


Optimizing the desalination rate in a photoelectrocatalytic desalination cell (PEDC) by altering operational conditions

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ABSTRACT

Desalination of seawater is a promising response to solving the lack of drinkable water. The separation of cations and anions is carried out by inserting a desalination cell in the middle of a novel design of photoelectrocatalytic desalination cell (PEDC). Different parameters were evaluated and optimized for increasing the capability of system to desalt hypersaline water. Ultraviolet illumination (UV) was used as the driving force, exciting coated titanium nanotubes on the anode electrode, producing electron/hole pairs that degraded organic matter. Methylene blue degradation by UV irradiation was performed, owing to a high salt concentration level, and desalinated to produce electrical current. Performance of PEDCs was investigated by salt content, pH, and ion-exchange resin. The results indicated that higher total dissolved solid (TDS) removal occurred in acidic environments in anode chamber whereas the maximum produced electrical current occurred in alkaline environments in the cathode chamber. Also, the higher amount of salt content in the middle chamber resulted in the high TDS removal until the amount of electrical conductivity in the middle chamber reached 190 mS/cm. The TDS removal rates with and without using resins in the middle of the desalination cell after 10 days were 70.69% and 51.37%, respectively.

Key words: desalination, ion-exchange resin, methylene blue, pH, photoelectrocatalytic desalination cell, salt content

HIGHLIGHTS

- The effects of salt content, pH, and ionic exchange resin on the performance of photoelectrocatalytic desalination cells were investigated.
- The efficiency of the TDS removal was improved in an acidic environment when pH of the anolyte was 3.
- Higher TDS removal occurred by adding salt content in the middle chamber.
- The speed of TDS removal was increased by addition of ionic exchange resins.

1. INTRODUCTION

Nowadays, millions of humans are suffering from a lack of drinkable water (Gorjian & Ghobadian 2015). It is estimated that four billion people (nearly two-thirds of the world population) experience water stress at least one month per year (Davis *et al.* 2013; Mekonnen & Hoekstra 2016). Unfortunately, 80% of diseases in developing countries are due to low water quality and inefficient wastewater treatment systems. Because of this issue, it is estimated that more than 1.5 billion people have no access to clean water and more than 2.6 million people suffer from malfunctioning sewage systems (Hameeteman 2013). Therefore, the only possible sustainable solution is to use unconventional or non-traditional sources like seawater. However, these sources, such as oceans and seawaters containing 97.5% of the total water volume in the world, need to be desalinated to meet water shortage needs (Hameeteman 2013).

Fortunately, there are different technologies, such as thermal, membrane, evaporation, freezing based on desalination methods (Elimelech & Phillip 2011), multi-stage flash distillation (MFD), multi-effect distillation (MED), and reverse osmosis (RO) as the most common technologies, to solve this devastating problem (Khawaii *et al.* 2008). Such technologies have one main drawback in producing hypersaline streams. Moreover, such desalination technologies are unsustainable due to the energy consumption that makes their economic feasibility doubtful (Jeon *et al.* 2018). Among the mentioned methods, the

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RO method has more tangible benefits; however, this method may cause severe problems for the environment due to produced brackish water in addition to high energy consumption (Khawaji *et al.* 2008; Mezher *et al.* 2011). Therefore, an alternative approach needs to be found for solving this problem. One of the most popular and emerging technologies for water desalination is applying the photoelectrochemical method. This technology uses an unlimited resource, i.e., solar energy, as a driver to remove salt, thus saving a lot of energy and lowering the cost of the procedure (Dariani *et al.* 2016; Jeon *et al.* 2018). It has been indicated that typical wastewater contains much higher energy content than the energy required for its treatment process.

Kim *et al.* (2018) developed a three-in-one sunlight-driven electrochemical system to enhance desalination function, organic photodegradation, and H₂ production. In this study, an innovative method was applied and the impact of membrane in the process was evaluated for the first time. Instead of a bio-anode used in microbial desalination cells (MDC) in previous studies, a nanophotocatalyst coated on an electrode is inserted into the anode. In fact, this study developed previous methods by an innovative change in the anode's electrode.

The photoelectrocatalytic (PEC) method is an advanced oxidation process (AOP) method applied to remove recalcitrant compounds (Jeon *et al.* 2018). The PEC mechanism is just like other photocatalytic systems and uses photo-induced charge transfer made by electron/hole pairs creation (Tian *et al.* 2020). The electricity generated from the photocatalytic procedure is utilized to desalinate the saline water. Since then, different studies have been performed to investigate the workability of saltwater desalination coupled with the PEC system which is called a photoelectrocatalytic desalination cell (PEDC) (Jeon *et al.* 2018; Chen *et al.* 2019; Tian *et al.* 2020). Unlike MDC, in PEDC, microorganisms do not need to degrade organic materials. Thus, this method does not have the limitations of biological processes. The results of this study show that PEDC desalinates hyper-saline streams. Thus, it is a suitable choice to desalinate the rejected stream part of RO and recycle the desalinated stream to create a zero liquid discharge system.

Moreover, untreated industrial wastewaters can jeopardize water sources; thus, they should be thoroughly treated (Dariani *et al.* 2016). Textile wastewater is one type of industrial wastewater existing in considerable volumes regarding the consumption of 200 L of water per 1 kg textile, containing a high concentration of organic matter and can be a good source for electrochemical degradation in this study (Yaseen & Scholz 2019). Such wastewaters are difficult to biodegrade with biological treatments due to their complex aromatic structure (Yuangpho *et al.* 2018). So processes such as MDC, which are used for seawater desalination successfully due to toxic compound in textile wastewater, cannot be a feasible method for treatment of this type of wastewater. While, in PEDC systems, overall efficiency does not rely on the performance of microorganisms, so the toxicity of textile wastewater would not interfere with the process. Methylene blue (MB) is one of the most common dye components in textile wastewater and is the main reason for toxic streams (Zhao *et al.* 2016; Hunge *et al.* 2017; Yuangpho *et al.* 2018). Degradation of MB accompanied by carbon reduction has been established to be a suitable electrochemical driving force to stimulate the desalination process and such studies give a good idea for integrating different processes to achieve the best result for MB degradation (Luan *et al.* 2022).

