma discharge effect on *V. cholerae* inactivation and re-growth

After plasma treatment of bacteria containing water, the water was centrifuged (120 rpm) in a shaker and then 100 µL of the water suspension was plated on TCBS agar plates using a spreader, and the plates were incubated at 37°C for 24 h. The CFUs on each plate were counted, and the CFUs/mL were calculated by using the following formula:

$$\text{Colony forming unit (CFU/mL)} = \frac{\text{No. of colonies} \times \text{Dilution factor}}{\text{Volume of culture plated}}. \quad (1)$$

Untreated water suspension and inoculated water were used as positive and negative controls. Figure 5(a) represents the control *V. cholerae* strain before plasma treatment. Figure 5(b–h) represents typical results of plasma-treated *V. cholerae* containing water under different experimental conditions, with and without the addition of H_2O_2. The results revealed that pure *V. cholerae* make a high concentration of colonies (10^7CFUs), while after plasma treatment the colonies were reduced enormously as shown in images of TCBS plates. The addition of hydrogen peroxide (H_2O_2) and oxygen (O_2) injected in a discharge-created oxidant species ($OH^{\cdot}$, H, and O), as represented in spectral results that played a vital role in sterilizing *V. cholerae* completely from drinking water.

The killing efficiency η (in %) of the plasma was calculated using the following formula and presented in Figure 6:

$$\text{Killing efficiency } (\eta)\ \% = \left(1 - \frac{\text{No. of CFU/mL in treated samples}}{\text{No. of CFU/mL in untreated control samples}}\right) \times 100. \quad (2)$$

The logarithmic value of bactericidal colonies, which represents the kill rate, before and after the plasma treatment was calculated as

$$\text{Kill rate} = \log \frac{N}{N_0}, \quad (3)$$

where N is the number of untreated colonies and N_0 is the number of colonies after plasma treatment. The kill rate is graphically illustrated in Figure 7.

Under optimum experimental conditions, the plasma-processed water samples were diagnosed after each 12 h interval, up to 36 h. Interestingly, the results demonstrated that with a higher oxygen injection rate and H_2O_2 addition to water, the inactivation efficiency of *V. cholerae* increased remarkably. Figure 8 represents the retardant effect of plasma-treated water observed up to 36 h, in 12 h of time-space each. The *V. cholerae* survival percentage was calculated by the following relation:

$$\%\ \text{Survival of } V.\ cholera = \frac{(\text{OD of test group}) - (\text{OD of blank})}{(\text{OD of control}) - (\text{OD of blank})} \times 100. \quad (4)$$

The OD of the blank was 0.03345, the OD of pure strain was 0.91, and the OD of the control was 0.405; the OD of the test group varied for different plasma treatment

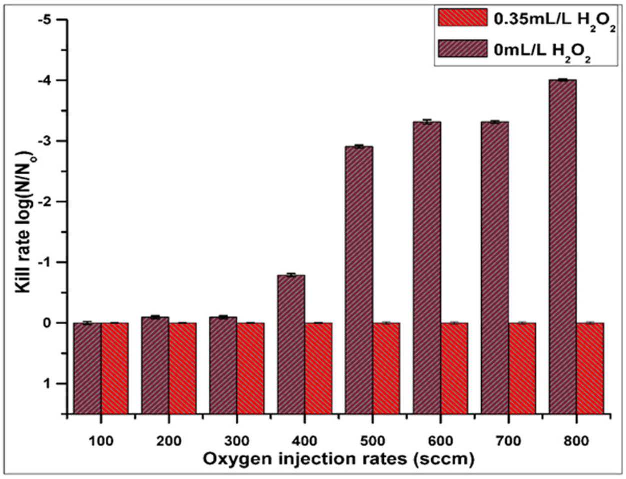

Figure 7: (Color online) Kill rate (the reduction in *V. cholerae* colonies) *vs* O_2 injection and H_2O_2 addition in water.

