An integrated approach to enhance the desalination process: coupling reverse osmosis process with microbial desalination cells in the UAE

Tarun Shivakumar and Vahid Razaviarani

ABSTRACT

The growing need for better sources of fresh water has led to water desalination to become a dominant technology in the water industry, especially in arid countries like the UAE. Across the globe, reverse osmosis (RO) has become the key method used to desalinate seawater. Due to the high energy requirements of RO desalination, the need to reduce the energy load has become a pertinent area of research. Microbial desalination cells (MDCs) are an emergent technology that show great promise when integrated into the RO desalination process. Studies have shown that a significant proportion of the energy utilized in RO desalination could be eliminated by using MDCs as a pretreatment process. In this study, the integration of various MDC types into the pretreatment process for RO desalination were compared and explored. Existing MDC integration setups were briefly explained. Research was split into possible configurations for the integration. This includes optimization of key parameters such as anodic inoculum, feed inlet ratios and accompanying pretreatment processes. The limitations and challenges faced in the integration were investigated and the required future studies aligned with subject was deliberated.

Key words | Global Water and Energy Crisis, microbial desalination cells, reverse osmosis, technology integration

Tarun Shivakumar
Vahid Razaviarani (corresponding author)
School of Engineering and Physical Sciences,
Heriot-Watt University,
Scotland,
UK
E-mail: *v.razaviarani@hw.ac.uk*

HIGHLIGHTS

- Water desalination using solo and integrated technologies.
- Numerous configurations of integrated microbial desalination cells and RO technology.
- Enhanced RO desalination process using pretreatment microbial desalination cells.
- Limitations and challenges of integration of microbial desalination technologies with RO.
- Critical parameters considered in the integration of microbial desalination cell with RO.

NOMENCLATURE

AD	Anaerobic Digester/ion
AEM	Anion Exchange Membrane
BOD	Biological Oxygen Demand
CEM	Cation Exchange Membrane
COD	Chemical Oxygen Demand
CTE	Charge Transfer Efficiency
DAF	Dissolved Air Floatation
ED	Electrodialysis
FO	Forward Osmosis
GO	Graphene Oxide

doi: 10.2166/ws.2020.375

HFM	Hollow Fiber Microfiltration
IEM	Ion Exchange Membrane
MCDI	Membrane Capacitive Deionization
MDC	Microbial Desalination Cell
MEC	Microbial Electrolysis Cells
MEDC	Microbial Electrolysis Desalination Cell
MF	Micro-Filtration
MFC	Microbial Fuel Cell
MSF	Multi-Stage Flashing
oMDC	Osmotic Microbial Desalination Cell
RO	Reverse Osmosis
SDR	Specific Desalination Rate
SMDC	Stacked Microbial Desalination Cell
SWRO	Seawater Reverse Osmosis
UMDC	Upflow Microbial Desalination Cell
UF	Ultrafiltration
USMDC	Upflow Stacked Microbial Desalination Cell

INTRODUCTION

Fresh water scarcity is becoming a global issue due to the available fresh water in the world being rapidly depleted. Fresh water makes up only 2.5% of the total water resources in the world, and less than 1% of it is accessible. This has led a large focus on alternative methods of obtaining fresh water, such as desalination of seawater or wastewater treatment, across the world (Qasim *et al.* 2019). In dry and arid countries such as the UAE and other Gulf Cooperation Council (GCC) countries, desalination is the most-utilized method of obtaining drinking water, with over 80% of drinking water generated exclusively from the desalination process. The demand for expansion of desalination facilities has steadily been increasing worldwide, with a 7–8% annual growth rate in the UAE. The most common types of desalination methods utilized worldwide are multistage flashing (MSF), reverse osmosis (RO) and electrodialysis (ED). In the UAE, the MSF and RO methods are the most preferred desalination technologies, with RO showing a growing demand due to its lower energy requirements when compared to the MSF technology. In Moccae (2016), it was noted that as of 2008, the UAE had over 18 RO facilities in operation with many more under construction.