Therefore, in this work, in a novel design the separation of cations and anions is carried out by inserting a desalination cell in the middle of PEC cells. This development in previous study optimizes the desalination rate and MB degradation significantly (Rahmaninezhad *et al.* 2019, 2020a, 2020b). By adding resin for the first time, the reduction of ionic resistance for transmission through the membranes and increase in the mobility will lead to a striking improvement in the process. Ultra-violet (UV) light is used as the driving force and excites coated titanium nanotubes (TNTs) on the anode electrode, producing electron/hole pairs that degrade organic matter. We investigated MB removal, and high salt removal with these new emerging technologies. This has, to the best of the authors' knowledge, not been presented in the literature before.

2. MATERIALS AND METHODS

2.1. Pilot description

The pilot is illustrated in Figure 1, consisting of three equal chambers separated by an anion exchange membrane (AEM) (Fuel Cell Store, FAB-PK-130, USA) and a cation-exchange membrane (CEM) (Fuel cell Store, FKB-PK-130, USA). A UV lamp (Philips Actinic BL TL, Poland) is used to excite titanium nanotubes (TNTs) coated on a titanium sheet (Sigma-Aldrich, 99.99% purity) as an anode electrode. MB is used in the anolyte as the only electron donor in the PEC process. Produced electrons are carried through a titanium wire as an external circuit to the cathode electrode (Avcarb, USA). An aerator (AP-9804, Aqua, China) is used to produce oxygen in the catholyte which consists of 800 ml of ethylene glycol, 0.3 weight percent (2.67 g)

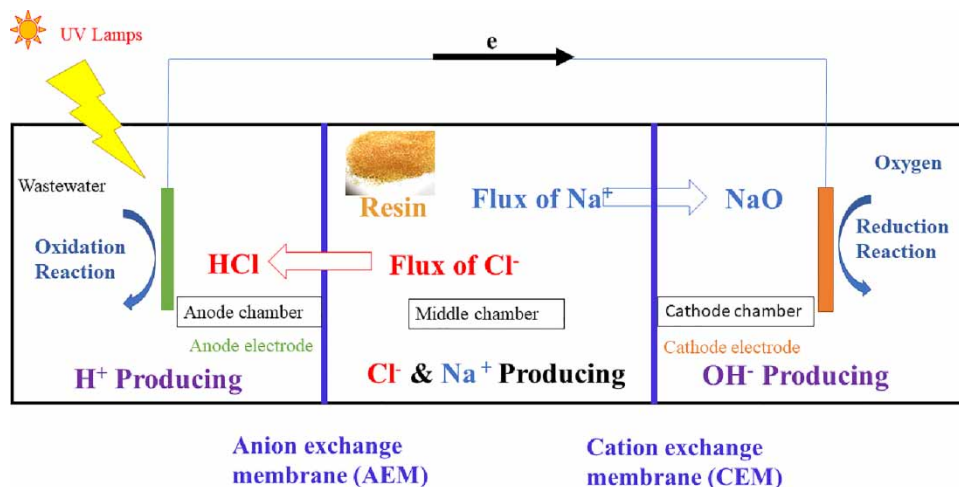


Figure 1 | Schematic of the photoelectrocatalytic desalination cell (PEDC) pilot.

of NH_4F , and 2 weight percent (17.81 g) of distilled water, as an electron scavenger. A titanate nanotube (TNT) anode electrode was fabricated by two-step electrochemical anodization thoroughly described in our previous research.

2.2. Desalination mechanisms

The driving force in this method is extracting the organic content of wastewater. In this study, MB is chosen as industrial wastewater to be degraded photoelectrocatalytically with photons emitted from the UV lamp. In our previous studies (Rahmaninezhad *et al.* 2019), the MB concentration and the illumination power led to maximum efficiency. Therefore, in PEDC, the MB concentration in the anolyte and the illumination power with the UV lamp are 17 mg/l and 8 W, respectively. Illuminated photons excite the TNT coating using the two-step anodization method on the titanium electrode. In the anodic half-reaction, excited TNTs produce pairs of holes/electrons. Holes oxidize the branched organic molecules of MB to smaller ones as the blue color changes to a colorless solution. During MB degradation, hydroxide is created as a product of a half anodic reaction (Equation (1)). The existence of OH^- in the anolyte creates a repellent force to anions and interferes with charge transfer between the anolyte and catholyte and the maximum produced power is in the highest amount of OH^- when the pH of the anolyte is maximum. Produced electrons from the surface of the anode electrode are transferred to the cathode electrode via an external circuit. In this study, titanium is used as a conductor wire to minimize external resistivity:



Electrons are spread all through the surface of the cathode electrode to react with oxygen molecules. High durability and conductivity are the main features of a suit electrode. Thus, a carbon cloth with a resistivity of less than 4 m Ω is used in PEDC. Mediators are usually utilized in biological electrochemical systems (BES) to assist electron movement in the catholyte (Khawaji *et al.* 2008). However, several mediators have been studied and, in this study, MB and platinum (Pt) wire are used as mediators that ease the transfer of electrons from the surface of cathode into the catholyte. Therefore, 1.7 mg/l MB is poured into the catholyte at the beginning of each step. Moreover, a 2.5 m Pt wire (Nano-Bazar Company, Iran) with a thickness of 40 μm is selected and woven on the surface of the carbon cloth electrode. During the cathodic half-reaction, hydroxide is produced as a result of electron and oxygen reactions.

