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Evaluation of anti-microbial activities of silver nanoparticles embedded in capacitive deionization electrodes

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ABSTRACT

In this study, silver nanoparticles (Ag-n) embedded in activated carbon (AC) electrodes were evaluated for anti-microbial activities against *Escherichia coli* and *Salmonella enteritidis*. The novel AC/Ag-n capacitive deionization electrodes were fabricated for high-performance desalination and disinfection of brackish water. The AC/Ag-n electrodes were prepared by mixing AC powder together with Ag-n and characterized by scanning electron microscope, Fourier-transform infrared spectroscopy and Brunauer–Emmett–Teller which affirm the formation of disinfecting electrode material. The desalination and disinfection performances of the fabricated electrodes were evaluated by carrying out batch mode experiment with cell potential of 2 V for 180 min (3 h). The AC/Ag-n CDI electrodes achieved 100% of *E. coli* and 98% *S. enteritidis* removal for water collected from the Nganana stream (natural water) with the electrosorption capacity of 2.56 mg/g and salt removal efficiency of 45%. The ions removal efficiency was 89%, 40%, 2.4% and 57.9% for Na^+, K^+, Ca^{2+} and Mg^{2+}, respectively. The microbial disinfection mechanisms are through CDI process and physical contacts. Thus, it is possible to disinfect the water while also removing salt simultaneously. Therefore, this study presents a novel AC/Ag-n electrode material which can be considered as an excellent antimicrobial agent for the CDI process.

Keywords: Disinfection; Capacitive deionization; Activated carbon; Silver nanoparticles; Antimicrobial

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1. Introduction

The world is facing challenges in the availability of safe and clean water [1]. According to the 2012 World Health Organization, about 780 million people worldwide lack access to clean and safe drinking water and 2.5 billion lack improved sanitation [2]. Since clean and safe water is essential to human health, reliable access to clean and affordable water remains a major global challenge for the 21st century [3–5]. Various technologies have been used for water purification including ion-exchange resin, electrodialysis, thermal distillation and reverse osmosis [6–8]. Most of these technologies have disadvantages such as secondary waste generation for ion-exchange resin, low energy efficiency for thermal distillation, high pressure and low water recovery for reverse osmosis [8,9]. Also, they are not effective in treating water with low salinity.

Capacitive deionization (CDI) is a novel technique which is more efficient in desalinating low saline water with

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concentration below 10 g/L [5]. This CDI process involves the application of an external voltage between two oppositely charged porous electrodes and work under constant voltage or constant current during adsorption/desorption processes [10]. Salt ions are electro-sorbed in the electrical double layer on a high surface area of porous carbon [11]. Currently, carbon materials such as carbon aerogel, ordered mesoporous carbon, carbon nanotube [7], graphene, fullerene [12], powdered activated carbon and activated carbon cloth are being studied. These materials have high surface area, high electrical conductivity and are chemically stable [8,9].

Recently, several studies developed the high-performance CDI porous carbon electrodes for improvement of electrosorption capacity and salt removal efficiency. It was reported by Hou and Huang [13] that, commercial AC powder electrode materials were used for the CDI experiment and the conductivity of the salt solution dropped from 478 to 51.4 µS/cm at 1.2 V after 1.5 h, the desalination efficiency was 89.25%. Alencherry et al. [14] use modified electrodes made by Ag impregnated AC and incorporated into multiwall carbon nanotube (AC/Ag-MWCNT), the initial concentration of salt solution was 600 ppm at 1.2 V for 16 min and enhance the electrosorption capacity of 5.3 mg/g with the desalination efficiency of 67%. Wang et al. [15] fabricate a highly mesoporous activated carbon (ACk2) electrode which has a maximum adsorption capacity of 10.9 mg/g. Also, N, P, S co-doped hollow carbon polyhedra derived from MOF-based core-shell nanocomposite electrodes developed by Zhang et al. [16] with the electrosorption performance of 22.19 mg/g at 1.2 V in a 500 mg/L NaCl solution. Yan et al. [17] design and produce sandwich-like nitrogen-doped graphene composites as high-performance CDI electrodes and the salt adsorption capacity reaches 18.4 mg/g in a 500 mg/L NaCl solution with a larger charge efficiency. Lignin-derived carbon electrode materials were produced by Zornitta et al. [18] and enhanced desalination with a maximum adsorption capacity of 18.5 mg/g and the removal efficiency of 80%.

Despite the use of CDI process for water treatment in several studies, the problem of microbes in the desalinated water is still a challenge. Some traditional antimicrobial agents such as hypochlorite and ozone commonly used in water disinfection produce harmful by-products which can be carcinogenic, mutagenic and are extremely irritant and toxic to human health and environment. So there is great interest in finding ways to create new types of safe and cost-effective biocidal materials. Various nanomaterials were being tested as bactericides including TiO_2 [19], ZnO [20], CuO [21] and carbon nanotubes [22]. Though many of these materials work as good antimicrobial agents, their activity is slow, taking a minimum of 4 h for the effective killing of bacteria [23]. Antimicrobial tests in the form of nanoparticles can be used as effective bactericidal materials [24]. Some of these nanoparticles with antimicrobial activity have been studied in CDI and show the improvement of electrosorption and efficiency for salt removal. Yasin et al. [25] used nitrogen-doped tin oxide intercalated activated carbon nanocomposite (N-AC/SnO_2) and composite nitrogen-TiO_2/ZrO_2 nanofibers incorporated activated carbon (NACTZ) electrode materials for disinfection and the results show good antibacterial effects as well as desalination performance [26]. Wang et al. [27], also use capacitive deionization disinfection (CDID) electrode made by coating an activated carbon (AC) with cationic nanohybrids of graphene oxide-graft-quaternized chitosan (GO-QC), (GO-QC/AC CDID electrode) and achieve to kill 99.9999% of *Escherichia coli* in water.

