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ORIGINAL PAPER

Electric current induced bacterial inactivation in seawater: effects of various operating conditions

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Abstract

Conventional water disinfection processes suffer from several disadvantages including safety and handling issues and may result in the formation of undesirable and often harmful by-products. Novel disinfection methods, such as the application of low electric current, may present more practical, viable, and sustainable processes. The present study investigates the effects of applying a low-intensity (0.1–1.0 A) direct electric current for short durations (5–30 s) on the inactivation of different bacteria in seawater. The effects of distance between electrodes (5, 10, 15 cm), pH of seawater (6, 8, 10), and operating temperature (10, 20, 30 °C) on the inactivation process are examined. The sole effect of electric current on the inactivation of bacteria, as opposed to the combined effects of current and chlorine generated by seawater electrolysis, was a set study objective. The results show that inactivation of bacteria is achieved at different rates reaching values of 100%. The level of inactivation was found to be influenced by current intensities, application times, bacteria, and distances between electrodes. The results also show that pH and temperature, within the ranges investigated, have an insignificant impact on the inactivation process. Scanning electron microscope imagery revealed inactivation to be the result of bacterial cell wall damage.

Keywords Bacterial inactivation · Scanning electron microscope · Direct current · Batch experiment

Introduction

Bacterial inactivation is an indispensable process in water treatment. In this context, several disinfection processes have been used, which include the use of halogens such as chlorine (Plewa et al. 2002), ozone, and ultraviolet light (Chin and Bérubé 2005). Each of these processes has limitations whether in terms of the type and quantities of the chemicals used, the nature and impact of the oxidation by-products, the lack of residual disinfectant, and the elevated costs associated with the use of one or any of the processes (Richardson et al. 2000).

The use of electric current in bacterial inactivation has been studied in limited, sporadic, and arbitrary manner. There are several gaps in the literature, which include the impact of electric current on the inactivation of different bacterial species under the same operating conditions and on the influence of various process parameters on the inactivation process. In this context, several of the studies conducted using a variety of applications are summarized in Table 1. These studies have employed various types of water (tap water, seawater, and chemically induced solutions) (Bergmann et al. 2002; Kerwick et al. 2005); several operating modes (batch and flowing with varied volumes and flow rates, respectively) (Gusmao et al. 2009; Gusmão et al. 2010); investigated different types of electric current (alternating and direct), current intensities [from low (mA) to high values (> 10 A)], and varying current application periods (ms to multiple hours); utilized limited species of specific bacteria (*Escherichia coli*, *Proteus species*, *Saccharomyces cerevisiae*, *Streptococcus faecalis*, *Staphylococcus aureus*); and used different electrode materials (platinum, stainless steel, titanium, copper, graphite, and combinations thereof)

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Table 1 Summary of studies on bacterial inactivation using electric current

Author name (date)	Volume of sample	Type of water	Current range	Types of bacteria	Exposure time	Electrodes material	AC/DC
Patermarakis and Fountoukidis (1990)	350 ml	Natural contaminated water	125–250 mA	Coliform bacteria, fecal Streptococci	5-min successive intervals	Titanium	DC
Matsunaga et al. (1992)	5 ml	Drinking water	NA	*E. coli*	10-min exposure	Carbon cloth	DC
Bergmann et al. (2002)	NA	Drinking, waste, and feeding waters	0–0.35 A	*E. coli*	0–35 min	Platinum electrodes (with activated titanium)	DC
Jorquera et al. (2002)	Flow 4L/min	Seawater	0.1–2 A	*Vibrio anguillarum*		prototype seawater electrolyzer	AC/DC
Dunlop et al. (2002)	100 micro L aliquots	Drinking water	NA	*Cryptosporidium*, *E. coli*	0–60 min	Prototype seawater electrolyzer TiO_2 electrodes	DC
Li et al. (2002)	265 ml	Saline wastewater Freshwater	0–2.5 A	Total coliforms	10–20 s	Electrochemical disinfector with stainless steel cathode and titanium anode	DC
Guillou and El Murr (2002)	51 ml	Phosphate buffer	0.1–1 A	Saccharomyces cerevisiae (Yeast)	1547–140 min	Platinum (20 mm apart)	DC
Drees et al. (2003)	250 ml	Buffer solution	25–350 mA	*E. coli* and *P. Aeruginosa*	5 s bursts	Platinum-tipped copper wire electrodes (5 cm apart)	DC
	5 ml	Seawater	1.5 mA to 2 A	*Vibrio parahaemolyticus*	100 ms	Platinum electrodes (10 mm apart, 10 mm wide and 80 mm long)	DC
Park et al. (2004)	Flow	Double-distilled water with NaCl	7.4–7.69 A	NA	NA	NA	DC
	Flow—850 mL/min	Seawater	NA	*Vibrio parahaemolyticus*		Titanium pipe and rod coated with 1 µm thickness of platinum	AC
	Flow—87 mL/min	Saline solution	4 mA/cm^2	*E. coli*	120 min	Anodes: 2 platinum clad niobium mesh Cathodes: 2 steel	DC
Park et al. (2004)	200 ml	Brine solution	0.5 A	Lipase, protease, and halophilic bacteria	30 min max	Platinum wire electrodes (1 mm diameter and 80 mm long separated by 40 mm)	DC
	150 ml	Phosphate buffer solution	0.1–100 mA/cm^2	*E. coli*	180 min	Anode: platinum Cathode: graphite rod (40 mm apart)	DC
Kerwick et al. (2005)	5 ml	Drinking water	1–10 mA cm^2	*Microcystis aeruginosa*	52 min	Ti/RuO_2 electrodes	DC
Birbir and Birbir (2006)	NA	Drinking water	NA	*Legionella*, *E. coli*, *P. Aeruginosa*	52	Carbon electrodes with diamond film	DC
Jeong et al. (2007)	NA	Wastewater	NA	NA	NA	Platinum electrodes	DC