The produced H^+ in the anolyte and OH^- in the catholyte create an electrochemical polarity between the two sides of the middle chambers. Since there is an ion-exchange membrane (IEM) between the anolyte and the middle chamber, and also, there is CEM between the catholyte and the middle chamber, H^+ and OH^- could not move to the middle chamber. Conversely, anions and cations in the middle chamber stem from polarity and attraction, moving toward the anolyte and catholyte, respectively. Therefore, the brine water is desalinated with the ionic separation process. Anions moved to the anolyte-like Cl^- for NaCl to create HCl and cations moved to the catholyte-like Na^+ to produce NaOH.

2.3. Measurement

A digital multimeter (UNI-T 139C, Hong Kong) is used to measure the voltage, amperage, and resistance between the anode and cathode electrodes. A pH meter (Metrohm 691, Swiss) is adjusted with sulfuric acid and sodium hydroxide to measure the pH of electrolytes. Moreover, a conductivity meter (Inolab cond 7110, Germany) is used to investigate conductivity. All the measurements are performed in triplicate and at room temperature (25 °C) to prevent the effect of temperature changes on the results. Because of the photoelectrocatalysis of organic matter, total electrons transferred from anode electrodes to maximum-produced electrons in the anolyte represent coulombic efficiency (CE) (Kim & Logan 2013) (Equation (2)) (Rahmaninezhad *et al.* 2019):

$$CE = \frac{M_{O_2} \int I dt}{n_e F V_{\text{anode}} \Delta \text{COD}_{\text{MB}}} \times 100 \quad (2)$$

In the aforementioned equation, M_{O_2} is the molecular weight of oxygen, F is the Faraday constant, n_e is the number of required electrons for oxygen reduction in the water, V_{anode} is the volume of the anode chamber, $\Delta \text{COD}_{\text{MB}}$ represents a difference in the initial and final chemical oxygen demand (COD) amount of MB, and I is the electrical current.

2.4. Analyses

Different concentrations of NaCl are poured into the middle chamber as saline water in these experiments. The electric conductivity (EC) of the solution is measured using a conductivity meter to calculate the removal percent of total dissolved solids (TDS). The pH of the chambers is determined using a pH meter to measure the acidity and alkalinity of the electrolytes. The amperage, voltage, and resistance of the external circuit between the electrodes are measured using a digital multimeter. The MB concentration in the anolyte is detected using a spectrophotometer (DR 5000, HACH, USA). The MB removal (%) of the anolyte, TDS removal (%) in the middle chamber, the pH and TDS amount of changes in the anolyte and catholyte, and the produced power between the two electrodes are calculated as dependent variables to investigate the PEDC performance.

3. RESULTS AND DISCUSSION

3.1. Salt content in the middle chamber

The middle chamber is filled with different salt concentrations in order to investigate the impact of initial salt content on TDS removal efficiency. The results show that PEDC can decrease the amount of EC in the middle chamber after 10 days. Moreover, the maximum TDS removal (51.37%) happens when the initial amount of EC in the middle chamber is 190 mS/cm. (Figure 2). An increase in the salt content of the middle chamber causes the removal percentage of TDS to increase up to the EC of 190 mS/cm. After this point, the TDS removal percentage decreases gradually.

High salt concentration reduces the internal resistivity of PEDC; therefore, the increase in ionic movements raises the TDS removal percentage up to the optimum point. After this point, the TDS removal percentage decreases due to the limitation in the external circuit's capacity. When one mole of the electron is produced and then transferred from the anode to the cathode electrodes, this allows one mole cation and one mole anion to move toward the catholyte and anolyte, respectively. When the capacity of the external circuit exceeds the number of cations and anions in the middle chamber, an increase in the salt content of the middle chamber cannot increase the TDS removal percentage. Moreover, it creates a disturbance in the ionic movement and decreases the TDS removal percentage. In previous research about MDCs, we witnessed a reduction in the TDS removal percentage (Mehanna *et al.* 2010; Zhang & He 2012; Zamanpour *et al.* 2017) and TDS removal rates by an increase in salt content in the middle chamber (Mehanna *et al.* 2010; Zhang & He 2012; Zamanpour *et al.* 2017).

An increase in the salt content of the middle chamber affects the maximum produced power between the cathode and anode electrode. In this study, the term produced power refers to the maximum amount of produced power which is measured. The amount of produced power is related to the value of voltages between two electrodes multiplied by electron current in the external circuit. Figure 3 demonstrates the initial salt concentration in the middle chamber which has a direct relation with produced power. Unlike produced power, TDS removal depends only on ionic movements, while ionic movements and cathodic and anodic half-reactions influence the produced power. The production of H^+ and OH^- increases the voltage difference between anolyte and catholyte. Therefore, it is concluded that after the optimum point in Figure 2, when ionic movement decreases, the production of H^+ and OH^- is the main reason for the increase in the produced