It is widely known that silver ions and its compound are highly toxic to microorganisms [28] such as *E. coli* and *Staphylococcus aureus* and nontoxic to the human body at low concentration [29–31]. Currently, Ag-n is used in medical application such as in coating medical devices to control bacteria growth including dental work, catheters and burn wounds [32,28]. Also, Ag-n is used in the formulation of dental resin composites and ion exchange fibers [24]. Since Ag-n can kill microbes and shows strong biocidal effect, they can be embedded in AC to make AC/Ag-n electrodes and used as CDI electrodes to enhance bacterial removal in water without compromising its salt removal efficiency. Therefore, this study investigates electrodes made by AC embedded with Ag-n (AC/Ag-n) in CDI electrodes for bacteria removal.

2. Materials and methods

Bio-contaminated water was collected from Nganana stream (natural water) located near the institution, activated carbon powder (purchased from FINAR Co. Ltd., Gujarat, India), polytetrafluoroethylene (PTFE) and carbon black, 99.9% ethanol (Sigma-Aldrich, St. Louis, United States), silver nitrate ($AgNO_3$), sodium borohydride ($NaBH_4$), sodium chloride (NaCl), polyvinyl pyrrolidone (PVP), polyvinyl alcohol (PVA) (purchased from Loba Chemie Pvt. Ltd., Mumbai, India), Hi chrome *E. coli* agar (purchased from Hi-media Co. Ltd., Mumbai, India), cellulose nitrate filter with pore size of 0.45 µm (from Sartorius Stedim Biotech GmbH, Göttingen, Germany) and deionized (DI) water produced within the institution.

The synthesis of Ag-n followed the chemical reduction method. The Ag-n production method was adopted from Mavani and Shah [33] with some modifications. 30 mL of 0.002 M $NaBH_4$ was placed into an Erlenmeyer flask and placed into an ice bath for stirring and then allowed to cool for about 20 min. The ice bath was used to slow down the reaction and give better control over the final particle size/shape. Then 2 mL of 0.001 M $AgNO_3$ was added into $NaBH_4$ solution dropwise while stirring until all $AgNO_3$ was added. In this stage, Ag ions were reduced and clustered to form monodispersed nanoparticles in the aqueous solution. To confirm the presence of nanoparticle aggregates, a small portion of the solution was transferred to a test tube and few drops of 1.5 M sodium chloride (NaCl) solution was added, the solution turned darker yellow and then grey. The remaining portion of the solution was transferred to a beaker followed by the addition of a few drops 0.3% PVP to prevent aggregation and 4% PVA solid was added into the solution to stabilize the nanoparticles. Then the mixture was poured into a mold, leaving air bubbles and undissolved PVA in the beaker. Finally, the mixture was kept into the oven for about 30 min for evaporation and removal of unwanted impurities and Ag-n were obtained. The silver nitrate reduction reaction is as follows:

$$AgNO_3 + NaBH_4 \rightarrow Ag + \tfrac{1}{2}H_2 + \tfrac{1}{2}B_2H_6 + NaNO_3$$

After obtaining Ag-n, the synthesis of AC/Ag-n electrodes was performed. Commercial AC powder with Brunauer–Emmett–Teller (BET) surface area of ~1,300 m^2/g, mixed with synthesized Ag-n and then stirred for 2 h and dried into the oven overnight. The dried mixture was then washed with DI water until the pH reached 7 and the conductivity close to that of DI water was attained then dried again at oven overnight. Then mix AC/Ag-n, carbon black, and PTFE in the ratio of 8:1:1, respectively, with 99.9% ethanol and stirred at 100°C till all ethanol evaporated and a uniform slurry was obtained. Then produced a slurry (dough-like structure) was pressed to a specified thickness of 1 mm then cut into 4 cm × 4 cm and oven dried at 60°C overnight to remove the remaining organic solvent. After drying, the actual weight of the electrodes was measured.

To characterize the materials, the surface morphology of the AC and Ag-n was examined using a field-emission scanning electron microscope (FESEM) (JSM-7600F NORAN System7, Thermo Fisher, Waltham, United States) with energy dispersive X-ray analysis. The specific surface area of the AC powder was measured based on N_2 adsorption isotherms at 77 K using BET surface area analyzer (NOVA 4200e, Quantachrome, UK). The pore size distribution was obtained by the Barrett–Joyner–Halenda (BJH) method. The functional groups of AC and AC/Ag-n were investigated using Fourier-transform infrared spectroscopy (FTIR) using Tensor 27 spectrometer fitted with a high-throughput screening device (HTS-XT). Tests were conducted in absorbance mode in spectral range 4,000–500 cm^{-1}.