Another escalating global issue is an increase in the global energy consumption and decrease in the supply of fossil-fuels (British Petroleum Company 2019). Desalination through the MSF and RO is not an economical method to obtain potable water due to high energy consumption. Additionally, these methods necessitate accompanying processes such as sludge treatment, aeration, high-pressure membrane operations and thermal distillation (Al-Mamun *et al.* 2018). This has initiated extensive research to find more economically reasonable and sustainable alternatives, or to modify the existing methods. With the advent of microbial desalination cells (MDCs), it could be very viable to integrate such technology with the RO pretreatment process. This could allow for a reduction in the time and energy spent in the conventional desalination process, while simultaneously treating wastewater and generating electricity.

Microbial Fuel Cells (MFCs) are a relatively new fuel cell technology conducting by the biochemical reactions mediated by microorganisms to induce ion transfer in ordinary fuel cells. Over the past decade, extensive research has been done on MFCs as a fuel cell alternative due to their potential for zero energy consumption and eco-friendly nature (Das 2017). The design of MDCs is very similar to that of the MFCs. However, the MDCs would place a greater emphasis on electrodialysis compared to the MFCs. This provides a method for diluting saline water or treating wastewater by removing organic matter. MDCs have been shown to possess tremendous potential incorporated into the desalination processes, either as a pretreatment to the existing processes or the stand-alone units if scaled up (Saeed *et al.* 2015).

Further details about the history of the MDCs and their configurations, the integrating of different technologies with MDCs, and a summary of RO desalination are discussed in the next sections. In addition, a thorough study was conducted on the proposed MDC-RO integration setup, the possible conditions and configurations of MDCs that could be used in the RO integration. The limitations and opportunities for the future research were also investigated.

MICROBIAL DESALINATION CELLS

MDCs are a variant of MFCs that are constructed in a similar fashion to the MFCs. They rely on the electric potential generated by exoelectrogenic bacteria in the anodic chamber in order to facilitate ion transport through ion membranes (Das 2017). MDCs typically consist of three chambers; an inoculated anodic chamber, a desalination chamber, and then a cathodic chamber. An Anion Exchange Membrane (AEM) separates the anodic chamber from the middle desalination chamber, and a Cathode Exchange Membrane (CEM) separates the middle chamber from the cathodic chamber. An external wire connects the anodic and cathodic chambers. Saline water is fed into the middle desalination chamber. Organic material is fed into the anodic chamber in the form of wastewater. This is then utilized by the bacteria as a substrate, resulting in the biofilm formation on the anode electrode. Electrons are released in this process that then travel towards the cathode through the external wire. This leads to the development of an electric potential inside the MDC. Due to this electric potential difference, anions and cations in the desalination chamber move towards the anode through the AEM, and towards the cathode through the CEM, respectively. This results in the water feed being desalinated in the desalination chamber (Saeed *et al.* 2015; Das 2017).

In order to optimize the application of the MDCs, its compartments and configurations have gone through several modifications over the last two decades. The first configuration was the air-cathode MDC, which used oxygen from air as the terminal electron acceptor. This was an effective configuration due to the high reduction capacity of oxygen and the high affordability and obtainability of air. However, it had a lot of shortcomings that required the expensive modifications, such as the use of platinum catalysts. It also required a large amount of maintenance operations due to the contamination of the compounds in the bacterial solution. This led to the development of new MDC configurations such as biocathode MDCs, capacitive MDCs, stacked MDCs and the osmotic MDCs (Al-Mamun *et al.* 2018).

Due to their distinctly low energy requirement, MDCs have been shown to have the potential to be a low energy-consuming desalination technology. This has driven research into finding ways to utilize them to decrease the energy consumption of traditional (and novel) desalination technologies.

DEVELOPMENTS IN INTEGRATION OF MDC TECHNOLOGY WITH OTHER PROCESSES

Over the past decade, research has been conducted into integrating MDC technology with different processes to enhance their efficiencies. The attempts at integration have been collated in Table 1.

