

Capacitive deionization and disinfection of water using graphene oxide-dendrimer-silver coated electrodes

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ABSTRACT

This study is aimed to explore highly efficient water desalination and disinfection using a new capacitive deionization (CDI) system. The novel nanocomposite based on graphene oxide was synthesized and grafted five generations of dendrimer and silver nanoparticles; subsequently, the CDI electrodes were coated by the new nanocomposite. The introduced nanocomposite was characterized using Fourier-transform infrared spectrometry, thermogravimetric analysis, Brunauer–Emmett–Teller surface area analysis, surface wettability, and field emission scanning electron microscopy. Different affecting parameters, including total dissolved solids (TDS) (500–20,000 mg L⁻¹), number of coliforms (500–100,000 MPN), different amounts of silver nanoparticles (0.2% and 5%), and contact time (15–120 min) were evaluated. The new electrodes can be converted to TDS from 20,000 to 400 mg L⁻¹. Thus, the new electrodes with an electrosorption capacity of 46.29 mg g⁻¹ presented 98% ion removal in saltwater treatment. The CDI system can also kill 99.9% of coliforms in the NaCl solution (500 mg L⁻¹) containing 1,000; 10,000; 100,000 MPN of coliforms within 30, 60, and 120 min, respectively. Moreover, the coliform removal performance was successful in high TDS water (5,000 mg L⁻¹). The new nanocomposite indicated high adsorption/desorption capacity in alternating cycles and regeneration quickly, which makes it an excellent candidate in the continuous process.

Keywords: Capacitive deionization; Disinfection; Deionization; Silver; Dendrimer; Coliform

1. Introduction

With an increase in the global population and developing agricultural and industrial activities, challenging stress is being placed on our decreasing clean water resources, and the demand for freshwater is significantly increasing while the freshwater resources are limited. The storage of clean water and drinking water safety has become one of the biggest problems in most countries [1–3]. Disinfection is always one of the most crucial processes to eliminate bio-hazardous in water treatment. However, nowadays, most disinfection materials and processes do not have appropriate efficiency for removing pathogenic microorganisms from drinking water and suffer from drawbacks such as

toxic and harmful disinfection by-products (DBPs) formation and pathogen regrowth [4]. Several techniques have been applied for disinfection, such as chlorination, UV irradiation, and ozonation, but they suffer from different limitations in real-world applications. Chlorination is one of the most common techniques for water disinfection around the world due to its cost-efficiency. The chlorination process may result in the formation of DBPs (e.g., haloacetic acids, bromate, and trihalomethanes), increasing the risk of cancer development in humans, a particular health concern [5,6]. According to the disadvantages of conventional disinfection techniques, finding a new, cost-effective, and effective disinfection method with a broad-spectrum of bactericidal

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effects has raised tremendous attention [6,7]. Recently, researches show that nanomaterials with a multi-purpose antibacterial potential have become a promising candidate to overcome the drug-resistant bacteria problem [8,9].

Recently, silver nanoparticles have been used in destroying a wide range of pathogenic bacteria as an antimicrobial agent. Although silver nanoparticles are an antibacterial agent, the destroying bacteria mechanism is not apparent yet [10,11]. One of the suggested mechanisms is the free radical formation from the silver surface that inhibits the microorganisms' growth. Free radicals attack the lipid membranes and consequently decompose its function [12]. Another antimicrobial mechanism of silver ions is interaction with thiol groups (as a deactivator of enzymes) in proteins and inactivating enzyme activity [13]. Reactive oxygen species is another type of Ag nanoparticle mechanism that caused damage or death by microorganisms by reacting with them [14]. Despite the good antibacterial properties of silver nanoparticles, they had remarkable biotoxic activity due to Ag⁺'s sustained release, and they can cause serious oxidative damage to nearby cells due to their surface and photocatalytic properties [15].

Numerous studies have reported the toxicity effects of Ag nanoparticles on rat liver and murine stem cells, human nerve and lung cells, and its poisonous impact on aquatic organisms [15,16]. The Ag nanoparticles have more effective antibacterial characteristics at nanomolar concentrations compared with micro-molar concentrations of Ag⁺, even though they are more toxicity than Ag⁺ [17]. In order to overcome to mentioned problems using Ag nanoparticles, a method is needed to prevent the release of silver nanoparticles and its ions into the water, which can lead to using antimicrobial properties of Ag nanoparticles. The proposed method is using the carrier with antimicrobial agents, and these carriers could be activated carbon, graphene oxide, or composite compounds [17,18]. Antimicrobial nanocomposite can efficiently inactivate microorganisms due to the high surface-to-volume ratio and increased reactivity of the antimicrobial nanoagents [18].

The researchers reported that the Ag nanoparticles coated with activated carbon efficiently perform water disinfection [19]. However, it seems unsafe for drinking water treatment and disinfection due to the possibility of transferring activated carbon particles through filter pores and transferring them to purified water.

In recent decades, graphene oxide (GO) has been known as a proper choice for composite materials [20,21]. GO is classified in two-dimensional (2D) materials, and it contains numerous carbon atoms in a honeycomb structure [22–24]. It is reported that the GO and its composites have been exhibited antibacterial properties using the chemical and physical mechanisms [23,25]. Studies reported that the GO-Ag composite has better antibacterial performance due to the synergistic antibacterial effect of Ag nanoparticles and GO [17,18]. Thus, GO-Ag composite composed of 40% silver particles indicated a similar antibacterial performance with silver nanoparticles [13]. Despite the mentioned advantages, GO-Ag composite is stable in water due to the nanoscale nature. So, the conventional methods are not effective for removing GO-Ag composite from drinking water [9]. Therefore, a proper method is required to stable

GO-Ag particles and prevent the release into the drinking water to utilize GO-Ag composite in drinking water disinfection.