The desalination and disinfection performance of AC/Ag-n electrode was evaluated by batch mode, CDI comprises of two electrodes placed parallel to each other and connected with IVIUM STAT (Vertex.1A.EIS 1A/10V/1MHz EIS, Ivium Technologies, The Netherlands) together with a peristaltic pump (Fig. 1). Then 30 mL of field bio-contaminated water collected from Nganana river with initial conductivity of 425 μS/cm was pumped between the two electrodes at a flow rate of 2.5 mL/min for 3 h while applying DC potential difference of 2 V to the cell.

Then the conductivity of outlet was recorded every 10 min. The concentration of salts were obtained by the summation of selected ionic concentration present in the water prior to the experiments which were measured by using flame photometer (FP 6440) in which 13.75 mg/L for Na^+, 40.25 mg/L for K^+, 30.63 mg/L for Ca^{2+} and 44 mg/L for Mg^{2+} and their removal efficiency (η) in %, adsorption capacity (Sc) in mg/g and salt adsorption rate (deionization rate) (SAR) in mg/g min^{-1} were calculated using Eqs. (1)–(3), respectively [25], as follows:

$$\eta = \left(\frac{C_0 - C_1}{C_0}\right) \times 100 \tag{1}$$

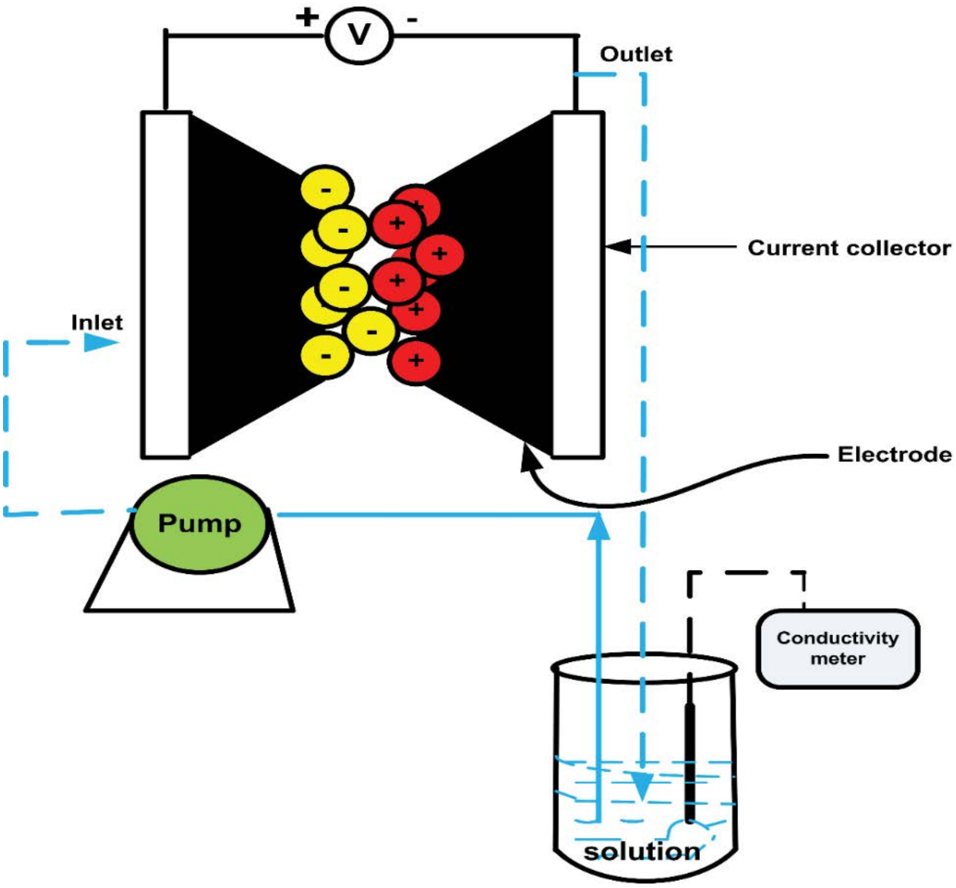

Fig. 1. Schematic diagram of the capacitive deionization experiment setup.

where C_0 = initial concentration (at inlet) in mg/L and C_1 = final concentration (at outlet) in mg/L.

$$Sc = \left(C_0 - C_1\right)\frac{V}{m} \tag{2}$$

where V = the total volume of the aqueous salt solutions in L and m = the mass of the active components in the working electrodes in g.

$$\text{SAR} = \left(\frac{\text{Sc}}{t_{\text{ch}}}\right) \tag{3}$$

where Sc = salt adsorption capacity in mg/g and t_{ch} = charging time in min.

For bacteria removal by CDI, membrane filtration method was used to culture bacteria, in which 30 mL of field bio-contaminated water was filtered using membrane filter (cellulose nitrate filter with diameter 0.45 μm) before and after treatment and the filter placed onto the surface of Hi Chrome *E. coli* agar plates. The plates were incubated at 30°C for 4 h and then at 44°C for 18 h. The colonies formed were counted and the percentage removal is determined using Eq. (4):

$$\text{Bacteria removal} = \left(\frac{A - B}{A}\right) \times 100 \tag{4}$$

where A = number of microbial viable cells before treatment and B = number of microbial viable cells after treatment.