Table 1 (continued)

Author name (date)	Volume of sample	Type of water	Current range	Types of bacteria	Exposure time	Electrodes material	AC/DC
Valle et al. (2007)	NA	Multiple sources	NA	NA	NA	Platinum group metal oxide electrodes	AC/DC
Liang et al. (2005)							
Martinez-Huitle and Brillas (2008)	200 ml	Sea and river waters	1, 1.5, 2A	*E. coli* and Fecal *E. coli*	35 min	Platinum wire electrodes (1 mm diameter, 8 mm length, 40 mm apart)	AC
Kraft (2008)	3 L	Artificially stained saline solutions.	1, 2 and 3 A	*E. coli*	60 min	Anode: titanium coated with an oxide layer of 70% TiO_2 and 30% RuO_2—Cathode: stainless steel	DC
	NA	Brackish and ballast water	0–10 A	*E. coli*	<5 min.	Diamond anode	DC
	320 ml	Tap water	0.1, 0.5, 0.9 A	*E. coli*		Ceramic electrodes containing non-stoichiometric titanium oxide	DC
Birbir et al. (2013)	200 ml	Saline solutions	0–1257 μA/m^2	Gram negative (*E. cloacae*, *V. fluvialis* and *P. luteola*), Gram positive (*S. cohnii* and *E. faecium*), etc.	16 min	Platinum wire electrodes (1 mm diameter, 80 mm long, 40 mm apart)	AC/DC
Gusmão et al. (2010)	Flow—200 mL/min	Seawater		*Vibrio alginolyticus*, *Edwardsiella tarda*, *Lactococcus garvieae* and *Vibrio anguillarum*	3 h	Honeycombed platinum-coated titanium electrodes	DC
Reimanis et al. (2013)	Batch	Brackish and ballast water	0–10 A	*E. coli*	Less than 5 min		DC
	3 L	Artificially stained solution	10 mA	*Staphylococcus aureus*, *Pseudomonas Aeruginosa*	2 h and 2.5 h, respectively	Copper electrodes (6 cm apart)	AC
Huang et al. (2013)	40 L	Wastewater	NA	*E. coli*, *Enterococcus*, Bacteriophage MS2	60 mim	Boron-doped diamond electrodes	DC
Cossali et al. (2016)	Flow	Tap water	2.8–13.5 mA/cm2	*E. coli* Legionella, Pseudomonas	10–45 min	Titanium electrodes	DC

(Tanaka et al. 2013; Mirzaii et al. 2015). The vast majority of these studies reported an acceptable level of bacterial inactivation, which is encouraging in terms of the potent use of this method for destroying bacteria and other microorganisms when present in water of different characteristics and operating conditions.

The experimental applicability of the process using samples of small water quantities in the range of milliliters, very low (< 1 mA) or very high (10 A) current intensities, and very low or very high application periods in the range of milliseconds up to hours could lead to results that are deemed impractical. A large majority of the studies conducted to date have employed electrochemical disinfection where the generation of chlorine was the major component effecting inactivation. In this context, it is worth mentioning that significant quantities of free chlorine as related to their bactericidal effect may be generated as a result of electrolysis of seawater. Jorquera et al. (2002) reported values amounting to 0.39–2.13 mg/L of chlorine being generated at current intensities ranging between 0.3 and 1.3 A and concentrations of 2.95–6.5 mg/L generated at 1.5–2.0 A, without reporting the time frame at which these concentrations were achieved. Such elevated concentrations could lead to relatively high residuals that will negatively impact the ultimate use of the water or may lead to the production of halomethanes when interacting with the natural organic materials present in seawater (Barrett et al. 2000). Furthermore, it is worth noting that inactivation in the absence of chlorine provides a solution to conditions where chlorine poses a negative impact on the durability of the process adopted in the treatment of water, such as membranes in reverse osmosis (RO) treatment (Kang et al. 2007). Also the elimination of chlorine will induce sustainability of the RO process as it will eliminate a costly unit that is presently used in pre-treatment processes, such as activated carbon adsorption, which is used solely for the purpose of removing residual chlorine before it reaches the membranes.

The viability and sustainability of using electric current for disinfection have been enhanced with the expanding deployment of renewable energy sources which may render this approach to be highly competitive when compared to the aforementioned disinfection methods (Chin and Bérubé 2005). In addition, this approach will eliminate the use of chemicals and their concomitant negative impacts such as the formation of harmful by-products.

In this study, tests conducted on the application of relatively low direct electric current intensities ranging between 0.1 and 1 A for relatively short application periods (5–30 s) to bacterially infested seawater inoculated with raw sewage were evaluated. The effect of various operating conditions, including the intensity of the electric current, application time, distance between electrodes, temperature, and pH, on the inactivation of bacteria was studied. The paper is set to investigate inactivation that is predominantly a consequence of the effect of the electric current rather than that effected by chlorine generated as a result of electrolysis of seawater. The research was carried out at the American University of Beirut, Lebanon, starting on August 2017 and over a period of 8 months.