Capacitive deionization (CDI) technology is an ion removing method from brackish water using activated carbon electrodes [26,27]. The CDI system is a continuous flow process that is alternately regenerated (under direct voltage (DC)) using ion adsorption/desorption cycles [28,29]. The properties of the electrode materials such as conductivity, pore size distribution, specific surface area, absorption characteristics, and the main chemical groups on the surface have consequential effects on the desalination performance of the CDI system [30,31]. The results obtained from desalination using the CDI system indicated that the CDI system has adequate and appropriate potential for removing organic particles, microbial agents, and other water pollutants [19,24]. The CDI system's disinfection property was evaluated using activated carbon cloth electrodes, and in this system, bacterial cells that have a negative charge absorbed on the positive electrodes [32]. Another study reported that the electrode coated with graphene oxide-graft-quaternized chitosan nanohybrid can kill 99.99% of *Escherichia coli* (*E. coli*) water within 5 h, while this disinfection duration is much longer than the conventional disinfection system [9].

The CDI system consists of two steps to complete the desalination process: adsorption and desorption. In the adsorption step, the charged electrodes adsorb electrostatically salt ions and produced fresh water until the electrodes become saturated. The second step is referred to as the desorption process. It undergoes the regeneration process and produced concentrated effluent [25,33]. In the regeneration process, the saturated electrodes can be regenerated by applying reverse voltage or short-circuiting them. In this process, the adsorbed salt ions from the electrodes' surface would be released back to the solution. Thus, the saturated electrodes can be regenerated several times when they were saturated by adsorbing the salt ions [9,30,31].

A schematic diagram of the CDI system is shown in Fig. 1. The CDI system has some advantages, including good regeneration ability, the high capability to remove salt ions without chemicals, no corresponding secondary chemical wastes, a quickly operational and maintenance process, environmentally friendly characteristics, and low energy consumption (2 V) [9]. Thus the development CDI system can be considered as one of the promising water desalination and disinfection technologies.

In this study, a new electrode coating using GO dendrimers and Ag particles is introduced via a facile and straightforward method. The introduced CDI system shows the higher water desalination and disinfection capacity than the other similar systems due to the capacitive deionization-disinfection system. The primary purpose is to fabricate an efficient desalination and disinfection system that no produce any harmful byproducts. For this purpose, five generations of dendrimer and Ag nanoparticles were grafted onto the GO particles to prepare an efficient electrode coating layer. Dendrimer branches could increase the absorption capacity due to the great specific surface area and the wide range of pore size, resulting in improving desalination and disinfection efficiency [34]. To avoid the short circuit and exploit the maximum capacity

of the electrodes, several baffles are placed throughout the water flow path. Two steps fabricated the new improvement electrodes: firstly, five generations of dendrimer were grafted onto the GO particles, and then Ag nanoparticles as a disinfection agent were assembled to GO-dendrimer composite. Secondly, the electrodes (activated carbon (AC)) were coated by a thin layer of GO/G5/Ag nanocomposite. The GO/G5/Ag nanocomposite as CDI electrodes indicated an excellent performance in desalination and disinfection applications. The obtained results showed that the improvement electrodes could kill 99.9% of the coliforms in NaCl solution (1,500 mg L⁻¹) containing 100,000 MPN of coliforms. Besides, the experimental results revealed that the improvement electrodes have an appropriate disinfection performance until 5,000 mg L⁻¹ of total dissolved solids (TDS). Also, they indicate 98% of water desalination by adsorbing salt ions in a concentration of 20,000 mg L⁻¹. Since the bond between the silver nanoparticles and GO is strong, the silver nanoparticles cannot release into the water. So, the suggested deionization method is considered a healthy and economical process for water disinfection.

2. Methods

2.1. Material supply

GO powder, AC powder, hydrochloric acid (HCl), sodium hydroxide (NaOH), epichlorohydrin (C₂H₅ClO), sodium borohydride (NaBH₄), sodium sulfide (Na₂S), sodium acetate

(CH₃COONa), anhydrous dimethylformamide (DMF), polyvinylidene fluoride (PVDF), and silver nitrate (AgNO₃) were purchased from Merck (Germany).

2.2. Dendrimers grafting on to GO

To wash the GO powder, 2 g GO powder was added into the hydrochloric acid (1%) and stirred at room temperature. After 24 h, the GO powder was washed with distilled water until the pH approached neutral and centrifuged at 10,000 rpm.

The dendrimers grafting onto GO was conducted via three following steps:

- GO (2 g) from the previous washing step, sodium borohydride (1 g), and epichlorohydrin (40 mL) were added into the 60 mL sodium hydroxide (2 M) and stirred for 24 h at ambient temperature in a dark environment. Then the mixture was centrifuged at 10,000 rpm, and the GO/G0.5 precipitate was produced.
- Hydrochloric acid (1%) was added to the GO/G0.5 and agitated for 6 h at room temperature. Next, the mixture was centrifuged at 10,000 rpm and the GO/G1 precipitate was obtained.
- These two steps (1 and 2) were repeated alternatively until they reached GO/G2.5.
- The GO/G2.5 plus 50 mL sodium sulfide (2%) was added into 10 mL sodium acetate buffer (pH 5) and