3. Results and discussion

The BET surface area of AC and AC/Ag-n was 1,037 and 786 m²/g, respectively, with a pore volume of 0.65 and 0.35 cm³/g, respectively, as shown in Table 1. The pore diameter varied from 3 to 4.2 nm. According to IUPAC classification, these results show that AC and AC/Ag-n electrodes composed of mesopores. Presence of mesopores leads to a highly active surface area available for ions adsorption [34,35]. Also, it is observed that the presence of both PTFE binder and Ag-n in AC tend to reduce the BET surface area and the pore volumes significantly, because they provide internal resistance which blocks some pores of electrodes which may decrease capacitance as well as the surface wettability [36,37] which in turn will affect electrosorption performance of AC/Ag-n electrodes.

The morphology of AC was characterized by the SEM. Fig. 2a shows the rock and rough-like structure revealing irregular surface morphology of AC. This reveals that AC powder will play an important role in the adsorption of ionic impurities during the deionization process. Fig. 2b displays the EDS results of the AC. It can be clearly observed that O, Si, S, Cl and Ca were existing in the AC alongside with C and K indicating the presence of impurities within AC powder as summarized in Table 2.

The FTIR transmission spectra were obtained to characterize the functional groups present on AC and AC/Ag-n electrode materials. Fig. 3 shows the FTIR spectra of AC and AC/Ag-n. It can be seen that AC revealed the strong characteristic wide peak of 3,388 cm⁻¹ which was attributed to the stretching vibration of O–H bond, peak at 2,915 cm⁻¹ attributed to stretching vibration of C–H and a peak at 1,041 cm⁻¹ attributed to C–O. On the other hand, AC/Ag-n revealed the strong characteristic wide peak of 3,388 cm⁻¹

Table 1
BET surface area, pore volume, pore size and pore diameter of the materials

Sample ID	$\text{BET}_{\text{surface area}}$ (m²/g)	Pore volume (cm³/g)	Pore diameter (nm)
Comm.AC powder	1,300	0.78	3.0
AC/Ag-n+PTFE	786	0.35	4.2
AC/PTFE	1,037	0.65	3.0

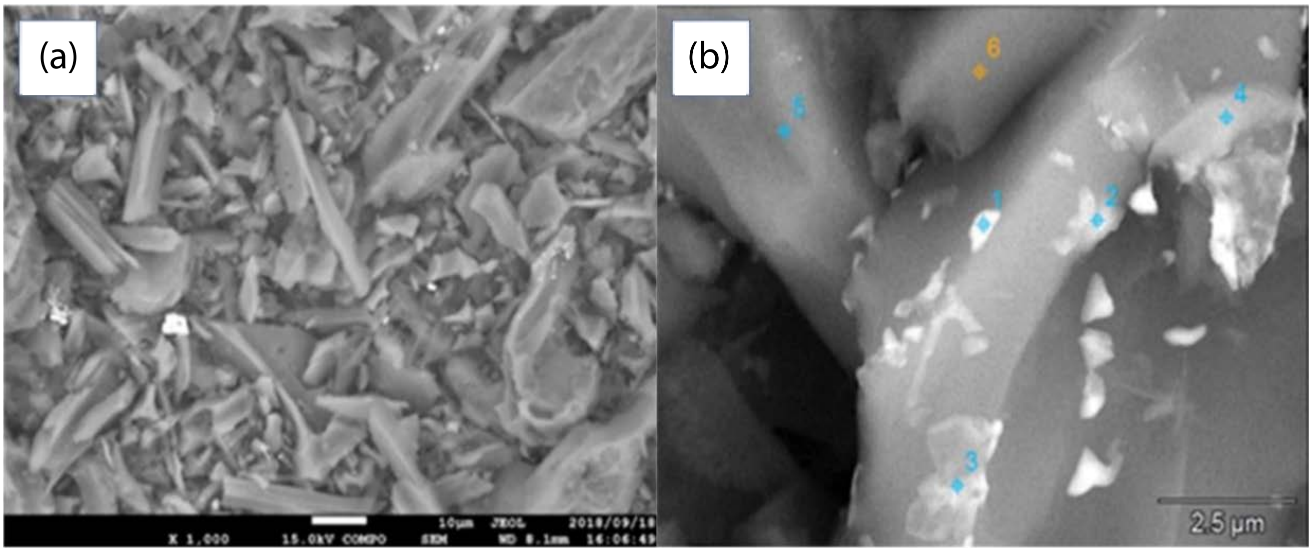

Fig. 2. (a) FESEM images of activated carbon powder structure and (b) SEM-EDS analysis.

Table 2
Percentage impurities present in AC materials during SEM-EDS analysis

Points	C–K	O–K	Si–K	S–K	Cl–K	Ca–K
1	98.95	–	0.04	0.41	0.11	0.49
2	95.49	1.76	–	1.34	0.07	1.34
3	99.62	–	–	0.15	0.11	0.12
4	96.14	2.86	–	0.53	0.09	0.38
5	99.75	–	–	0.1	0.14	–
6	99.69	–	0.07	0.11	0.09	0.04