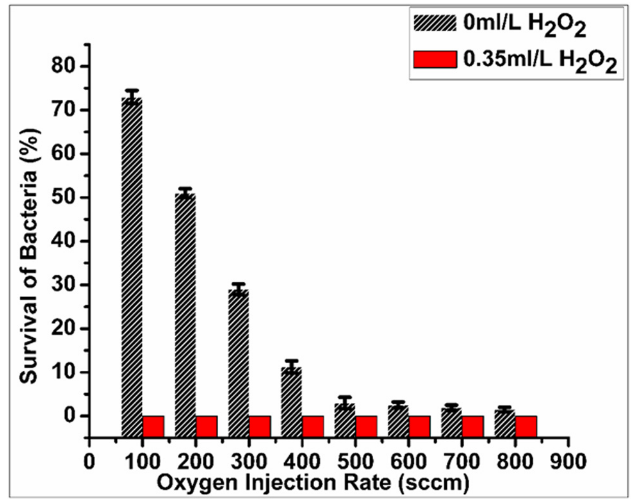

Figure 9: (Color online) Survival of *V. cholerae* in water after plasma treatment at various oxygen-injected rates with and without H_2O_2 addition in water.

conditions. Figure 9 represents the kinetics and % viability of *V. cholerae* under different treatment conditions.

The O_2-injected and H_2O_2-added discharge resulted in higher anti-bacterial effects compared to the only O_2- or H_2O_2-injected discharge. The presence of electrical discharge creates highly intense shock waves and UV radiations, which not only destroy the DNA structure of bacteria but also cause a high dissociation rate of water molecules that generate an excess of oxidant species that are more amplified by O_2 injection and H_2O_2 addition. The presence of plasma between two water inserted electrodes causes thermal effects in water, which also plays an important role in *V. cholerae* disinfection. The plasma-treated water was observed after each 12 h by new agar plates that were preserved at −20°C, and no increase in colonies was observed.

5 Conclusions

Underwater capillary discharge is proven to be an efficient and non-toxic method of water purification from *V. cholerae*. The addition of H_2O_2 in *V. cholerae* containing water and its treatment with O_2-injected discharge at various O_2 injection rates (100–800 sccm) with a step of 100 sccm can generate large concentrations of highly

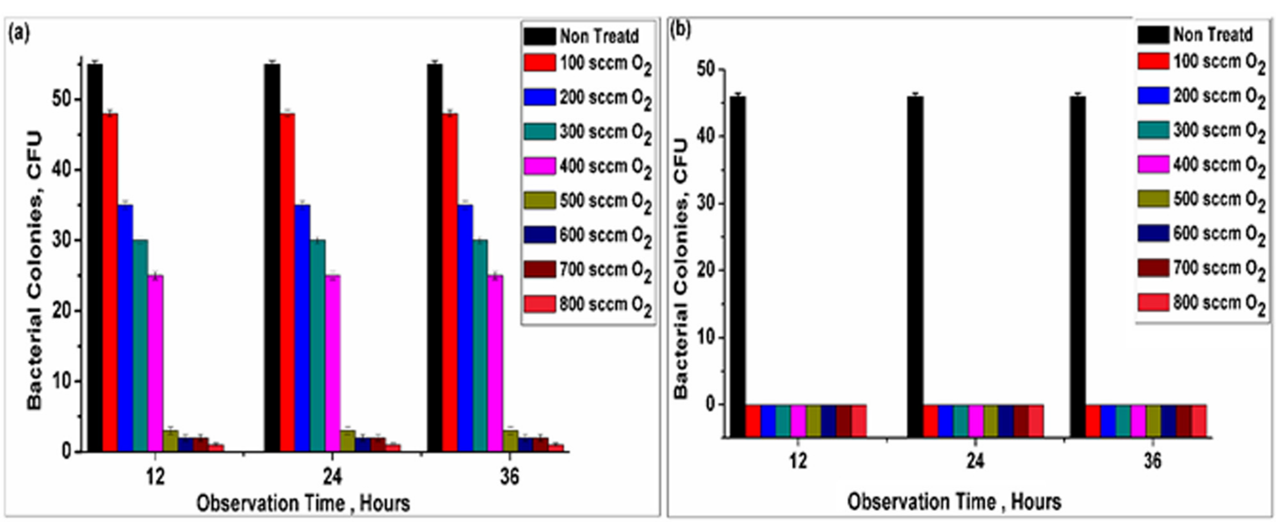

Figure 8: Retardant effect on the colony growth rate of plasma treated water observed after every 12 h up to 36 h (a) O_2 injected 0 mL/L H_2O_2 added treated samples (b) O_2 injected 0.35 mL/L H_2O_2 added treated samples.

oxidant reactive species (OH·, H_2O_2, O_3, H_α, H_β, and O); moreover UV radiations, shock waves, electrical field, and thermal effects play a vital role in sterilizing drinking water from *V. cholerae*. Complete elimination of *V. cholerae* from drinking water can be achieved by O_2 injection and H_2O_2 addition by underwater capillary discharge. This research will provide a foundation for practical applications for the sterilization of large volumes of drinking water more effectively.