All the research shows that an integration of the two technologies would allow for a massive overall reduction in energy consumption, as well as an eco-friendlier method to obtain potable water.

The goal of this study was to find the optimal configuration of MDC that would integrate easily into the RO desalination process. This optimal configuration should provide high-water recover and have minimal (or negligible) drawbacks. This study will do a comparative review of the integration of different MDC configurations into pretreatment for RO desalination. In addition, explicit attention will be given to three forms of MDCs: stacked MDCs, Osmotic MDCs and Upflow MDCs.

MDC CONFIGURATION COMPARISON

As the MDC is the core aspect of the proposed setup, a comparison needs to be done into the different MDC

Table 1 | Description of integration of MDC technology with other existing technologies

Term for the integrated setup	Process characteristics	References
Upflow MDC coupled with RO	Energy requirement of downstream RO reduced by up to 41.9%	Jacobson *et al.* (2011b)
Osmotic MDC coupled with 3-chamber MDC	COD removal of about 85% and conductivity reduction of 95.9%	Zhang & He (2013)
MCDI	59% increase in deionization compared to traditional methods	Wen *et al.* (2014)
MDC integrated with Donnan Dialysis	52–60% removal of boron in water sample	Ping *et al.* (2015)
MEC	Removal of 95.1% of nitrogen, 99.5% of lead and 63.7% of salt	Li *et al.* (2017)

configurations that can be used in the setup. Laboratory-scale studies have shown that stacked MDCs, osmotic MDCs, upflow MDCs and upflow stacked MDCs show the most promise for integration as pretreatment with RO on a larger scale. A rundown of these MDC configurations and their advantages and disadvantages are presented in Table 2.

Stacked MDCs (SMDCs)

Stacked MDCs (SMDCs) were first proposed by Chen *et al.* (2011) as an attempt to increase the desalination capacity of regular three-chambered MDCs. The SMDCs consisted of several IEM pairs fitted into the main cell body. The presence of these multiple pairs allows for greater desalination and ion transfer. The setup essentially acts as multiple MDCs in one unit and, as a result, it significantly increases the ion transfer and the salinity removal capacity. The effectiveness of such a configuration has been proven due to their larger energy recovery efficiency. A schematic diagram of an SMDC is shown in Figure 1.

Osmotic MDCs (oMDCs)

The concept of the oMDC was put forth by Zhang & He (2012). The proposed setup involves the traditional AEM in the MDC replaced with an forward osmosis (FO) membrane. This configuration would significantly improve the desalination capability, but with a reduction in the electricity-producing capability of the MDC. It also allows for higher saltwater dilution and better removal of organic matter from the wastewater streams. A schematic diagram of an oMDC is shown in Figure 2.

Upflow MDCs (UMDCs)

Jacobson *et al.* (2011a) proposed the configuration of an UMDC, which is constructed as a tubular bioreactor consisting of compartments separated by an AEM. The term 'Upflow' is due to the influent entries being located on the bottom of the setup, with the influents flowing upwards through the setup. As shown in Figure 3, the anodic IEM surrounds the anodic graphite rod within the cylinder where wastewater influent is pumped and passed through the internal hollow space. The seawater influent is pumped into the compartment separated by the membrane, and this results in the salt being removed from the seawater. A very high desalination capacity was achieved with this configuration, and was theorized to be a good addition into the pretreatment section of RO and, if scaled up enough, could possibly work as a replacement for it.

Upflow stacked MDCs (USMDCs)

The concept of USMDCs was first put forth in Wang *et al.* (2020) as an attempt to combine SMDCs with UMDCs. The construction was simply a case of introducing the IEM pairs inside a tubular upflow configuration. The IEM pairs would be in an alternating pattern of IEMs similar to the SMDC. Both SMDC and UMDC configurations, once combined, would present a better performance by covering for each other's limitations. The main issue faced by the solo SMDCs configuration is that increasing the number of IEM pairs would lead to a lower current output and result in an eventual decrease in desalination efficiency. By introducing the USMDC model, the tubular structure allows for a greater surface area for mass and charge transfer, and hence increases the desalination efficiency. Providing a low power output is the main limit of the UMDC configuration and therefore the USMDC model, which fully covers the limitation, is considered as the ultimate MDC model. The schematic diagram of this is shown in Figure 4.