Materials and methods

Experimental setup

Experiments were conducted in a batch mode using 19.5 cm internal diameter (I.D.), 11 cm deep cylindrical Plexiglas containers, each with a water capacity of 2.4 L (Fig. 1).

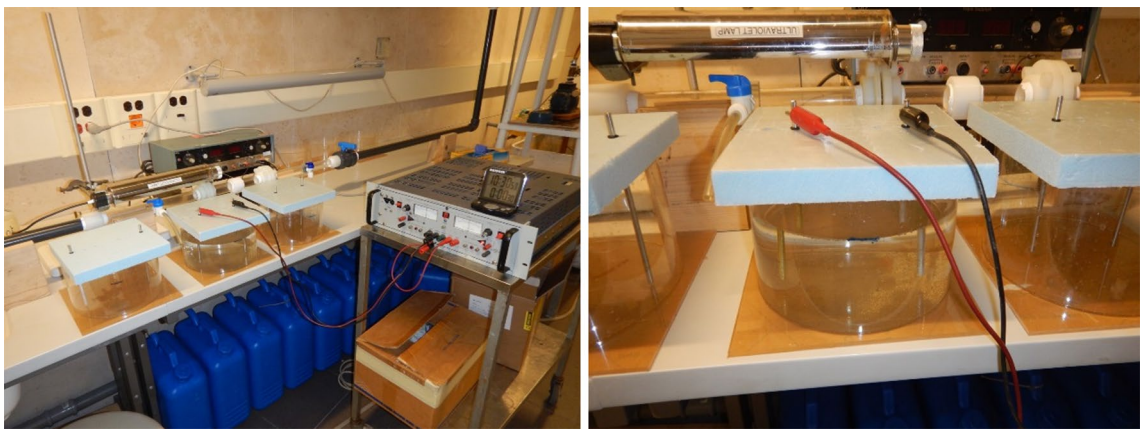


Fig. 1 Experimental setup

Experimental procedure

Seawater was collected in 20-L containers from the beach at the American University of Beirut, filtered, and stored in the feed tank at room temperature for later use. The maximum sample holding time was set at 4 days to avoid variations in the chemical composition of the collected seawater. The characteristics of the sea water tested using Standard Methods (Rice 2012) are presented in Table S1. On preparation for testing, predetermined quantities of sewage (20 ml per 2.4 L) enough to produce relatively high bacterial concentrations that can be statistically evaluated were added to the seawater sample. The electrodes used were made of 15-cm-long (8 cm submerged section), 5-mm-diameter stainless steel bars fixed at distances of 5, 10, and 15 cm apart. Tests related to the effects of current intensity and application time were conducted by the application of an array of different currents (0.1, 0.5, 0.75, and 1.0 A) and time durations (5, 10, 15, 20, 25, and 30 s). Caution was exercised in insuring that inactivation was solely due to the effect of the electric current and not by the subsequent production of chlorine gas through electrolysis of the seawater. In this context, continuous measurement of residual chlorine in the reactor water was conducted using a HACH DR 3900 spectrophotometer in order to establish the time at which chorine is generated and the rate of increase in concentration with time. Tests were also performed to determine the impact of temperature and pH on the inactivation process. For this purpose, tests were conducted at temperatures of 10, 20, and 30 °C at a pH of 8. Tests were also conducted at pH values of 6, 8, and 10 at a temperature of 20 °C. It should be noted that tests at lower and higher pH values than those reported above were not carried out, as it is well reported that operation at pH values < 5 and pH values > 10 will lead to bacterial inactivation (Ayoub et al. 1999). Variation in pH was achieved by adding measured quantities of either 1 N NaOH or 0.12 N HCl for increasing or lowering the pH, respectively. The variation in temperature was achieved by adding aliquots of preheated seawater to the reactor, monitoring the temperature, adjusting the volume in the reactor to 2.4 L, followed by the addition of 20 mL wastewater. Lower temperatures were attained by pre-immersing ice packs, followed by the addition of wastewater.

Electrical power was supplied through a 220 V/50 Hz input rated KEPCO power supply, Model BOP 200-1 M, Flushing, N.Y., that provides a direct current output ranging between 0.1 and 1 A. The resistance of seawater was established to be 100 ohms which results in a voltage range of 10–100 V.

Bacteria tested

Inactivation studies were conducted on two bacterial groups, namely total coliforms (TC) and fecal coliforms (FC); three species including *Escherichia coli* (E. coli), *Enterococcus faecalis* (EF), *Pseudomonas aeruginosa* (PA); and one genus Streptococcus (S).

Methodology

Three reactors were used simultaneously to carry out the tests with electrodes spaced at 5, 10, and 15 cm, respectively. After filling the reactors with the test water, the current was applied at the set intensities (0.1, 0.5, 0.75, and 1.0 A) and 100-mL samples were withdrawn at every current application time interval (5, 10, 15, 20, 25, and 30 s) and transferred to sterilized cups to be tested for both chlorine residuals and bacterial concentrations.

The membrane filtration technique (MF) was employed to determine the bacterial counts using the appropriate substrate for each bacterial culture tested. In this context, the procedures adopted in testing were APHA 9222H for TC and E-coli, APHA 9222D for FC, APHA 9213E for PA, and APHA 9230C for EF and S. The agars used included Chromocult Coliform Agar (MERK), mFC broth base (Difco), Pseudomonas CFC/CN Agar (MERK), KF Streptococcus Broth (Difco), and m-Enterococcus Agar (Difco).