Acknowledgments: The authors are thankful for funding this research by Scientific Research Deanship at the University of Ha'il – Saudi Arabia through project number RG-21 126.

Funding information: This research was funded by Scientific Research Deanship at the University of Ha'il - Saudi Arabia through project number RG-21 126.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

References

[1] Hart CA, Kariuki S. Antimicrobial resistance in developing countries. Br Med J. 1998;317(7159):647–50.
[2] Hashizume M, Armstrong B, Hajat S, Wagatsuma Y, Faruque ASG, Hayashi T, et al. Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups. Int J Epidemiol. 2007;36(5):1030–7.
[3] Pascual M, Bouma MJ, Dobson AP. Cholera and climate: revisiting the quantitative evidence. Microbes Infect. 2002;4:237–45.
[4] Osunla CA, Okoh AI. Vibrio pathogens: A public health concern in rural water resources in sub-saharan Africa. Int J Environ Res Public Health. 2017;14(10):1188.
[5] Luby SP, Rahman M, Arnold BF, Unicomb L, Ashraf S, Winch PJ, et al. Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Bangladesh: a cluster randomised controlled trial. Lancet Glob Health. 2018;6:e302–15.
[6] Huq A, Xu B, Chowdhury MA, Islam MS, Montilla R, Colwell RR. A simple filtration method to remove plankton-associated Vibrio cholerae in raw water supplies in developing countries. Appl Environ Microbiol. 1996;62(7):2508–12.
[7] Lukasik J, Cheng Y-F, Lu F, Tamplin M, Farrah SR. Removal of microorganisms from water by columns containing sand coated with ferric and aluminum hydroxides. Water Res. 2000;33(3):769–77.
[8] Craun G, Swerdlow D, Tauxe R, Clark R, Fox K, Geldreich E, et al. Prevention of waterborne cholera in the United States. J Am Water Works Assoc. 1991;83(11):40–5.
[9] Ahmed MW, Choi S, Lyakhov K, Shaislamov U, Mongre RK, Jeong DK, et al. High-frequency underwater plasma discharge application in antibacterial activity. Plasma Phys Rep. 2017;43(3):381–92.
[10] Maho T, Binois R, Brulé-Morabito F, Demasure M, Douat C, Dozias S, et al. Anti-bacterial action of plasma multi-jets in the context of chronic wound healing. Appl Sci. 2021;11(20):9598.
[11] Sakudo A, Misawa T. Antibiotic-resistant and non-resistant bacteria display similar susceptibility to dielectric barrier discharge plasma. Int J Mol Sci. 2020;21:6326.
[12] Bekeschus S, Favia P, Robert E, von Woedtke T. White paper on plasma for medicine and hygiene: Future in plasma health sciences. Plasma Process Polym. 2019;16(1):1800033.
[13] Gavahian M, Sarangapani C, Misra NN. Cold plasma for mitigating agrochemical and pesticide residue in food and water: Similarities with ozone and ultraviolet technologies. Food Res Int. 2021;141:110138.
[14] Hong YC, Park HJ, Lee BJ, Kang W-S, Uhm HS. Plasma formation using a capillary discharge in water and its application to the sterilization of E. coli. Gene Ther. 2010;17:53–502.
[15] Sein MM, Nasir ZB, Telgheder U, Schmidt TC. Studies on a nonthermal pulsed corona plasma between two parallel-plate electrodes in water. J Phys D: Appl Phys. 2012;45(22):225203.
[16] Ahmed MW, Yang JK, Mok YS, Lee HJ, Yu YH. Underwater capillary discharge with air and oxygen addition. J Korean Phys Soc. 2014;65(9):1404–13.
[17] Takeuchi N, Ishibashi N, Sugiyama T, Kim H-H. Effective utilization of ozone in plasma-based advanced oxidation process. Plasma Sources Sci Technol. 2018;27(5):055013.
[18] Cortez S, Teixeira P, Oliveira* R, Mota M. Evaluation of Fenton and ozone-based advanced oxidation processes as mature landfill leachate pre-treatments. J Env Manage. 2011;92(92):749–55.
[19] Hwang I, Jeong J, You T, Jung J. Axial load transmission through the elbow during forearm rotation. Biotechnol Biotechnol Equip. 2018;32(2):530–4.
[20] Ehlbeck J, Schnabel U, Polak M, Winter J, von Woedtke Th, Brandenburg R, et al. Low temperature atmospheric pressure plasma sources for microbial decontamination. J Phys D: Appl Phys. 2010;44:013002.
[21] Vijayarangan V, Delalande A, Dozias S, Pouvesle JM, Robert E, Pichon C. New insights on molecular internalization and drug delivery following plasma jet exposures. Int J Pharm. 2020;589:119874.
[22] Vijayarangan V, Delalande A, Dozias S, Pouvesle JM, Pichon C, Robert E. Cold atmospheric plasma parameters investigation for efficient drug delivery in HeLa cells. IEEE Trans Radiat Plasma Med Sci. 2017;2(2):109–15.
[23] Leduc M, Guay D, Leask RL, Coulombe S. Cell permeabilization using a non-thermal plasma. N J Phys. 2009;11:115021–33.
[24] Robert E, Darny T, Dozias S, Iseni S, Pouvesle JM. New insights on the propagation of pulsed atmospheric plasma streams: From single jet to multi jet arrays. Phys Plasmas. 2015;22:122007.