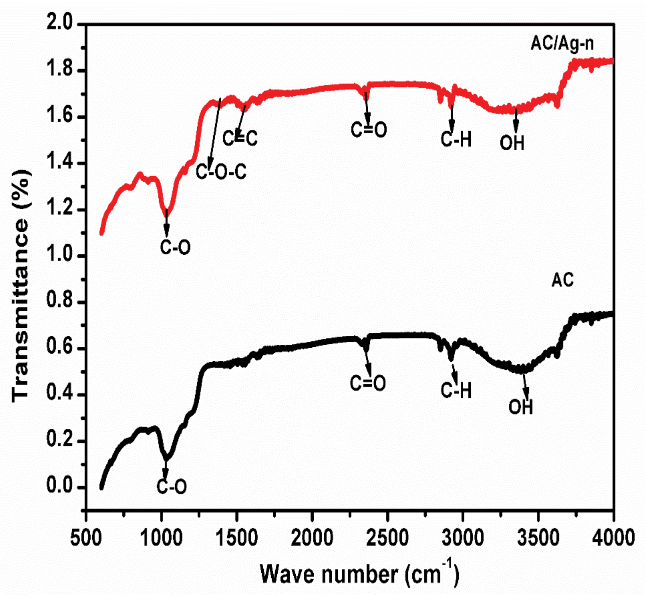

Fig. 3. FTIR spectra of pristine AC and AC/Ag-n.

is attributed to stretching and bending vibration of O–H bond, peaks at 1,550 and 2,915 cm^{-1} attributed to stretching vibration of C=C and C–H, respectively. The strong absorption peak at 1,394 cm^{-1} is caused by the stretching vibration of C–O–C. These results show that the reaction of the surface Ag-n was hindered due to the reaction of the active groups, such as C–O–C [38], and the reductive group such as C=C around the surface of Ag-n can react with an oxidizing substance which protect the Ag-n from oxidation to the surrounding environment [33]. Presence of these surface hydrophilic groups such as phenolic, carboxyl and hydroxyls will enhance wettability and electrosorption capacity of carbon materials [36].

The salt removal efficiency of pristine AC and AC/Ag-n electrodes were performed during the CDI process. Fig. 4 shows the conductivity change of water when pristine AC and AC/Ag-n electrodes were used at 2.0 V. Initially the conductivity dropped quickly, indicating that the ions are adsorbed more onto the oppositely charged electrodes under the applied voltage, after 150 min the conductivity tends to be stable, indicating the electrodes are saturated. Noticeably, pristine AC electrode reveals the higher adsorption capacity compared with AC/Ag-n as they reduce the pore sizes and volumes when Ag-n embeds AC hence the electrosorption capacity decreases.

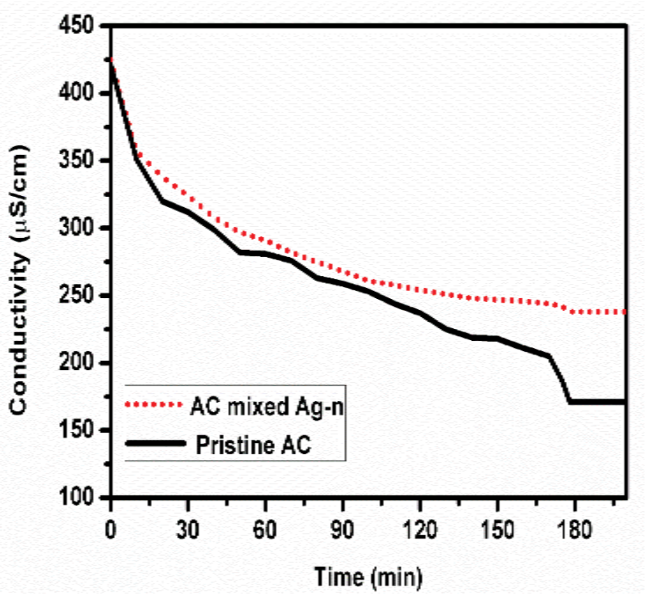

Fig. 4. CDI performance for the fabricated electrodes in salt solution.

From Fig. 5a, the salt removal efficiency (η) of the pristine AC electrode was higher reaching 61% compared with the AC/Ag-n which have desalination efficiency of 45%. The pristine AC electrode has a higher electrosorption capacity and salt adsorption rate (SAR) of 4.34 mg/g and 0.0241 mg/g min^{-1}, respectively, compared with AC/Ag-n with 2.56 mg/g and 0.0142 mg/g min^{-1} as calculated from Eqs. (2) and (3) and presented in Fig. 5b. This is due to the reduced surface area pore volume during embedded (mixing) process as shown in Table 1. The higher electrosorption performance of AC indicates that more ions were easily adsorbed than that of AC/Ag-n. The results reveal that (Figs. 5a and b) the removal efficiency is proportional to the electrosorption capacity of the material.

It was reported by Park et al. [39] that the incorporation of conductive carbon black (CB) during the fabrication process enhances the capacitance of the electrodes, CB has a high proportion of mesopore, thus can improve both electrical conductivity and SAR. Also, the effects of PTFE binder level on the capacitance of the electrodes have been studied and found that the higher level of polymeric binder resulted in decrease of capacitance. Nadakatti et al. [40] prove that higher capacitance of the electrode provides better salt removal and electrosorption efficiency. Since AC has better electrosorption capacity and salt removal efficiency also expected to have a higher capacitance. Therefore, AC suggested having better desalination performance in the CDI process than AC/Ag-n.