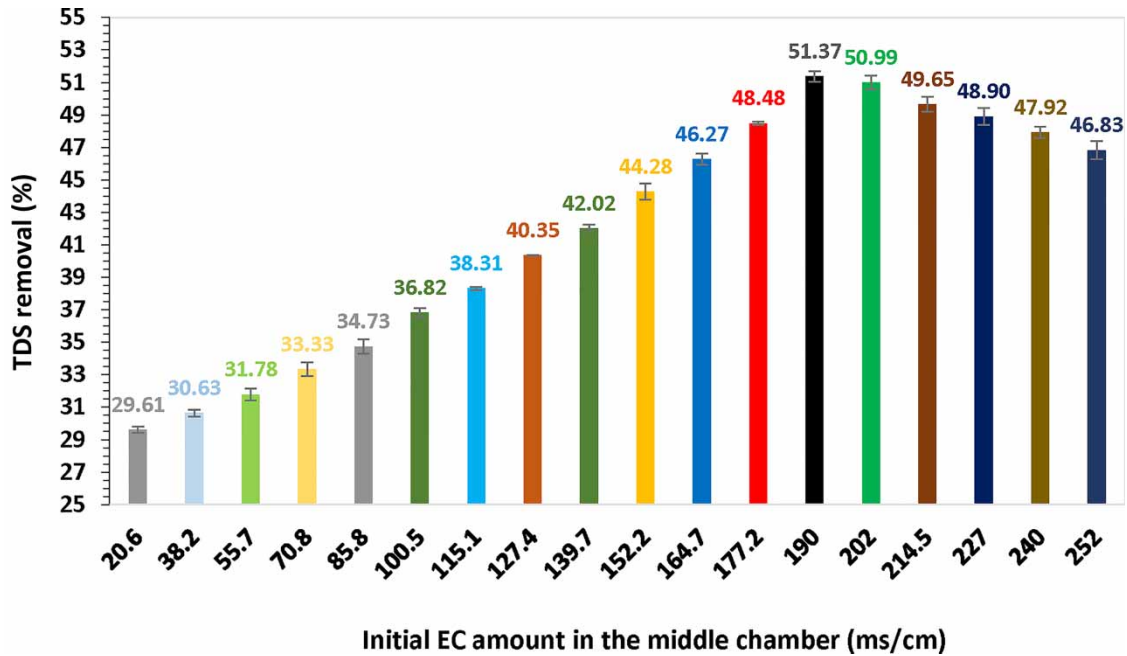


Figure 2 | TDS removal percent vs. initial EC amount in the middle chamber.

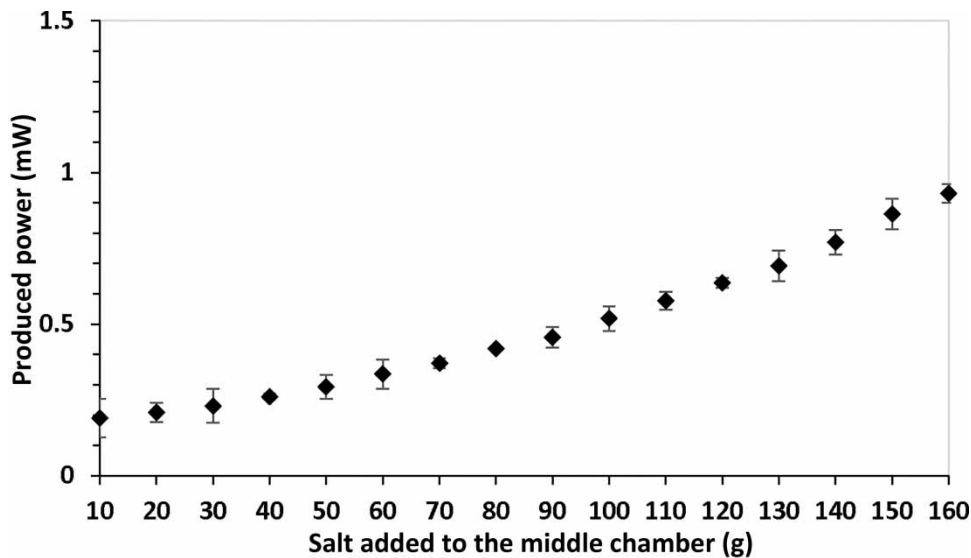


Figure 3 | The effect of salt content of the middle chamber on produced power.

power. Tian *et al.* reached the same conclusion that the higher the inlet TDS of the middle chamber, the higher the produced power will be as a result (Tian *et al.* 2020).

Due to the electrochemical reactions of redox, as time moves forward, the intensity of electrical current in the system between two electrodes slightly falls, as demonstrated in Figure 4 (Chen *et al.* 2019). It can be inferred that, because the concentration of MB is decreased as the reaction is conducted, the density of electron donation is decreased. The same trend is also observed in similar studies applying these methods (Luo *et al.* 2012; Tian *et al.* 2020). It should be noted that in this method, unlike microbial fuel cells or MDC (Jacobson *et al.* 2011; Zhao *et al.* 2016), there is no need to have a start-up time before and after operation and recovery time. After passing the first minutes of the experiment, the electrical current rises to its maximum value.

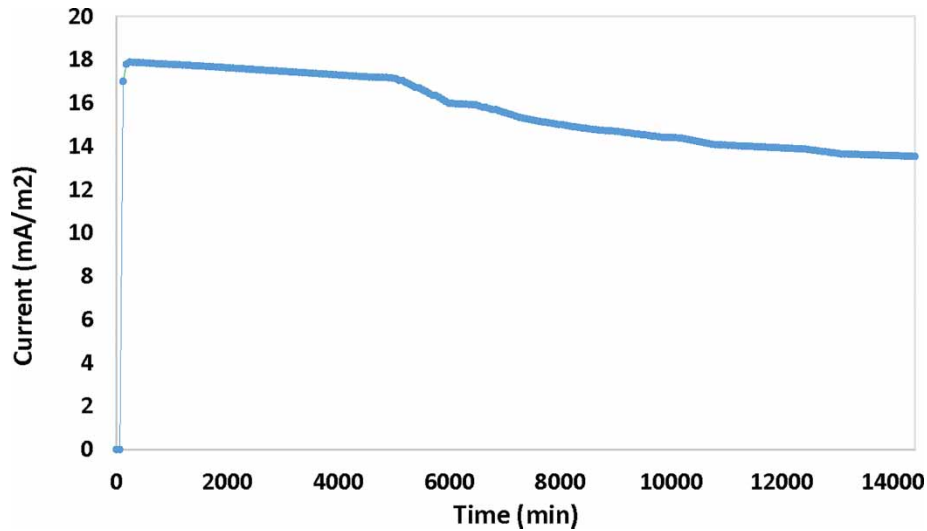


Figure 4 | The current values versus time.