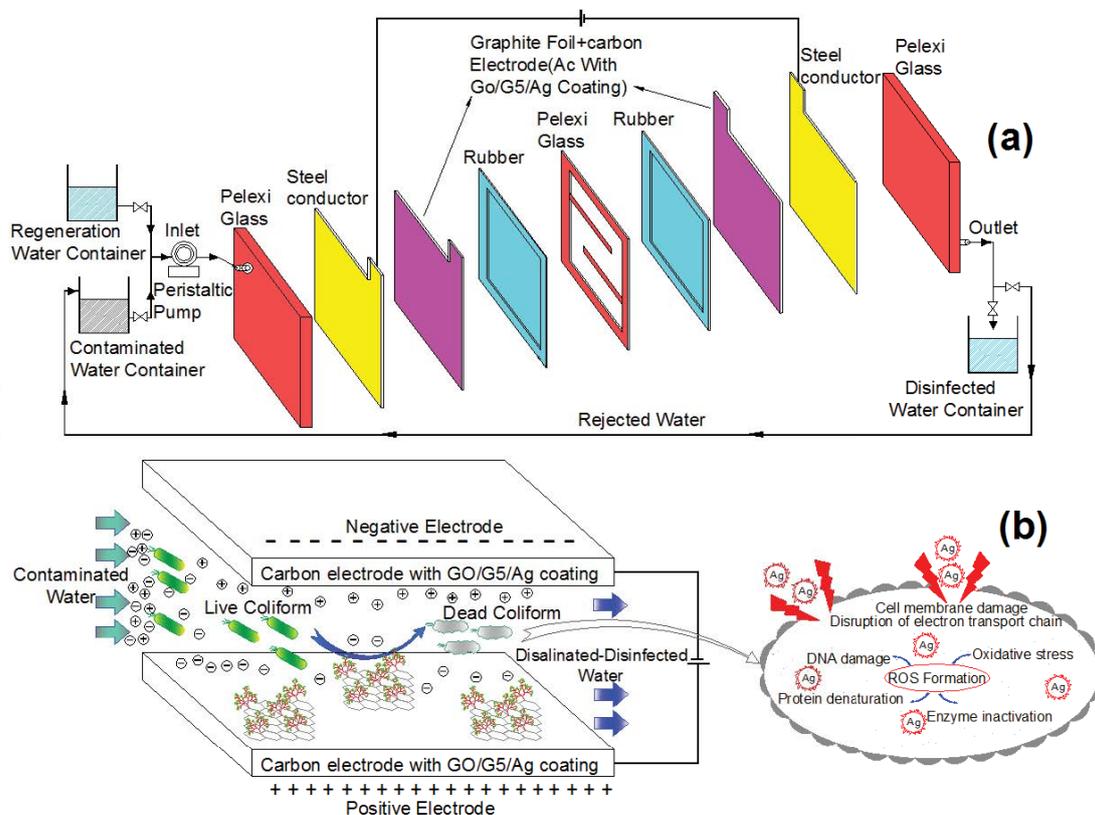


Fig. 1. (a) Schematic illustration of CDI cell arrangement, continuous water disinfection, and regeneration and (b) schematic illustration of disinfection-desalination performance between two electrodes (antibacterial mechanism of silver nanoparticles).

magnetically stirred for 6 h at 50°C. In order to synthesize high branches dendrimer, these three steps (1, 2, and 3) were repeated alternatively until reached to GO/G5. Finally, the reaction mixture was centrifuged at 10,000 rpm, and the produced precipitate (GO/G5) dried at 30°C.

2.3. Preparation of Ag nanoparticle assembled on GO/G5

Herein, 100 mL sodium borohydride solution (2 mM) was prepared and magnetically stirred for 20 min in an ice bath. Next, silver nitrate (1 mM) was added dropwise into the sodium borohydride solution until it reached a light yellow solution (approximately 3 min) [35] and the Ag nanoparticles were obtained. Then the GO/G5 precipitate was added into the Ag nanoparticles solution and magnetically stirred for 24 h at room temperature. Ultimately the GO/G5/Ag nanocomposite was produced.

2.4. Fabrication of CDI electrode by GO/G5/Ag nanocomposite

Firstly, a protective layer for CDI electrodes was prepared. For this purpose, AC powder and PVDF (ratio 9:1 w/w) was dissolved in an appropriate DMF amount. Next, the mixture was centrifuged at 15,000 rpm for 30 min until homogeneous carbon slurry. A graphite foil was then coated with a thin layer of the carbon slurry and dried in an oven for 2 h at 50°C. After that, the graphite foil was dried in a vacuum oven for 12 h at 50°C to remove any remaining solvent [9].

Secondly, the CDI electrodes were coated by a thin layer of GO/G5/Ag nanocomposite to achieve disinfection characteristics. GO/G5/Ag nanocomposite was mixed with the PVDF (ratio 1:1) and then centrifuged at 15,000 rpm for 30 min. After that, this mixture was drop cast onto a graphite foil sheet (obtained from the previous step) at the height of 20 μm and dried in an oven for 2 h at 50°C. Finally, the steel electrodes were coated by a graphite foil using a conductive binder, obtaining the dimension of the 100 cm^2 (10 cm \times 10 cm) and a mass loading of 3.6 mg cm^{-2} .

2.5. Measurement and characterization

Fourier verified the functional groups in the produced samples transformed infrared spectroscopy with a FT-IR-410 (JASCO, Japan). The size and morphology were investigated using a field-emission scanning electron microscopy (FE-SEM Sigma VP, Germany). The existence of elements in the samples was confirmed using an energy-dispersive X-ray spectrophotometer (EDS) attached to the FE-SEM. The samples' thermal properties were studied using thermogravimetric analysis (TGA, Q2000 DSC, TA Instruments, USA) with the temperature ranging from 0°C to 600°C at the heating rate of 10°C/min under N_2 atmosphere. The specific surface area (SSA) of samples were analyzed by the Brunauer–Emmett–Teller method of nitrogen sorption with BELSORP-mini II (MicrotracBEL Corporation, Japan). The surface wettability was investigated by measurement of water contact angles with a CAG-20 (Jikan, Iran). Temperature and pH adjustment were carried out using ultrameter II (Myron L Company, USA). The TDS of the samples was measured by conductivity meter Metrohm

(Switzerland). The number of coliforms in the samples was determined using the Microbe-Check – c/e test kit (AS-714, Iran).

2.6. Electrosorption experiments

The GO/G5/Ag-CDI electrode desalination and disinfection performance were conducted using batch experiments in a continuous recirculating system that contained the CDI cell and peristaltic pump. The peristaltic pump was used for the continuous supply of the NaCl solution to the CDI cell and each effluent sample was returned to the feed container at a flow rate of 30 mL min^{-1} (Figs. 1a and b). The CDI system performance was evaluated in different conditions, including initial numbers of coliform (MPN), contact time, and TDS. The CDI experiments were conducted using different concentrations of NaCl solution (1,000–20,000 mg L^{-1}) containing the different number of coliforms (1,000; 5,000; 10,000; 100,000 MPN). In order to compare the results obtained from NaCl solutions with a real sample, treated wastewater before the disinfection step was tested as a real sample. The percentage of coliform removal and log reduction (LR) of coliform in the CDI system was calculated using the following equations, respectively:

$$\text{Coliform Removal Percentage (\%)} = \left(\frac{C_0 - C_e}{C_0} \right) \times 100 \quad (1)$$

$$\text{Log Reduction (LR)} = \text{Log}_{10}(C_0) - \text{Log}_{10}(C_e) \quad (2)$$

In the above equations, C_0 and C_e (MPN) are the number of coliforms before treatment and after treatment, respectively.