[25] Dozias S, Pouvesle JM, Robert E. Comment on ‘Mapping the electric field vector of guided ionization waves at atmospheric pressure’, (2020) Plasma Res. Express 2 025014. Plasma Res Express. 2021;3(3):038001.
[26] Obradović BM, Ivković SS, Kuraica MM. Spectroscopic measurement of electric field in dielectric barrier discharge in helium. Appl Phys Lett. 2008;92(19):191501.
[27] Moeini I, Ahmadpour M, Gorji NE. Modeling the instability behavior of thin film devices: Fermi Level Pinning. Superlattices Microstruct. 2018;117:399–405.
[28] Liu Z, Fan B, Zhao J, Yang B, Zheng X. Benzothiazole derivatives-based supramolecular assemblies as efficient corrosion inhibitors for copper in artificial seawater: Formation, interfacial release and protective mechanisms. Corros Sci. 2023;212:110957.
[29] Jin HY, Wang ZA. Global stabilization of the full attraction-repulsion Keller-Segel system. Discret Contin Dyn Syst- Ser A. 2020;40(6):3509–27.
[30] Li H, Peng R, Wang Z. On a diffusive susceptible-infected-susceptible epidemic model with mass action mechanism and birth-death effect: analysis, simulations, and comparison with other mechanisms. SIAM J Appl Math. 2018;78(4):2129–53.
[31] Liu Q, Peng H, Wang Z. Convergence to nonlinear diffusion waves for a hyperbolic-parabolic chemotaxis system modelling vasculogenesis. J Differ Equ. 2022;314:251–86.
[32] Guo W, Luo H, Jiang Z, Fang D, Chi J, Shangguan W, et al. Ge-doped cobalt oxide for electrocatalytic and photocatalytic water splitting. ACS Catal. 2022;12(19):12000–13.
[33] Liang Y, Li J, Xue Y, Tan T, Jiang Z, He Y, et al. Benzene decomposition by non-thermal plasma: A detailed mechanism study by synchrotron radiation photoionization mass spectrometry and theoretical calculations. J Hazard Mater. 2021;420:126584.
[34] Huang Z, Chen Z, Qayum A, Zhao X, Xia H, Lu F, et al. Photocatalytic degradation of organic pollutants by MOFs based materials: A review. Chin Chem Lett. 2021;32(10):2975–84.
[35] Xiang X, Wu L, Zhu J, Li J, Liao X, Huang H, et al. Photocatalytic degradation of sulfadiazine in suspensions of TiO_2 nanosheets with exposed (001) facets. Chin Chem Lett. 2021;32(10):3215–20.
[36] Yan YT, Wu G, Chen SC, Wang YZ. Synthesis and characterization of poly(p-dioxanone)-based degradable copolymers with enhanced thermal and hydrolytic stabilities. Chin Chem Lett. 2022;33(4):2151–4.
[37] Foster JE, Mujovic S, Groele J, Blankson IM. Towards high throughput plasma based water purifiers: Design considerations and the pathway towards practical application. J Phys D: Appl Phys. 2018;51(29):293001.
[38] Bruggeman P, Schram D, González MÁ, Rego R, Kong MG, Leys C. Time dependent optical emission spectroscopy of sub-microsecond pulsed plasmas in air with water cathode. Plasma Sources Sci Technol. 2009;18:027017.
[39] Montgomery JM. Water treatment principles and design. New York: Wiley; 1985.
[40] Eisenberg G. Colorimetric determination of hydrogen peroxide. Ind Eng Chem Anal. Ed. 1943;15(5):327–8. doi: 10.1021/560117a011.