3.2. Salt content in the catholyte

The effect of the decrease in the ohmic resistivity of the cathode chamber is investigated by adding different salt concentrations to the catholyte. Here, 1, 5, or 10 g salt are added to the catholyte and its TDS removal is compared with no salt added catholyte. As Figure 5(a) shows, the concentration of salt has a reverse relationship with TDS removal efficiency. Adding salt to the catholyte has positive and negative effects on the performance of PEDC. The positive effect, as reported in the previous section, is about the increase in the conductivity of PEDC by adding salt content to the catholyte, therefore, it is predicted to raise the TDS removal efficiency. But the negative effect is related to the desalination mechanisms in PEDC. PEDC can desalinate salt water by two distinct mechanisms. Cations and anions are separated in electrolysis because of an electrical field created between cathode and anode electrodes. Produced H^+ in the anolyte and OH^- in the catholyte attract anions and cations; therefore, saltwater is desalinated. Dialysis is another mechanism that works because of the difference in the osmotic pressure of the middle chamber with the anode and cathode chambers. Ions migrate from the high concentration of salt in the middle chamber to the lower one at the electrolytes. According to these mechanisms, an increase in the salt

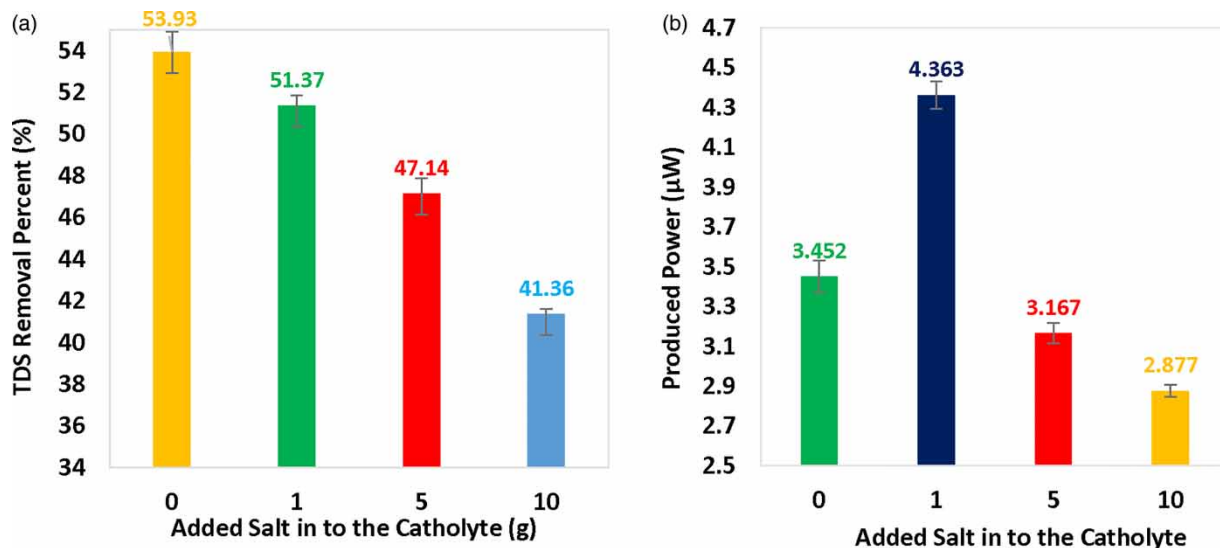


Figure 5 | (a) TDS removal percent with different salt content in the catholyte. (b) Produced power with different salt content in the catholyte.

concentration of electrolytes eliminates the osmotic pressure differences, decreasing the TDS removal efficiency. Since dialysis plays a more important role in comparison with conductivity, the TDS removal efficiency falls when the salt content in the catholyte increases.

PEDC has the maximum produced power when 1 g of salt is added to the catholyte (Figure 5(b)). Added salt increases the conductivity in the catholyte but, when this amount is more than 1 g, it has an adverse effect on the ion separation because of ionic disturbance and diminishing the dialysis, therefore produced power decreases. Similar results confirmed this effect, which is caused by an increase in the ion concentration augmenting EC so it decreases ohmic resistance and makes the separation and transfer of the photogenerated charge carriers easier and increases the speed of the ion transport from the middle chamber (Kim *et al.* 2018). When the added salt is increased to 5 g, the maximum amount of CE occurs, 80%. When 1 g of salt is added to the catholyte, an increase to a maximum of produced power is seen, establishing observed current and observed voltage differences, reaching 0.68 (mW/m²), 32.63 (mA/m²), and 20.88, respectively.