The mechanism by which inactivation is effected on the bacteria was studied through a comparative evaluation of the change in the bacterial morphology by comparing images of the bacteria before and after inactivation, using scanning electron microscope (SEM) (MIRA 3 LMU with OXFORD EDX detector) by TESCAN, Czech Republic.

All experiments were conducted in triplicates.

Analytical procedures

Upon calculating the percentage inactivation for the bacterial contaminants, statistical analysis was conducted using the statistical software Minitab 16, produced by Minitab Inc. State College, PA., to assess the effect of the proposed treatment on inactivation efficiency. One-way ANOVA was performed to evaluate the separate impact of the various parameters including time, current, spacing between electrodes, pH, and temperature, while two-way ANOVA allowed the assessment of the combined effect of these parameters.

Results and discussion

Chlorine generation with different current intensities and application time

To establish the effect of chlorine that is generated due to electrolysis of seawater, a series of tests were conducted to determine the variation in chlorine concentration attained with current application time at different current intensities (Fig. 2).

The results indicate that at the specified experimental current intensities (0.1–1 A) and current application durations (5–30 s), the concentrations of chlorine generated remain below 0.05 mg/L. This value does not have an impact on bacterial inactivation as the literature indicates a minimum of 0.2 mg/L of free residual chlorine is required (Blokker et al. 2014; Collivignarelli et al. 2018). Furthermore, the applied contact time is too short for a reaction to take place between the bacteria and the chlorine generated, as the recommended contact time is between 15 and 30 min (Collivignarelli et al. 2018). Consequently, the inactivation results should be attributed to the effect of the electric current rather than chlorine disinfection. However, the possibility of an early formation of free radicals could play a role in the inactivation process (Li et al. 2002).

Inactivation of bacteria

The results of the inactivation tests conducted are summarized in Table 2. A complete set of the data obtained from the experimental results are presented in Tables S2–S7 of the supplementary material. It should also be noted that data presented in these tables include the standard deviations as well as the standard errors.

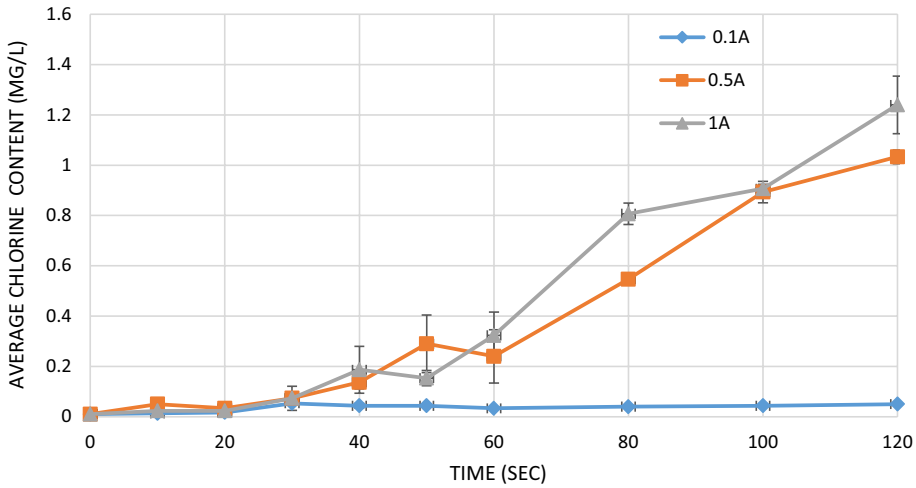


Fig. 2 Average* chlorine content with application time at different currents intensities. * Average of three tests

Table 2 Percent[a] bacterial inactivation with electrode distance, current intensity, and application time

Distance (cm)	Current (A)	Time (s)	Bacterial inactivation (%)					
			F.C.	T.C.	*E. coli*	EF	PA	S
5	0.1	5–30	55–79	39–60	44–69	90–94	19–71	9–73
10	0.1	5–30	65–85	57–91	46–71	79–87.5	41–94	4–72
15	0.1	5–30	84–99.4	71–95	83–93	96–98	40–97.2	19–83
5	0.5	5–30	84–100	69–93	80–98	91–98	41–94	34.5–86
10	0.5	5–30	91–100	71–99.6	87–100	94–99.6	43–95	36–86
15	0.5	5–30	98–100	87–99.7	87–100	95–99.4	45–97.8	32–90
5	0.75	5–30	99–100	77–99	68–100	91–100	43–98	33–94
10	0.75	5–30	99–100	92–99.8	87–100	96–100	54–98	30–93
15	0.75	5–30	83–100	95.4–99.7	94–100	96–100	52–99.6	40–95.5
5	1	5–30	97–100	93–100	81–100	93–100	48–98	44–97
10	1	5–30	99–100	93–99.9	85–100	96.7–99.5	56–99	35–96.5
15	1	5–30	98.2–100	95–100	91–100	96.5–100	66–99.9	55–98

[a]Average of three readings

Table 2 depicts the levels of inactivation of the bacteria at the minimum and maximum current application periods, current intensities, and electrodes spacing. The results are very consistent in showing that inactivation is directly related to all three parameters, where inactivation increases with current application time and with the increase in current intensities, as well as with the increase in electrode spacing. This is in agreement with the results reported by Gusmao et al. (2009), indicating that inactivation of *E. coli* and *S. aureus* increased with time and current intensity. However, the current application period in the referenced study varied between 30 and 60 min. With regard to the spacing effect, this may be attributed to the widening of the landscape that results within the reactor as distances between the electrodes increase.