3. Results and discussion

3.1. Characterization

3.1.1. Fourier-transform infrared spectroscopy analysis

Fourier-transform infrared spectroscopy (FT-IR) was used to confirm the presence of functional groups in the synthesized samples. The FT-IR spectra of GO, GO/G5, and GO/G5/Ag are shown in Fig. 2. In the GO spectrum (Fig. 2a), the peaks at 3,422; 1,704; 1,561; 1,460, and 1,053 cm^{-1} are related to the stretching vibration of OH, C=O, C=C, CH_2 , and CO groups, respectively. As shown in the GO-G5 spectrum (Fig. 2b), bands at 3,412 and 2,923 cm^{-1} are attributed to the stretching vibration of OH and stretching vibration of the aliphatic CH group, respectively. The peak located at 1,618 cm^{-1} corresponds to the out of plane stretching of the OH group. Also, two characteristic peaks at 1,384 and 1,107 cm^{-1} are expounded to the CH_2 and CO groups, respectively. The FT-IR spectrum of the GO/G5/Ag (Fig. 2c) revealed that the strong peak at 3,418 cm^{-1} is related to the OH groups. Furthermore, the bands at 2,923; 2,275; 1,721; 1,580; and 1,111 cm^{-1} are attributed to the stretching vibration of the aliphatic CH group, SH group, out of plane stretching of OH group, C=C, and CO groups, respectively. The spectrum of GO/G5/Ag was a combination of both GO

and GO/G5 spectra, which indicates the GO/G5/Ag nanocomposite was successfully synthesized.

3.1.2. Field-emission scanning electron microscopy/energy-dispersive X-ray spectroscopy

The surface morphology and size of synthesized GO and GO/G5/Ag nanocomposite were characterized using the FE-SEM. According to the FE-SEM image of GO (Figs. 3a and b), GO has a few-layer thickness. From Figs. 3c and d it is clear that GO/G5/Ag nanocomposite has a layer structure similar to the GO, but the distribution of dendrimers and Ag nanoparticles are observed on the GO surface. In the GO/G5/Ag nanocomposite, dendrimer branches on the GO surface tend to be aggregated with each other due to the dendrimer branches' interaction.

The EDS analysis was conducted to confirm the presence of the elements in GO and GO/G5/Ag nanocomposite. The obtained results are listed in Table 1. According to the EDS data, it can be stated that no additional impurities existence on the surface of the produced samples. The EDS spectrum showed that the GO has no content of Ag and S. The weight percentages of the carbon and oxygen in the GO/

G5/Ag nanocomposite were decreased due to the grafting of dendrimers. Thus, it can be concluded that the GO/G5/Ag nanocomposite was synthesized correctly.

3.1.3. TGA analysis

The thermal behavior of the GO and GO/G5/Ag nanocomposite was studied using the TGA. In the GO curve (Fig. 4a), the amount of mass loss below 150°C was about 10% related to the adsorbed water. The GO appears weightlessness between 150°C–400°C owing to the loss of OH and COOH groups. The GO backbone was decomposed at 400°C–600°C. Thus, the TGA curve of GO shows a 76.6% mass loss in the temperature range between 0°C to 600°C. For the GO/G5/Ag nanocomposite (Fig. 4b), initial mass loss was approximately 5% due to the adsorbed water's loss. The second and significant mass loss occurred in the range of 250°C–400°C because of the decomposition of dendrimers, and the lost mass is 28%. The third mass loss was observed over 400°C, which belongs to the GO backbone's degradation. The GO/G5/Ag nanocomposite showed a 77.3% mass loss. The TGA results indicate that dendrimers and Ag nanoparticles have been successfully grafted on the GO sheets.

3.1.4. Water contact angle

The wettability of GO and GO/G5/Ag nanocomposite were evaluated at room temperature by water contact angle (Fig. 5). The water contact angle was $85^\circ \pm 4.2^\circ$ for the GO, and $53.4^\circ \pm 3.5^\circ$ for the GO/G5/Ag. The GO/G5/Ag nanocomposite samples' water contact angles were decreased compared with GO samples due to an increase in hydrophilic groups' presence on the surface of GO/G5/Ag by dendrimers grafting on to GO, it resulting in improving the absorption capacity.

3.2. Effect of operation conditions on desalination and disinfection performance

3.2.1. Effect of Ag nanoparticles on disinfection performance

The GO/G5/Ag nanocomposite electrodes were fabricated with two different amounts of Ag nanoparticles (0.2% and 5%) to investigate Ag nanoparticles' effect on disinfection performance. Also, the GO electrode was fabricated to compare disinfection performance with the GO/G5/Ag nanocomposite electrodes. The disinfection performance was tested with a feed solution containing NaCl (500 mg L⁻¹) and 10,000 MPN coliforms within different time intervals (30 and 60 min). As shown in Fig. 6, the GO/G5/Ag (0.2%) nanocomposite electrode's removal efficiency is less than the GO/G5/Ag (5%) nanocomposite electrode. As shown, the disinfection performance of the GO/G5/Ag (0.2%) nanocomposite electrode and GO electrode was about 40% and 30% after 1 h, respectively. While the disinfection performance of the GO/G5/Ag (5%) nanocomposite electrode was about 99.99% under the same conditions. The results obtained from the regeneration process indicate that the coliforms were alive and just absorbed onto the GO/G5/Ag (0.2%) nanocomposite electrode and GO electrode, while the coliforms were entirely killed by the GO/G5/Ag (5%)