3.3. pH of the anolyte

The amount of initial pH is another parameter that influences the performance of PEDC. PEDC was run in three steps when the initial pH of anolyte was 3, 7, and 11. These three pH were selected to investigate the system operation efficiency when the anolyte is in the acidic, neutral and alkaline range. During this experiment, 1 g salt is added to the catholyte. The results show (Figure 6) that the maximum TDS removal happens in an acidic condition, while the minimum one occurs under alkaline condition. Protons are naturally produced in the anolyte as a product of anodic half-reaction. In acidic conditions, a higher H⁺ concentration in the anolyte attracts more anions from the middle chamber and, as a result, TDS removal percentage increases. In contrast, the existence of OH⁻ in the anolyte creates a repellent force to anions and interferes with charge transfer between anolyte and catholyte.

The maximum produced power is the highest amount when the pH of the anolyte is 11. It should be noted that the maximum produced power, the maximum observed current and the maximum observed voltage difference are 1.93 (mW/m²), 55.05 (mA/m²), and 35.23, respectively. Also, F. Chen *et al.* claimed that electrical current increases in the photoredox desalination method (Chen *et al.* 2019).

3.4. Ion-exchange resin

The effect of ion-exchange resin (IER) on the performance of PEDC is evaluated (Figure 7). The strong resin added to the middle chamber (5 × 11 × 11 cm) that filled all the 605 ml chamber volume was used as a porous medium. The result shows that IERs resins speed the desalination rate up and raise the amount of ionic separation because of a decrease in

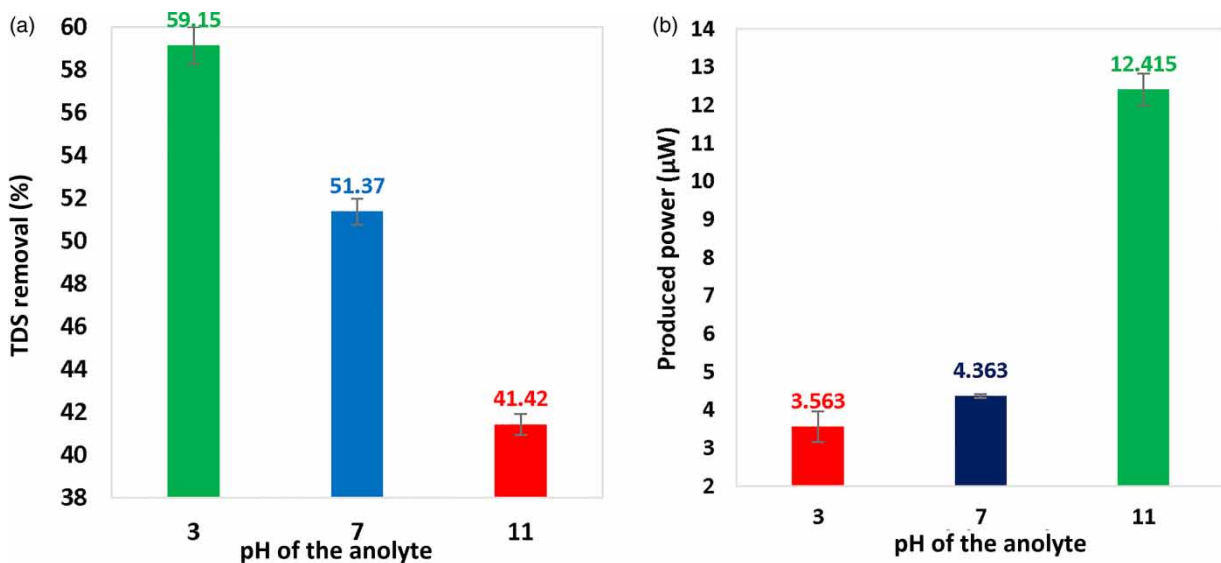


Figure 6 | (a) TDS Removal Percent with different pH of the anolyte, (b) Produced power with different pH of the anolyte.

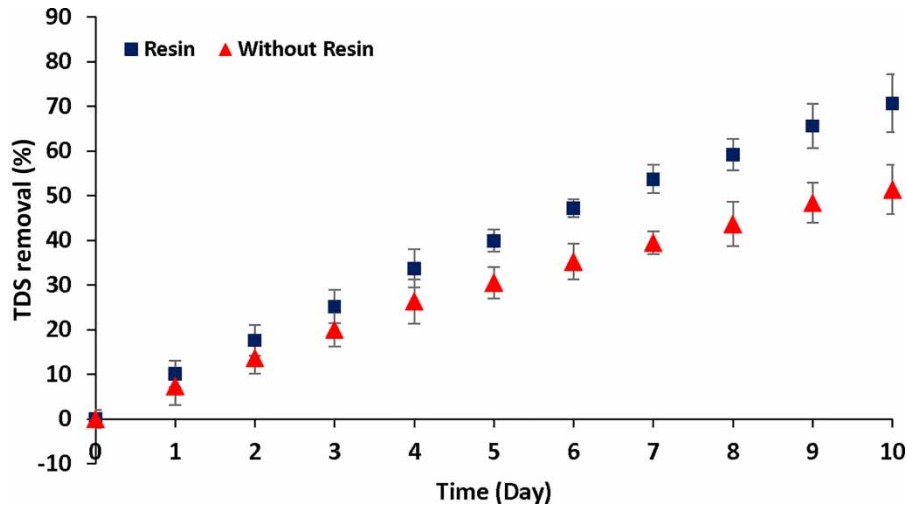


Figure 7 | TDS removal percent on different days.

internal resistivity (Figure 3). The TDS removal efficiency with and without using resins after 10 days is 70.69% and 51.37%, respectively. Also, the salt removal rate is 11.52 and 9 g/d.m² when PEDC is run with and without IERs. Resins decrease the internal resistivity and assist ions to transfer quickly. In addition, adding resins increases the electron moving via an external circuit. As a result, resins augment the amount of produced power between the anode and cathode electrodes. When there is no resin in the PEDC, the maximum produced power is 4.363 mW/m² while, when the resin is added, this figure rises to 5.468 mW/m².