Furthermore, the results indicate that very high levels of inactivation, reaching 100% at 30 s, and in some cases between 5 and 30 s of current application, and a current intensity of 0.5–1 A, can be achieved under the selected parametric ranges. The most vulnerable of the bacteria to the effect of the electric current includes the FC and EF, and this high inactivation in a short period of time (5 s) is not surprising as the literature has indicated high removal of these bacteria at lower contact times (Ghasemian et al. 2017). *Escherichia coli* and TC were found to be less vulnerable, and PA and S the least vulnerable. However, relatively high inactivation levels can still be attained with all of these bacterial types.

Li et al. (2002) reported a 99.9% kill efficiency for TC in saline wastewater subjected to a current ranging between 0 and 2.5 A for a period of less than 20 s, with chlorine being discounted as the inactivating agent. Also Gusmao et al. (2009) reported complete inactivation for *S. aureas* in an artificially contaminated saline solution at a current of 3A and an application time of 30 min and a 98% inactivation for *E. coli* at 3 A and 60 min application time with lower inactivation levels amounting to 50% and 90% at 1 A and 2 A, respectively. Inactivation was not caused by chlorine since the electrolytic medium did not contain any chloride ions.

Further comparison of the results with previous studies was not possible as the experimental conditions used in this work are very different from those reported in the open literature.

The results of the statistical analyses conducted on the effect of time, current intensity, and electrode distance by running ANOVA at 95% confidence and $\alpha = 0.05$ showed p values of less than 0.05, which implies that all three parameters had a significant effect on the inactivation of bacteria. The combined effect of distance and current intensity using ANOVA also provided evidence that at 95% confidence interval and $\alpha = 0.05$ to support the claim that there is significant effect imposed by the variation of these parameters.

Kinetics of bacterial inactivation

Figure 3a–c depicts the rates at which inactivation of the different bacteria is effected at several current intensities and electrode spacing.

The graphs indicate that high rates of inactivation are achieved in a short period of time (less than 5 s) and tend to level off beyond this period to reach inactivation levels close to or equal to 100%. This trend is consistent at current intensities of 0.5 A and up to 1.0 A. This trend is also invariably noted at the different electrode spacing where increased rates of inactivation are depicted at increased spacing. At a current intensity of 0.1 A, lower inactivation rates are recorded at the start, leading in some cases to limited inactivation at the end of the application period. However, electrode spacing seems to have a positive effect on the inactivation rate at this current intensity, leading to inactivation levels that are similar to those attained at the higher current intensities. As stated earlier, this effect could be attributed to the widening of the landscape between the electrodes as distances are increased.

This trend is consistent for the studied bacteria except for PA and S where the rates tend to be lower at the initial application periods and current intensities and tend to maintain a reduced rate with current application time and current intensities, leading to inactivation levels approaching 100% at the 30 s application period.

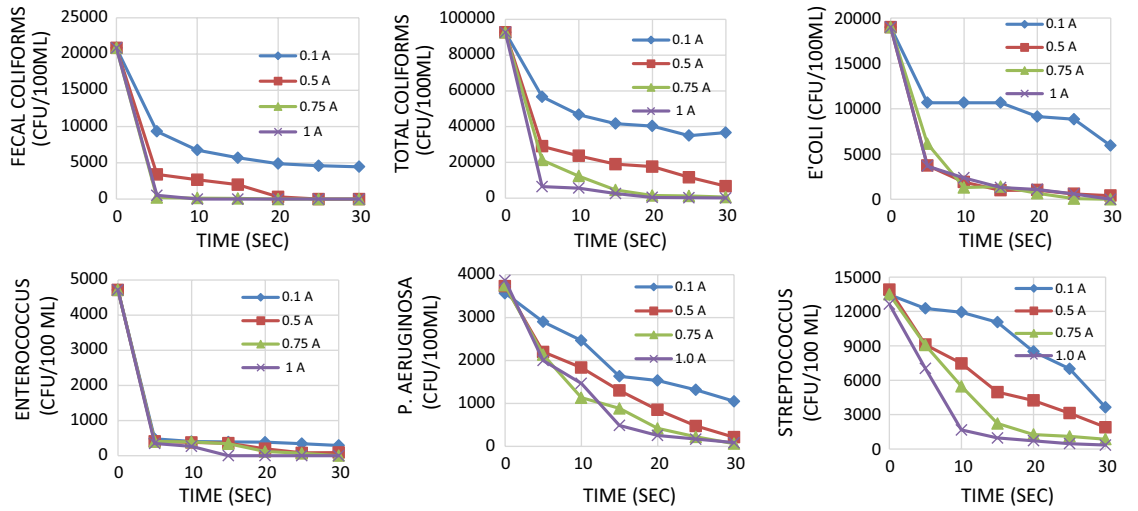
Based on the foregoing results, it may be concluded that improved inactivation rates at shorter application periods for the more resistant bacteria may be achieved by an increase in current intensity.