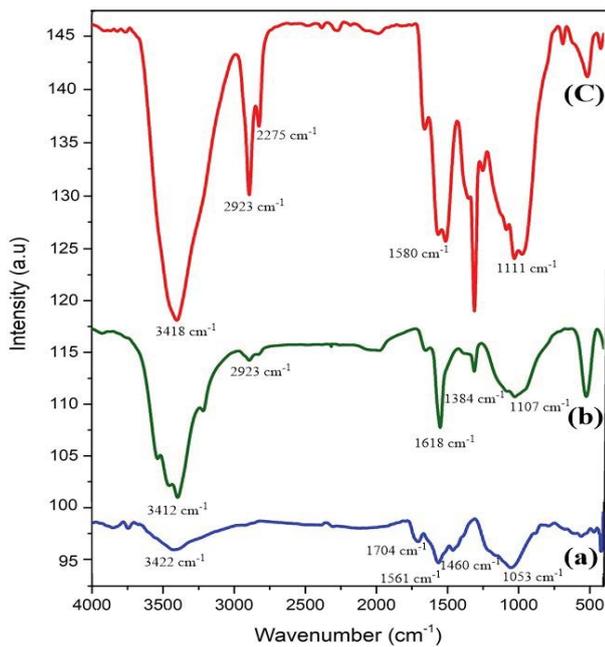


Fig. 2. Fourier-transform infrared spectrum of (a) GO, (b) GO/G5, and (c) GO/G5/Ag.

Table 1
Energy-dispersive X-ray spectroscopy information

Sample name	C	O	Ag	S
GO	75.6%	24.4%	N.D. ^a	N.D. ^a
GO/G5/Ag ^b	64.3%	17%	5.8%	0.5%

^aN.D.: not detected;

^bGO/G5/Ag: graphene oxide-dendrimer-silver.

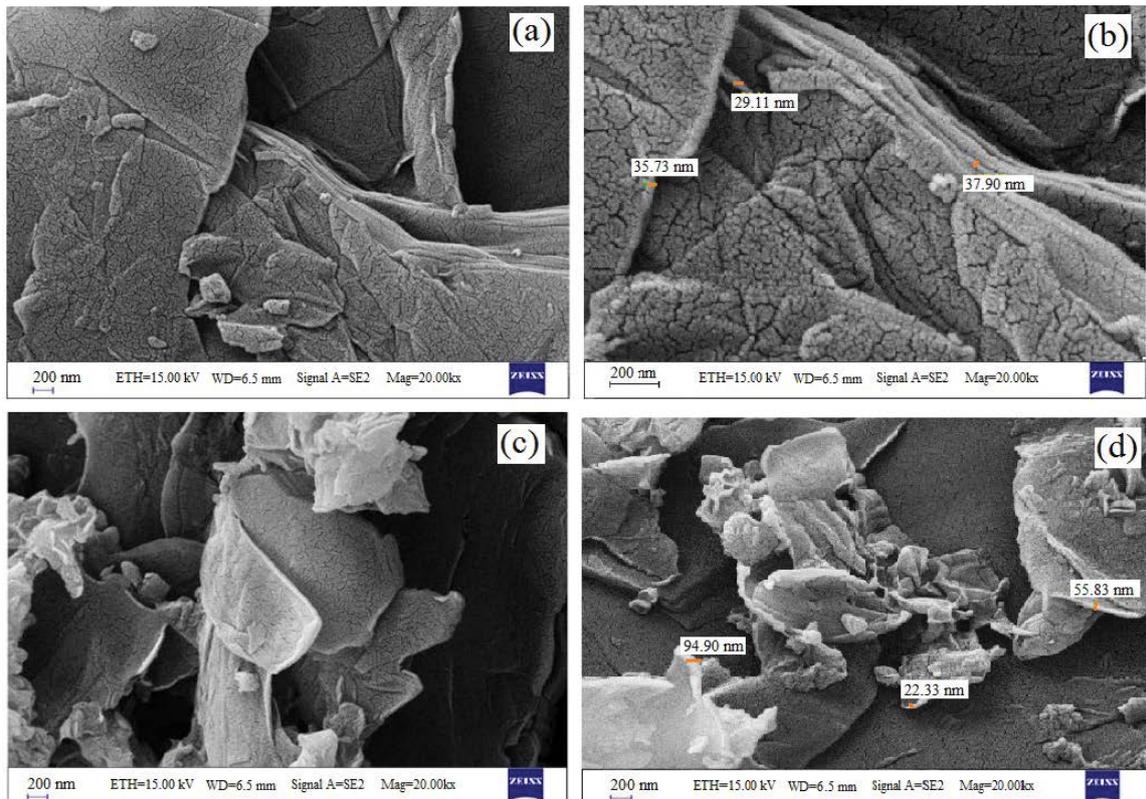


Fig. 3. Field-emission scanning electron microscopy images of (a and b) GO and (c and d) GO/G5/Ag.

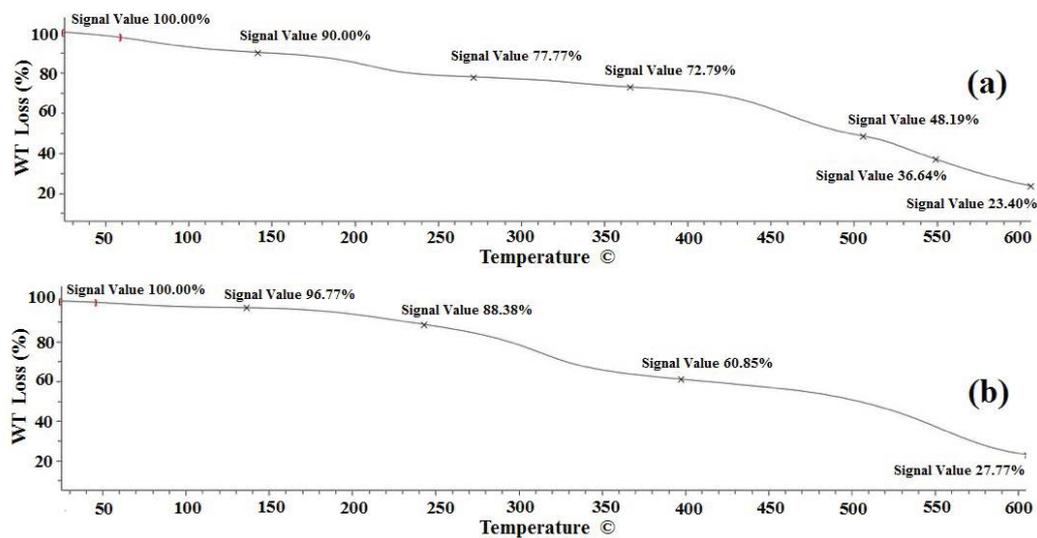


Fig. 4. Thermogravimetric analysis curves of (a) GO and (b) GO/G5/Ag.