Higher desalination and flow efficiency can be achieved by mixing anion- and cation-exchange resins in desalination chambers (Zhang *et al.* 2012, 2015). Considering the higher conductivity of the IER than the bulk solution, almost all ions are transferred to the IEM by IER. The existence of these resins results in an increase in the conductivity of the desalination chamber and the facilitated transfer of ions from the bulk solution to the IEM. Similarly, the presence of IER both increases the desalination efficiency and reduces the concentration of salt extracted from the desalination chamber. The lower the initial salt concentration, the higher the efficiency would be, probably due to the limited ion transport capacity of the resins (Zhang *et al.* 2012, 2015).

IERs can act as a bridge between ions and IEMs through the bulk liquid which decreases the resistance for transferring ions and increases the mobility of these transportations. In Zhang *et al.* (2012, 2015), MDC cells reduced the salt concentration from 720 mg/l to 50 mg/l within 80 h. However, the concentration decreased from 720 mg/l to 40 mg/l within 30 hours when the desalination chamber was filled with resin. Moreover, the internal ohmic resistance decreased due to the presence of IERs.

According to the report (Zhang *et al.* 2015), when using the resin, the internal ohmic resistance decreased from about 7,383 to 159 ohms and from 641 to 277 ohms for the salt concentrations 50 and 700 mg/l, respectively.

Table 1 | Comparison of the maximum produced current density of some previous studies in the PEC process

Photocatalyst	Sacrificial agent	Current density (mA m ⁻²)	Ref.
TiO ₂	Formic acid	1,500	Seger <i>et al.</i> (2012)
TiO ₂	Ar + H ₂ O	150	Iwu <i>et al.</i> (2013)
WO ₃	Ethanol	6,000	Sfaelou <i>et al.</i> (2016)
WO ₃	Water	800	Esposito <i>et al.</i> (2012)
Ti-Fe ₂ O ₃	Ethanol	3,200	Kalamaras <i>et al.</i> (2016)
TNT	Methylene blue	55.05	This work
CdS	Ascorbate + glucose	1,670	Liang <i>et al.</i> (2016)

The maximum produced current density in this process was compared to other similar PEC process studies which are shown in Table 1.

4. CONCLUSION

In this study, the degradation of MB was investigated using a desalination method called photoredox desalination. Also, high salt removal was calculated in this method for the first time. A photocatalyst can produce protons in the anolyte and hydroxide ions in the catholyte. A desalination cell is placed in the middle of the anode and cathode chambers, causing a separation of the anions and cations from the middle chamber. These separations cause a movement for anions to the anolyte and for cations to the catholyte. It should be noted that the former creates acid and the latter creates the base. The advantages of this desalination method outweigh the benefits of MDCs. These results show that the concentration of salt has a direct effect on TDS removal and also it increases the produced power. Also, the more acidic the condition in the anolyte, the higher TDS removal will be. In contrast, the existence of OH^- in the anolyte increases produced power. Moreover, IERs increase the speed of TDS removal.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Chen, F., Karthick, R., Zhang, Q., Wang, J., Liang, M., Dai, J., Jiang, X. & Jiang, Y. 2019 Exploration of a photo-redox desalination generator. *Journal of Materials Chemistry A* **7** (35), 20169–20175.
- Dariani, R. S., Esmaeili, A., Mortezaali, A. & Dehghanpour, S. 2016 Photocatalytic reaction and degradation of methylene blue on TiO_2 nano-sized particles. *Optik* **127** (18), 7143–7154.
- Davis, R. J., Kim, Y. & Logan, B. E. 2013 Increasing desalination by mitigating anolyte pH imbalance using catholyte effluent addition in a multi-anode bench scale microbial desalination cell. *ACS Sustainable Chemistry & Engineering* **1** (9), 1200–1206.
- Elimelech, M. & Phillip, W. A. 2011 The future of seawater desalination: energy, technology, and the environment. *Science* **333** (6043), 712–717.
- Esposito, D. V., Forest, R. V., Chang, Y., Gaillard, N., McCandless, B. E., Hou, S., Lee, K. H., Birkmire, R. W. & Chen, J. G. 2012 Photoelectrochemical reforming of glucose for hydrogen production using a WO_3 -based tandem cell device. *Energy & Environmental Science* **5** (10), 9091–9099.
- Gorjian, S. & Ghobadian, B. 2015 Solar desalination: a sustainable solution to water crisis in Iran. *Renewable and Sustainable Energy Reviews* **48**, 571–584.
- Hameeteman, E. 2013 Future water (in)security: facts, figures, and predictions. *Global Water Institute* **1**, 1–16.
- Hunge, Y. M., Mahadik, M. A., Moholkar, A. V. & Bhosale, C. H. 2017 Photoelectrocatalytic degradation of phthalic acid using spray deposited stratified WO_3/ZnO thin films under sunlight illumination. *Applied Surface Science* **420**, 764–772.
- Iwu, K. O., Galeckas, A., Kuznetsov, A. Y. & Norby, T. 2013 Solid-state photoelectrochemical H_2 generation with gaseous reactants. *Electrochimica Acta* **97**, 320–325.
- Jacobson, K. S., Drew, D. M. & He, Z. 2011 Use of a liter-scale microbial desalination cell as a platform to study bioelectrochemical desalination with salt solution or artificial seawater. *Environmental Science & Technology* **45** (10), 4652–4657.
- Jeon, T. H., Koo, M. S., Kim, H. & Choi, W. 2018 Dual-functional photocatalytic and photoelectrocatalytic systems for energy-and resource-recovering water treatment. *ACS Catalysis* **8** (12), 11542–11563.
- Kalamaras, E., Dracopoulos, V., Sygellou, L. & Lianos, P. 2016 Electrodeposited Ti-doped hematite photoanodes and their employment for photoelectrocatalytic hydrogen production in the presence of ethanol. *Chemical Engineering Journal* **295**, 288–294.
- Khawaji, A. D., Kutubkhanah, I. K. & Wie, J. M. 2008 Advances in seawater desalination technologies. *Desalination* **221** (1–3), 47–69.
- Kim, Y. & Logan, B. E. 2013 Microbial desalination cells for energy production and desalination. *Desalination* **308**, 122–130.
- Kim, S., Piao, G., Han, D. S., Shon, H. K. & Park, H. 2018 Solar desalination coupled with water remediation and molecular hydrogen production: a novel solar water-energy nexus. *Energy & Environmental Science* **11** (2), 344–353.