Effects of temperature and pH on the inactivation process

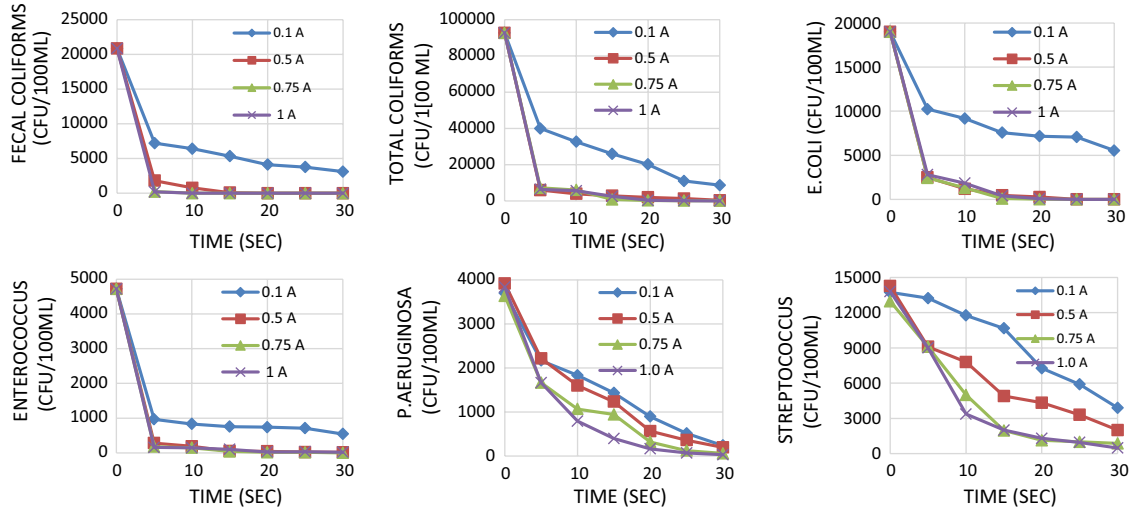
Tabulated results of the effects of temperature and pH on the inactivation process are presented in Tables S8–S 13 of the supplementary material. Also to be stated is that no change was noted in the temperature and pH during the course of the experiments. This was the case for studies that were reported when operating at relatively low currents (Bergmann et al. 2002) and low application periods (Li et al. 2002).

Figure 4 depicts the effect of temperature on bacterial inactivation. The curves indicate that within the range investigated, which is the normal practical operating range, temperature does not induce any effect on the inactivation of all bacteria considered in this study. It is to be noted that if lower or higher temperatures were to be investigated, some effect would be recorded, as at low and high temperatures bacteria would either cease activity or be destroyed, respectively.

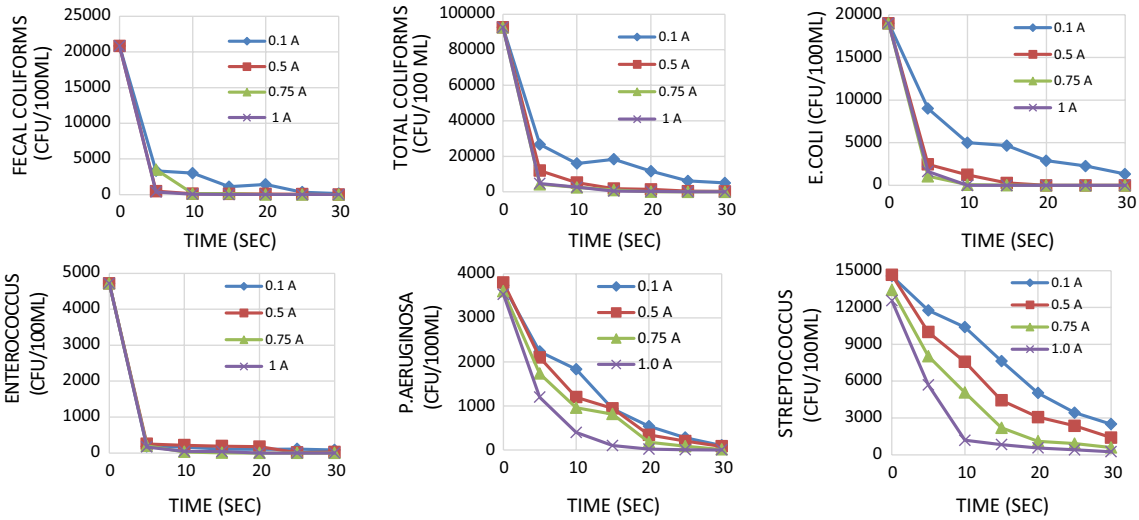
It is also noted from Fig. 5 that pH within the practical range investigated (6–10) also does not show any effect on



(a) 5-cm electrode spacing



(b) 10-cm electrode spacing



(c) 15-cm electrode spacing

Fig. 3 Kinetics of bacterial inactivation at different current intensities. **a** 5-cm electrode spacing, **b** 10-cm electrode spacing, **c** 15-cm electrode spacing