nanocomposite electrode. Eventually, the results showed that the CDI system with 5% Ag nanoparticles has a better and more appropriate disinfection performance.

3.2.2. Effect of initial coliform

Initial coliforms are one of the critical parameters in disinfection performance evaluation. For this purpose, NaCl

solution (500 mg L^{-1} , maximum allowable concentration in drinking water) containing different numbers of coliforms (500; 1,000; 1,0000; 10,000 MPN) was tested using a GO/G5/Ag (5%) nanocomposite electrode at two different contact time (30 and 60 min). Fig. 7 shows that the coliforms' killing rate (500–1,000 MPN) is 99.9% at 30 min. This retention time is the same as the required retention time for the disinfection in the conventional chlorination system with the

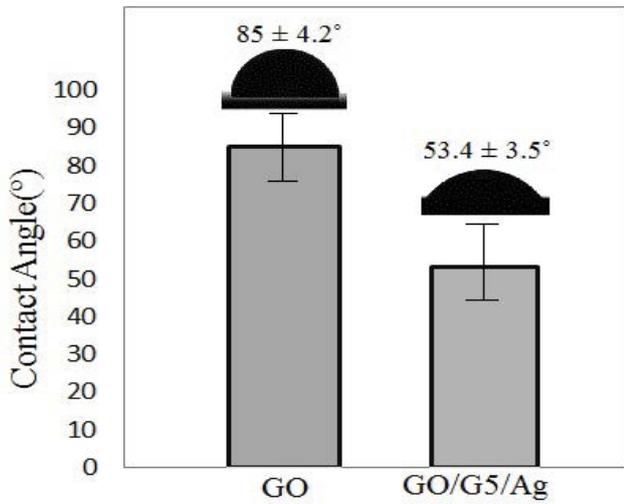


Fig. 5. Water contact angle for the GO and GO/G5/Ag.

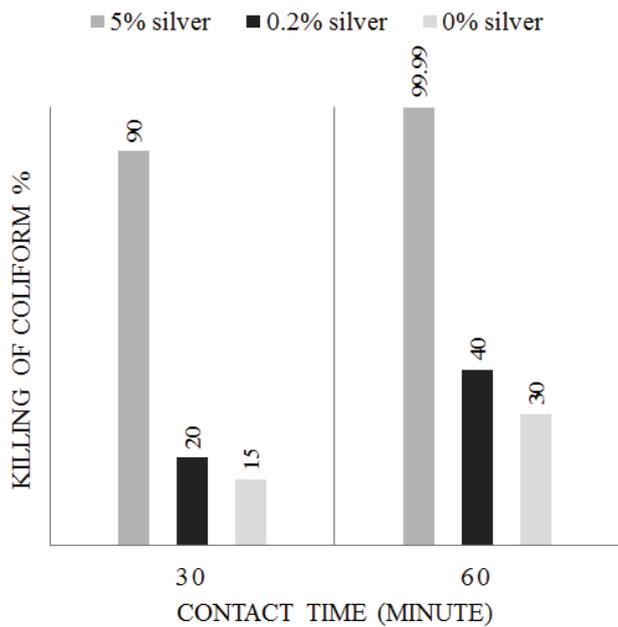


Fig. 6. Effect of Ag nanoparticles (0%, 0.2%, and 5%) on disinfection performance in NaCl solution (500 mg L⁻¹) containing 10,000 MPN coliforms at different contact times (30 and 60 min).

advantages of not consuming any chemical and no remaining by-products in disinfected water. Furthermore, this system reveals 99.9% coliform removal (10,000 MPN) at 60 min. Once the number of coliforms increases to 100,000 MPN, the coliform removal was decreased to 90% at 60 min.

3.2.3. Effect of contact time

The effect of different contact times (30–120 min) on coliform killing was investigated using NaCl solution (500 mg L⁻¹) containing 1,000; 10,000; 100,000 MPN coliforms. According to Fig. 8, the required contact times for

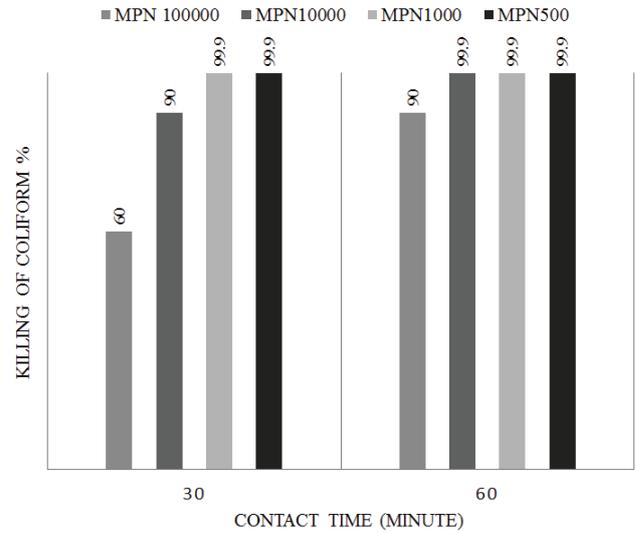


Fig. 7. Effect of initial coliforms (500; 1,000; 10,000; 100,000 MPN), NaCl solution (500 mg L⁻¹) on disinfection performance of GO/G5/Ag (5%) nanocomposite electrode.