The regeneration performance of both AC and AC/Ag-n electrodes was conducted by repeating the charge-discharge experiment for 4 h by applying a constant voltage of 2 V. during charging and 0 V during discharge. Fig. 6 shows the conductivity and time profile over two charge–discharge cycles. In the first cycle, conductivity dropped to 40 min for

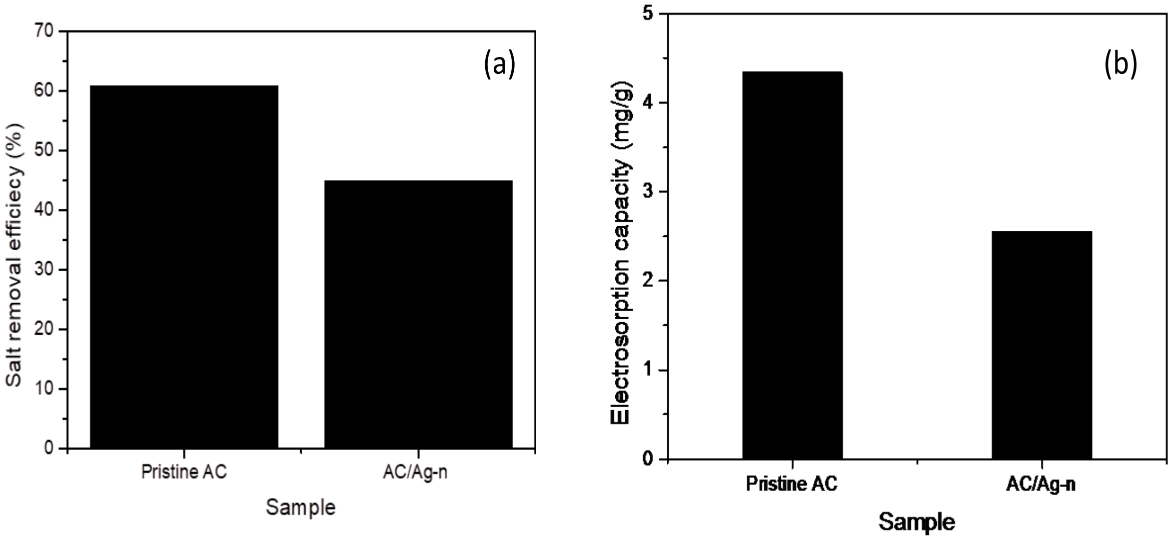

Fig. 5. (a) Salt removal efficiency and (b) electrosorption capacity of the pristine AC and AC/Ag-n electrodes.

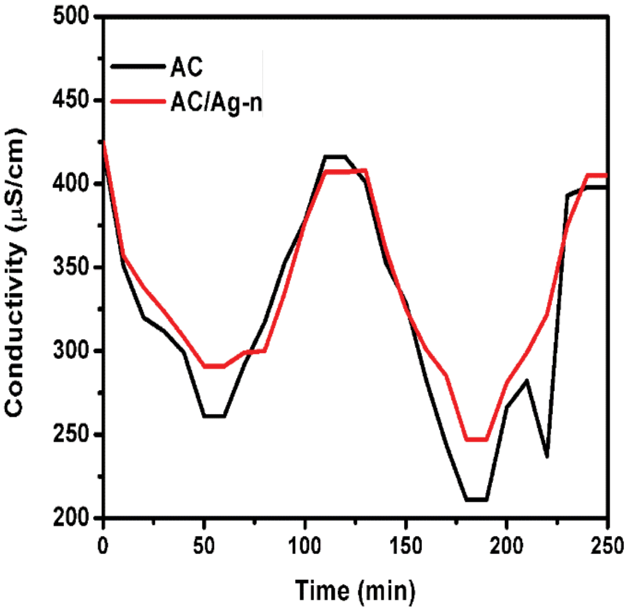

Fig. 6. Charge–discharge cycles in a CDI experiment at 2 V.

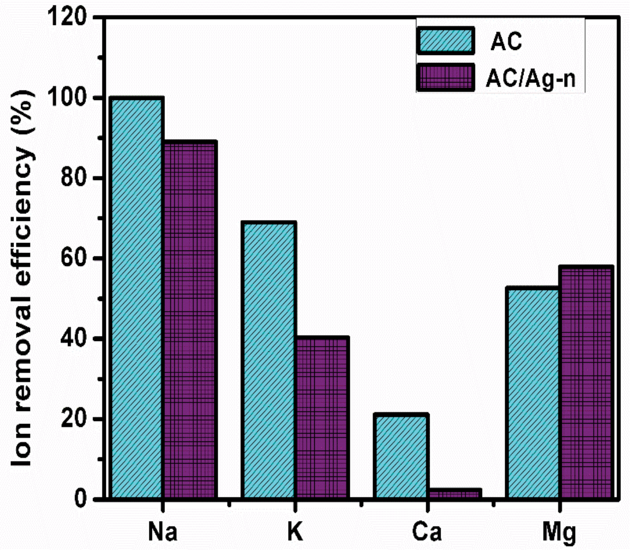

Fig. 7. Removal efficiency of ionic impurities in natural water.

AC and 30 min for AC/Ag-n and dropped further to 180 min in the second cycle. It was observed that the ions were released rapidly after discharged but the conductivity of the solution does not reach the initial value. These results show that upon the removal of the applied voltage, some of the ions were not released back to the solution, and there was no decline in desalination performance observed after the first cycle, thus indicating that the AC and AC/Ag-n electrodes can be re-used without affecting its capacity.

The results of the ionic composition of bio-contaminated natural water after treating with CDI using AC and AC/Ag-n electrodes are presented in Fig. 7.