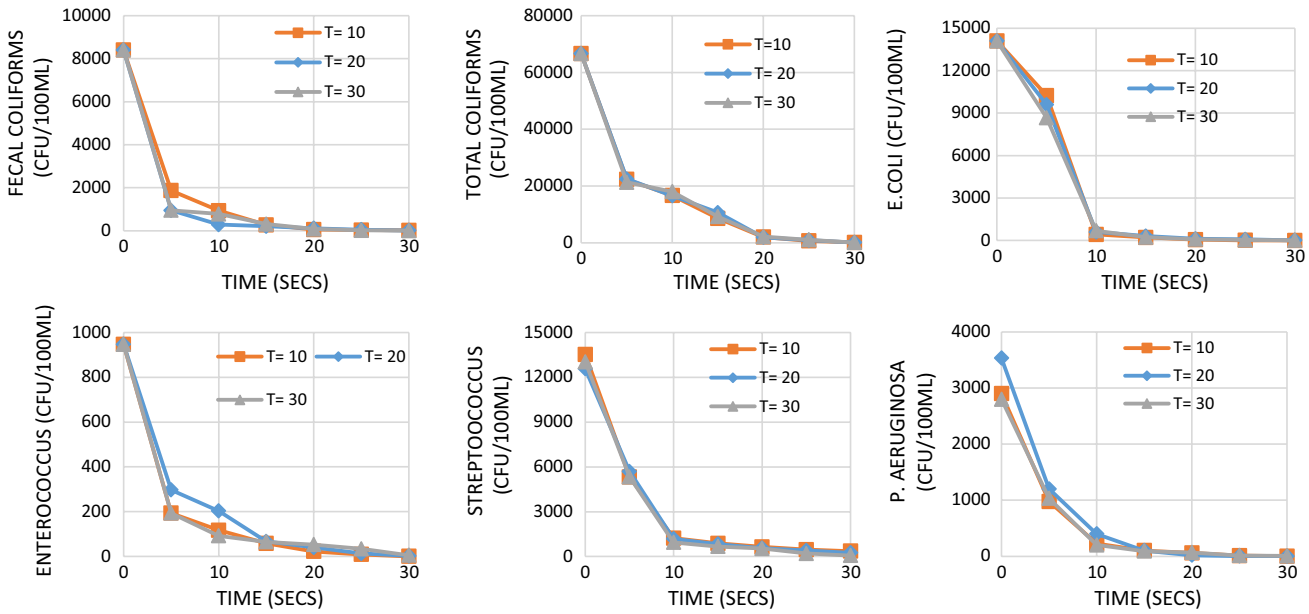


Fig. 4 Effect of temperature variation at pH 8 (distance of electrode = 15 cm, current intensity = 1 A)

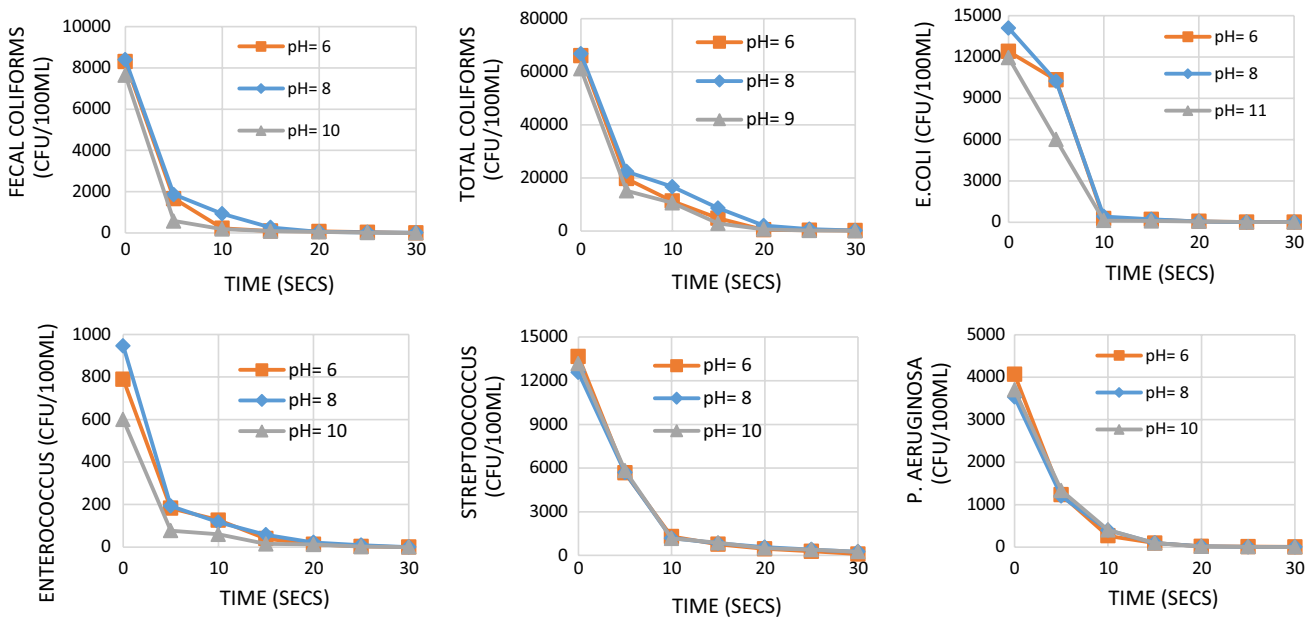


Fig. 5 Effect of pH variation at temperature 20 °C (distance of electrodes = 15 cm, current intensity = 1 A)

the inactivation of the various bacteria examined. Again if tests were to be conducted at pH values < 5 and > 10, a definite effect would be noted since at these pH values bacteria could be inactivated (Ayoub et al. 1999).

These results are further confirmed through statistical analysis by running two-way ANOVA on the effect of temperature and pH on the percent inactivation of the bacteria which returned p values greater than 0.05, and thus at 95% confidence and $\alpha = 0.05$ both the effects of temperature and pH were deemed insignificant.