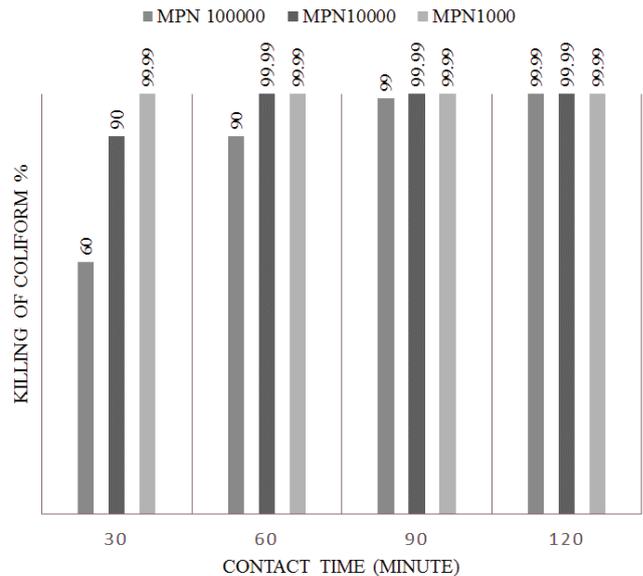


Fig. 8. Effect of contact time (30–120 min) on coliform killing at different conditions (1,000; 10,000; 100,000 MPN of coliforms, NaCl solution (500 mg L⁻¹)).

complete coliform removal by CDI system are 30, 60, and 120 min for 1,000; 10,000; 100,000 MPN coliforms, respectively. The highest removal rate of coliform (5 LR) and 4 LR occurred for 100,000 and 10,000 MPN coliform at 120 and 60 min, respectively.

3.2.4. Effect of TDS

The GO/G5/Ag (5%) nanocomposite electrode's water deionization capability was determined using different concentrations of NaCl solution (1,000; 1,500; 5,000; 20,000 mg L⁻¹) at 5–90 min contact times. Also, Caspian

seawater (20,000 mg L⁻¹) was tested as a real sample. Experimental results (Fig. 9a) showed that the introduced system has excellent potential for water desalination.

To determine TDS's impact on coliform removal, NaCl solution with various concentrations (500; 1,000; 1,500; 5,000 mg L⁻¹) containing 10,000 MPN coliform was tested

within 15–60 min. The experimental results (Fig. 9b) indicated that the increasing TDS of water has no significant effect on the CDI system's disinfection performance. Moreover, the experimental results confirmed that the introduced electrodes could disinfect water at TDS values up to 5,000 mg L⁻¹. Simultaneously, in the previous work,