Generally, the ions adsorption rate were higher in AC than in AC/Ag-n electrodes (Fig. 5) due to the fact that AC has larger BET surface area and pore volume compared with AC/Ag-n as shown in Table 1. Zou et al. [38], Park et al. [39] and Nadakatti et al. [40] previously reported that surface area, pore size and pore structure of the electrodes are important parameters to consider during ion adsorption/desorption process because they affect electrosorption capacity as well as removal efficiency of the ions during water purification.

Field water comprises of a mixture of selected cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), with different concentrations as presented in Table 3 whereby each ion was having an adsorption capacity corresponding to the valency of the ionic species. It can be observed that, using both CDI porous AC and AC/Ag-n electrodes, monovalent cations (Na^+ and K^+) were removed to the large extent from the solution over divalent cation (Ca^{2+} and Mg^{2+}) because small monovalent cations

Table 3
Ionic concentration for the feed field water (C_0), ions charge (valence) (V), ionic radii (IR) and hydrated radii (HR), removal efficiency (η) and electrosorption capacity (Sc)

Ion type	C_0 (mg/L)	V	IR (pm)[a,b]	HR (pm)[c]	η (%)		Sc (mg/g)	
					AC	AC/Ag-n	AC	AC/Ag-n
Na^+	14	+1	116	358	100	89	0.43	0.40
K^+	40	+1	133	331	69	40	0.99	0.47
Ca^{2+}	31	+2	65	428	21	2.4	0.18	0
Mg^{2+}	44	+2	86	412	57	52	0.79	0.83

[a,b,c]References [41–43].

have larger ionic radii hence can penetrate through the pores and attached on the surface of electrode more easily while divalent cation due to their larger size and smaller ionic radii, thus it was difficult to pass the ions through the pores of the electrode deeply [42,44], but those ions (Na^+, K^+, Ca^{2+}, Mg^{2+}) are thermodynamically favored for adsorption during the deionization process [3,45,46]. From Table 3 and Fig. 7, the adsorption capacity of the various ions in natural water shows that the selectivity of the ions depends on the valency, concentration and the size of the ions present in water.

Bacterial removal efficiency with CDI in natural water was characterized before treatment and found to have *E. coli* and *Salmonella enteritidis* as indicated by Fig. 8a, which were detected as model pathogens in testing antimicrobial activities. After treating with AC and AC/Ag-n electrodes the result in Figs. 8b and c indicates the reduction of those 2-g negative (*E. coli* and *S. enteritidis*) bacteria.

AC/Ag-n electrodes show the excellent antimicrobial effect toward both bacteria *E. coli* and *S. Enteritidis* and their removal efficiency was 100% and 98%, respectively, after 3 h of charging without dilution compared with pristine AC electrodes (Fig. 9). During the CDI charging process, the bacteria were electrically attracted toward the positive electrodes due to the presence of negative charges on their cell envelope [27] and then killed by the embedded Ag-n when in physical contact. AC only removes bacteria by absorbing 91% and 87% for *E. coli* and *S. Enteritidis*, respectively.

Ag-n and AC/Ag-n can remove bacteria by physical contact (Fig. 10) without the CDI process. After culturing the bacteria which were in contact with AC/Ag-n materials into agar plate, they were not grown while those in contact with AC grew. This implies that using only AC may result in

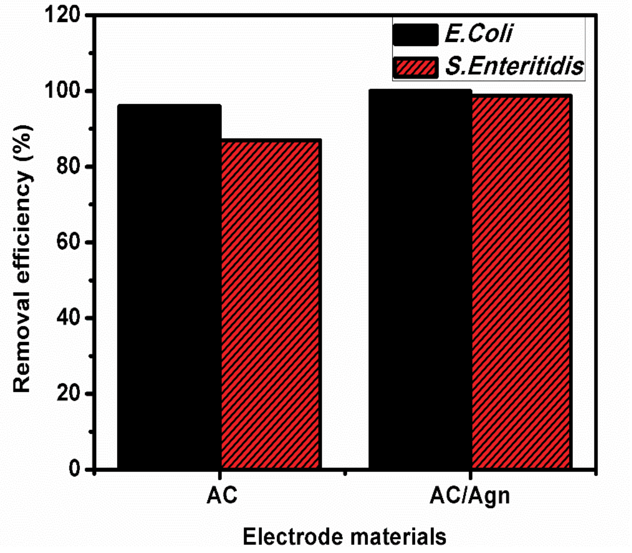

Fig. 9. Bacteria removal efficiency during CDI process.