Various mechanisms, most of which remain unsubstantiated, have been reported by various studies as being responsible for bacterial inactivation using an electric current. Matsunaga et al. (1992) attributed inactivation of *E. coli* to oxidizing substances in the form of free radicals or some metal ions formed as the electric current passes through the

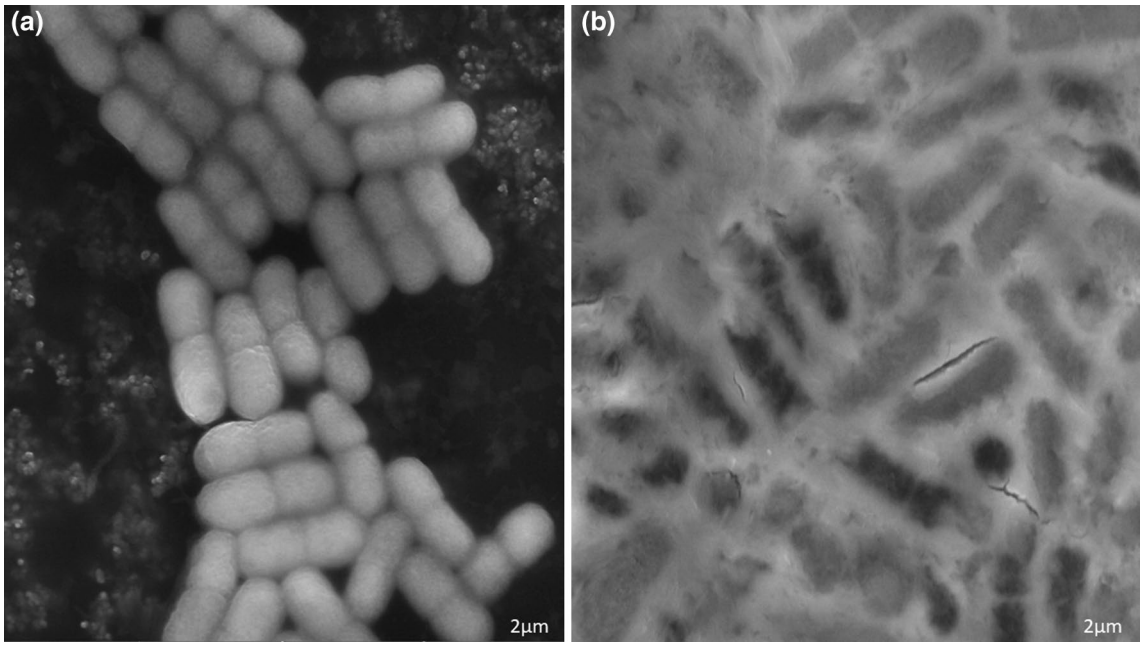


Fig. 6 SEM of untreated (**a**) and treated (**b**) cells in seawater. Images are a result of treatment with 0.5 A for 10 s

medium, while Li et al. (2002) hypothesized inactivation to be due to short-lived powerful germicidal substances that exert a strong killing function with a short contact time such as O_2^-, HO^-, $HClO^-$, and ClO_2^-. Gusmao et al. (2009) reported bactericidal effect to be due to hydroxyl ions and cellular lyses due to electroporation in cell membrane resulting from high electric fields at electrode surface causing bacterial cell damage. Lacasa et al. (2013) also attributed inactivation to the direct oxidation on the surface of the conductive anode. Drees et al. (2003) attributed inactivation to electrochemically generated oxidants, irreversible permeabilization of cell membranes, and electrochemical oxidation of vital cellular constituents during exposure to electric current. Ghasemian et al. (2017) reported that electrochemically generated reactive oxygen species (ROS) (e.g., hydroxyl radicals, hydrogen peroxide, ozone) and reactive carbonyl species (RCS) (e.g., Cl_2, HOCl, ClO^-) were mainly responsible for inactivation of bacteria at high and low current densities, respectively. On the other hand, Park et al. (2004) reported inactivation to be due to substantial structural damage at the cellular level where irreversible cell membrane rupture is noted at a number of locations with leakage of intracellular content. Birbir et al. (2009) referred to the disruption of bacterial membrane integrity and electrolysis of molecules on cell surfaces as being the main cause of inactivation. This diversity in the reported mechanisms may be explained by the difference in testing conditions and procedures used to carry out the respective studies.

Following a negative staining procedure and the isolation of E. coli, the change in morphology before and after application of treatment process as determined by SEM is exhibited in Fig. 6, which confirms the hypothesis of structural damage in the cell wall where fissures noted in the figure are indicative of cell lysis and consequently bacterial inactivation. Furthermore, it is also possible that fast acting toxic by-products which may be generated in the form of free radicals might have contributed to the inactivation process; however, this was not investigated in the present study.

Conclusion

The results of the present study demonstrate that inactivation of bacteria is viable through the application of a low-intensity direct electric current. The conclusions arrived at are presented as follows:

1. At a current intensity ranging between 0.1 and 1 A and an application period of 5 to 30 s, bacterial inactivation levels > 90% and up to 100% may be attained.

2. Electric current inactivation displays different impacts on different bacteria.
3. Inactivation rates are directly related to current intensity, application period, and distance between electrodes.
4. At the current intensities and application periods, studied inactivation rates are not affected by temperature variation in the range of 10–30 °C, and pH variations of 6–10.
5. Inactivation of bacteria by an electric current is effected through a morphological change exhibited by the destruction (rapture) of the bacterial cell wall.

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