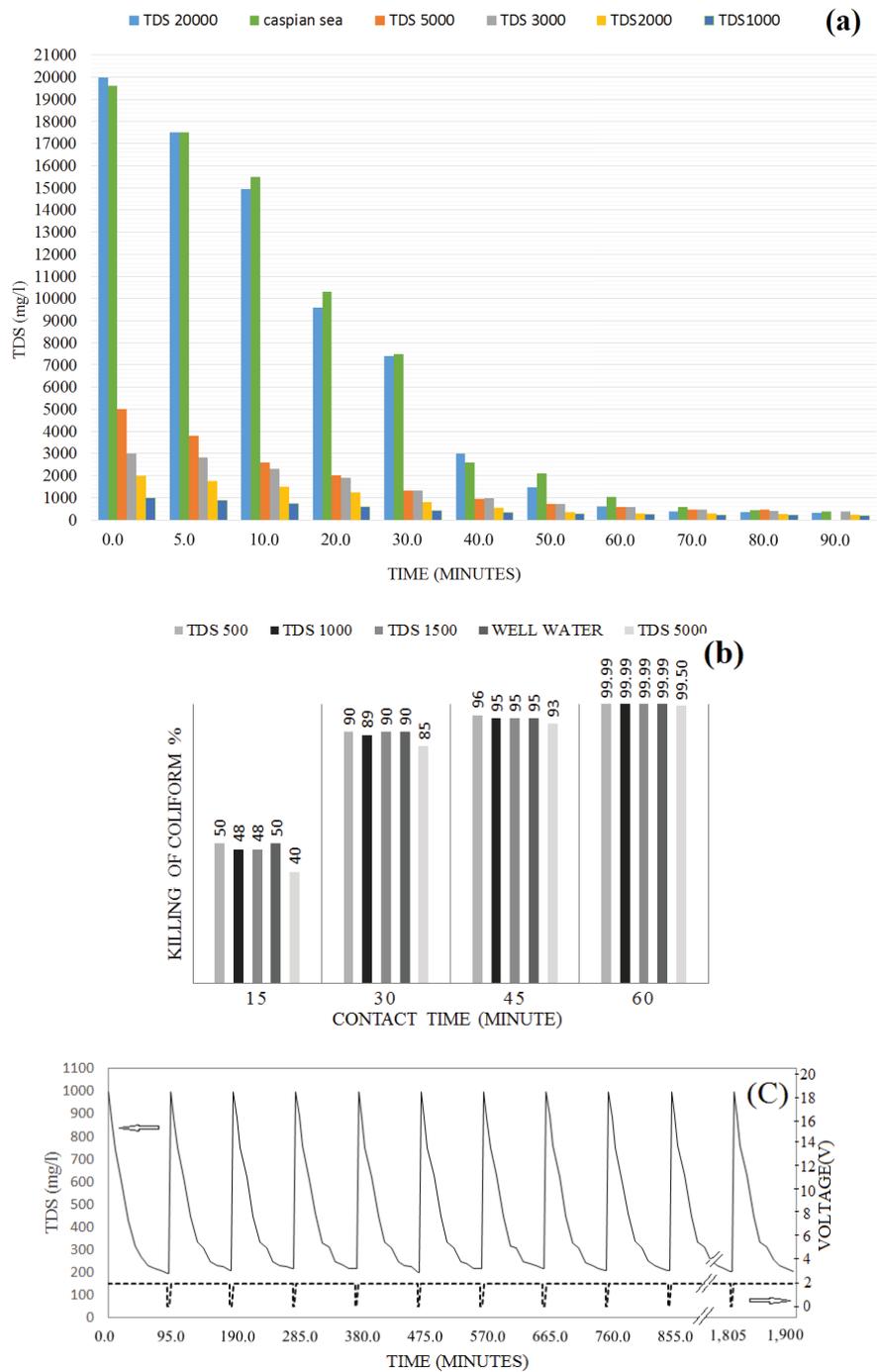


Fig. 9. (a) Effect of TDS on deionization performance in different concentrations of NaCl solution (1,000; 1,500; 5,000; 20,000 mg L⁻¹) at 5–90 min contact times, (b) effect of TDS on disinfection performance of GO/G5/Ag (5%) nanocomposite electrode in different concentrations of NaCl solution (500; 1,000; 1,500; 5,000 mg L⁻¹; 10,000 MPN of coliforms), and (c) cycle performance of GO/G5/Ag (5%) nanocomposite electrode in NaCl solution 1,000 mg L⁻¹.

the CDI system’s disinfection performance was evaluated using a NaCl solution with concentration varying from 200 to 500 mg L⁻¹ [5]. Also, the comparison between the prepared salt solution and a real sample was performed in which the well water (1,500 mg L⁻¹ and 10,000 MPN) was selected as a real sample, and similar results were obtained. The results showed that the introduced CDI system could reduce salinity and remove coliform successfully at the same time. Besides the disinfection, this CDI system also can be deionized water up to 80% (5,000 mg L⁻¹ and 10,000 MPN). In other words, the introduced CDI system can be converted TDS from 5,000 to 1,000 mg L⁻¹ within 60 min.

Also, the adsorption/desorption performance of the GO/G5/Ag (5%) electrode was evaluated for 20 cycles (Fig. 9c) under the same conditions (1,000 mg L⁻¹ NaCl solution). The result indicated no significant change in the efficiency of the electrodes in alternating cycles, which makes it an excellent candidate for the CDI electrode.

To further prove that GO/G5/Ag is beneficial to improving the CDI performance, the reported data about the

electrosorption capacity, SSA, desalination, or disinfection for different electrodes are listed in Table 2.

4. Conclusion

A potentially efficient system for water desalination and disinfection was developed via the synthesis of a new nanocomposite combined with the CDI system. Synthesized GO/G5/Ag is a novel nanocomposite composed of GO, five generations of the dendrimer, and Ag nanoparticles. The GO/G5/Ag nanocomposite was used to fabricate new electrodes for the CDI system. The surface of the AC electrodes was coated by a thin layer of GO/G5/Ag nanocomposite. The synthesized nanocomposite can be assumed as a practical and safe combination of Ag nanoparticles for water disinfection due to the covalent bonds between dendrimer and GO and also strong complexation between sulfur and Ag nanoparticles on the surface of dendrimer branches. The amounts of nanoparticles used in the electrodes showed a fundamental effect on the capacitive deionization system’s disinfection property.

Table 2
Comparison of proposed capacitive deionization electrode with the different electrodes

Material of electrode	Initial concentration	Electro sorption capacity (mg g ⁻¹)	Specific surface area (m ² g ⁻¹)	Applied voltage (V)	Efficiency (%)	References
TiO ₂ /ZrO ₂ nanofibers/ nitrogen co-doped activated carbon	NaCl: 50 mg L ⁻¹	3.98	3,675.47	0.8–1.2	Deionization: 71.19% Bacterial inactivation: maximum 55%	[2]
Straw waste derived graphitic porous carbon nanosheets	NaCl: 500 mg L ⁻¹	19.3	2,695	1.2	Deionization: 91%–100%	[25]
Carbon aerogel	NaCl: 100–1,000 mg L ⁻¹	21.41	779.04	1.5	Deionization: maximum 70%	[27]
Graphene oxide-graft-quaternized chitosan (GO-QC/AC)	NaCl: 100–200 mg L ⁻¹ Bacteria loading: 10 ⁶ CFU mL ⁻¹	N.S. ^a	N.S. ^a	2	Disinfection: 99.99%	[9]
Nanoporous activated carbon cloth	NaCl: 1,000–5,000 mg L ⁻¹ Bacteria loading: 10 ⁴ CFU mL ⁻¹	10.5	1,200	1.6	Deionization: 32% Disinfection: 66%	[32]
Flexible 3D nanoporous graphene	NaCl: 300 mg L ⁻¹ Bacteria loading: 10 ⁴ CFU mL ⁻¹	18.43	2,680	1.4	Disinfection: 98.55%–100% killing	[36]
GO/G5/Ag (5%) ^b	NaCl: 1,000–5,000 mg L ⁻¹ Bacteria loading: 10 ⁴ CFU mL ⁻¹	46.29	785	2	Deionization: 80% Disinfection: 99.9%	This work

^aN.S.: not specified;

^bGO/G5/Ag (5%): graphene oxide-dendrimer-silver (amounts of silver nanoparticle: 5%).

Moreover, contact time played an essential role in coliform removal and water desalination. The feed solution containing 1,000–100,000 MPN coliform and NaCl solution with 1,000–20,000 mg L⁻¹ concentrations was tested at 15–120 min and 5–90 min, respectively. The new CDI system showed that the desalination was 98% in salt concentration of 20,000 mg L⁻¹ at 90 min. Also, the introduced electrodes indicated that the disinfection was 99.9% (4 LR of coliform) and 90% (5 LR of coliform) within 60 min, and it could altogether remove coliform (100,000 MPN) at 120 min. Moreover, experimental results showed that the introduced electrodes could be disinfecting water in salinity level up to 5,000 mg L⁻¹, whereas in the previous work, the CDI system could be disinfecting water at 200 mg L⁻¹ of TDS [5]. To sum up, the designed CDI system is an excellent and appropriate alternative for desalination and traditional disinfection system due to low energy consumption (over 2 VDC), easy operation, low-cost, fast regeneration without any chemical consumption, and produce a by-product.

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