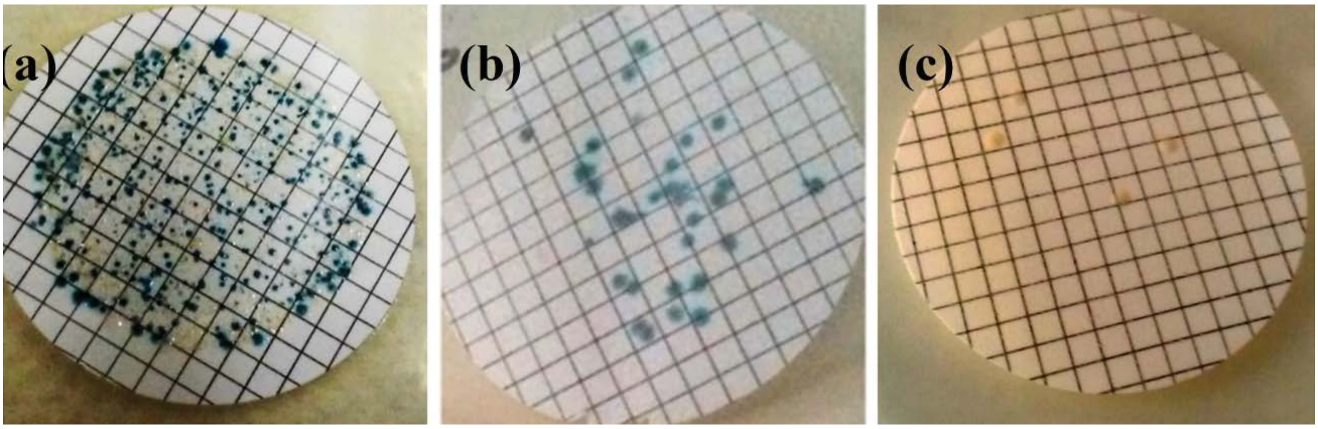

Fig. 8. Plates showing bacteria growth (a) before treatment, (b) treated with AC, and (c) treated with AC/Ag-n electrodes (Blue colonies indicate *E. coli* and cream colonies indicate *S. enteritidis*).

Table 4
Salt and bacterial removal efficiency and electrosorption capacity reported in the literature and the findings of these studies

Electrode materials used	Volt (V)	Flowrate (mL/min)	Initial concentration (mg/L)	Salt removal efficiency (%)	Electrosorption capacity (mg/g)	Bacteria removal (%)	Reference
AC	2	1	100	66	–	82 (6 log reduction)	[24]
			200	63	–		
AC/GO-QC	2	1	100	73	–	99.9999 (6 log reduction)	
			200	69	–		
N-AC/SnO_2	1.2	0.8	50	61.13	3.42	Good	[22]
NACTZ	1.2		50	71.19	3.98	Good	[23]
AC	2	2.5	250	61	4.34	91-*E. coli* 87-*S. enteritidis*	This study
AC/Ag-n	2	2.5	250	45	2.56	100-*E. coli* 98-*S. enteritidis*	

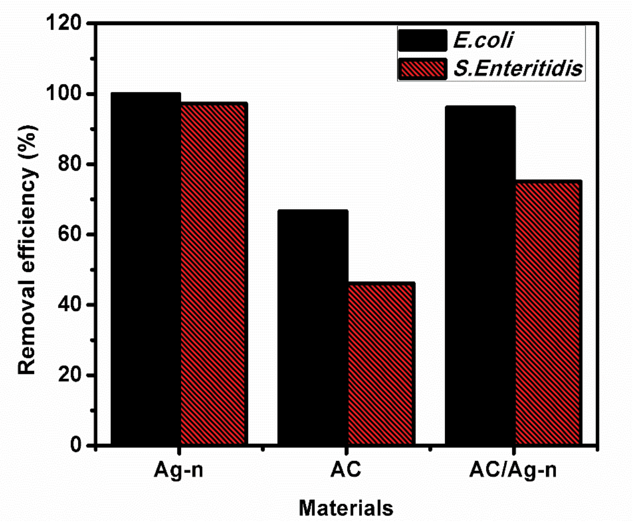

Fig. 10. Bacterial removal efficiency by physical contact.

a decrease in the CDI stack life span as the microorganisms do not die in the cell.

The concentration of salt ions in these studies which was 250 mg/L in the solution has little effect on the bacteria killing. This is because the salinity is the one among the factors which favor the bacterial growth and the optimum salt concentration for bacteria to survive is about 200–500 mg/L [47], hence the presence of Ag-n have critical effects for disinfection of saline water. Different studies in which nanomaterials have been used as an antimicrobial agent in CDI-AC electrodes are presented in Table 4. From the table, it is observed that Ghosh et al. [20] used CDI disinfection (CDID) electrode made by coating an AC with cationic nanohybrids of graphene oxide-graft-quaternized chitosan (GO-QC), (GO-QC/AC CDID electrode) and achieve to kill 99.9999% of *E. coli* in water for 6 log reduction. Kim and Kwak [19] and Nightingale [41] used nitrogen-doped tin oxide intercalated activated carbon nanocomposite (N-AC/SnO_2) and composite nitrogen-TiO_2/ZrO_2 nanofibers incorporated activated carbon (NACTZ) electrode materials which show good antimicrobial effects as well as desalination performance. This study achieved 100% *E. coli* and 98% *S. enteritidis* removal using AC/Ag-n electrode after 3 h without dilution of the original sample.

4. Conclusion

In this study, Ag-n has been embedded in AC and used as CDI electrode. The Ag-n is an excellent disinfectant and can remove bacteria by physical contact as well as during CDI process against representative gram-negative species (*E. coli* and *S. enteritidis*) but AC alone cannot kill bacteria by physical adsorption. The fabricated AC/Ag-n was tested for desalination and antimicrobial performance. The electrosorption capacity of pristine AC was 4.43 mg/g and that of AC/Ag-n was 2.56 mg/g when 30 mg/L of field bio-contaminated water was used. Compared with the pristine AC, AC/Ag-n revealed high disinfection performance for gram-negative bacteria (*E. coli* and *S. enteritidis*). The AC/Ag-n electrode contact killing process was fast, continuous, energy-efficient and does not require complicated infrastructure. Therefore, this study presents a novel AC/Ag-n composite electrode material which can be considered as an excellent antimicrobial agent for the CDI process.

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