- Liang, X., Liu, J., Zeng, D., Li, C., Chen, S. & Li, H. 2016 Hydrogen generation promoted by photocatalytic oxidation of ascorbate and glucose at a cadmium sulfide electrode. *Electrochimica Acta* **198**, 40–48.
- Luan, N. H., Yang, Y. T. & Chang, C. F. 2022 Electrochemical degradation of methylene blue accompanied with the reduction of CO₂ by using carbon nanotubes grown on carbon fiber electrodes. *Sustainable Environment Research* **32** (1), 1–14.
- Luo, H., Xu, P., Jenkins, P. E. & Ren, Z. 2012 Ionic composition and transport mechanisms in microbial desalination cells. *Journal of Membrane Science* **409**, 16–23.
- Mehanna, M., Saito, T., Yan, J., Hickner, M., Cao, X., Huang, X. & Logan, B. E. 2010 Using microbial desalination cells to reduce water salinity prior to reverse osmosis. *Energy & Environmental Science* **3** (8), 1114–1120.
- Mekonnen, M. M. & Hoekstra, A. Y. 2016 Four billion people facing severe water scarcity. *Science Advances* **2**, e1500323.
- Mezher, T., Fath, H., Abbas, Z. & Khaled, A. 2011 Techno-economic assessment and environmental impacts of desalination technologies. *Desalination* **266** (1–3), 263–273.
- Rahmaninezhad, S. A., Mehrdadi, N. & Mahzari, Z. 2019 Comparison of the ultra-filtration and cation exchange membrane performance in photo electro catalytic degradation of methylene blue. *International Journal of Energy and Environment* **10** (5), 271–280.
- Rahmaninezhad, S. A., Mehrdadi, N. & Mahzari, Z. 2020a Using ultra filtration membrane in photo electrocatalytic desalination cell (UF-PEDC). *Desalination* **486**, 114483.
- Rahmaninezhad, S. A., Mehrdadi, N. & Mahzari, Z. 2020b Modeling and optimizing the photo-electro-catalytic degradation of methylene blue by response surface methodology. *Optik* **202**, 163711.
- Seger, B., Lu, G. Q. M. & Wang, L. 2012 Electrical power and hydrogen production from a photo-fuel cell using formic acid and other single-carbon organics. *Journal of Materials Chemistry* **22** (21), 10709–10715.
- Sfaelou, S., Pop, L. C., Monfort, O., Dracopoulos, V. & Lianos, P. 2016 Mesoporous WO₃ photoanodes for hydrogen production by water splitting and PhotoFuelCell operation. *International Journal of Hydrogen Energy* **41** (14), 5902–5907.
- Tian, H., Wang, Y. & Pei, Y. 2020 Energy capture from thermolytic solutions and simulated sunlight coupled with hydrogen peroxide production and wastewater remediation. *Water Research* **170**, 115318.
- Yaseen, D. A. & Scholz, M. 2019 Impact of pH on the treatment of artificial textile wastewater containing azo dyes using pond systems. *International Journal of Environmental Research* **13** (2), 367–385.
- Yuangpho, N., Trinh, D. T., Channei, D., Khanitchaidecha, W. & Nakaruk, A. 2018 The influence of experimental conditions on photocatalytic degradation of methylene blue using titanium dioxide particle. *Journal of the Australian Ceramic Society* **54** (3), 557–564.
- Zamanpour, M. K., Kariminia, H. R. & Vosoughi, M. 2017 Electricity generation, desalination and microalgae cultivation in a biocathode-microbial desalination cell. *Journal of Environmental Chemical Engineering* **5** (1), 843–848.
- Zhang, B. & He, Z. 2012 Integrated salinity reduction and water recovery in an osmotic microbial desalination cell. *RSC Advances* **2** (8), 3265–3269.
- Zhang, F., Chen, M., Zhang, Y. & Zeng, R. J. 2012 Microbial desalination cells with ion exchange resin packed to enhance desalination at low salt concentration. *Journal of Membrane Science* **417**, 28–33.
- Zhang, Y., Zhao, G., Shi, H., Zhang, Y. N., Huang, W., Huang, X. & Wu, Z. 2015 Photoelectrocatalytic glucose oxidation to promote hydrogen production over periodically ordered TiO₂ nanotube arrays assembled of Pd quantum dots. *Electrochimica Acta* **174**, 93–101.
- Zhao, Q., Li, Z., Deng, Q., Zhu, L., Luo, S. & Li, H. 2016 Paired photoelectrocatalytic reactions of glucose driven by a photoelectrochemical fuel cell with assistance of methylene blue. *Electrochimica Acta* **210**, 38–44.

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