REVERSE OSMOSIS SETUP

RO is a process by which pressure is exerted on a fluid (that contains removable impurities such as dissolved solids, organic matter, nitrates, etc.) in a two-chambered vessel. Each chamber in the vessel is separated by a semipermeable membrane. The exertion of pressure induces the pure liquid to flow through the membrane to the other side while leaving the impurities behind and creating pure liquid. It is one of the most common methods used for seawater desalination and wastewater treatment (Garud *et al.* 2011).

The common RO configurations include a pretreatment stage followed by the main RO unit. The main configuration is a vessel with two chambers separated by a semi-permeable membrane with a pressure device (usually a

Table 2 | Description of promising laboratory-scale MDC configurations and future upscaling

MDC Configuration	Characteristics	Capacity	Feed	Objective of study	Advantages	Disadvantages	References
Three-chamber MDC (as comparison)	First MDC design; three chambers; AEM and CEM between electrodes	14 mL each	Sodium acetate (1–2 g/L)	Testing viability of MDC as pretreatment of RO	High desalination (63%); used air cathode instead of $[Fe(CN)_6]^{3-}$	Insufficient desalination to produce drinking water; charge balance issues in chambers	Mehanna *et al.* (2010)
Osmotic MDC	Replaces AEM with FO; $K_3Fe(CN)_6$ catalyst	140 mL each	NaCl 10 g/L	Development and improvement of a model that combines MDC with FO	High-water recovery; FO membrane cheaper and easier to replace	Low charge transfer resulting in ion transport issues; high membrane fouling tendency	Zhang *et al.* (2011); Zhang & He (2012)
Stacked MDC	AEM and CEM in alternating pairs	Anode: 21.2 mL Rest: 7.1 mL	Sodium acetate (1.64 g/L)	Develop an MDC configuration with high desalination capacity	Very high desalination rate; better energy recovery	Expensive construction; slow rate of desalination over long periods of use	Chen *et al.* (2011)
Upflow MDC	Constructed vertically tubular; outer and inner sections separated by IEM	Inner: 500 mL Outer: 350 mL	NaCl 30 g/L	Develop an MDC with high desalination capacity and high power generation	Very high desalination and current generation	Low ion transfer; difficult maintenance	Jacobson *et al.* (2011a)
Upflow stacked MDC	Vertical tubular structure with alternating AEM and CEM pairs	Combined volume of 1 L	NaCl 25 g/L	Development of an MDC configuration that combines the advantages of SMDCs and UMDCs	Very high desalination; current generation greater than SMDC	Current generation not as high as in UMDC	Wang *et al.* (2020)

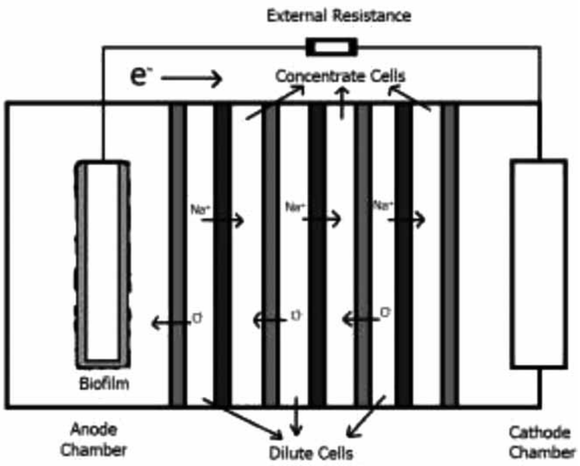

Figure 1 | SMDC Schematic Diagram [adapted from Al-Mamun *et al.* (2018)].

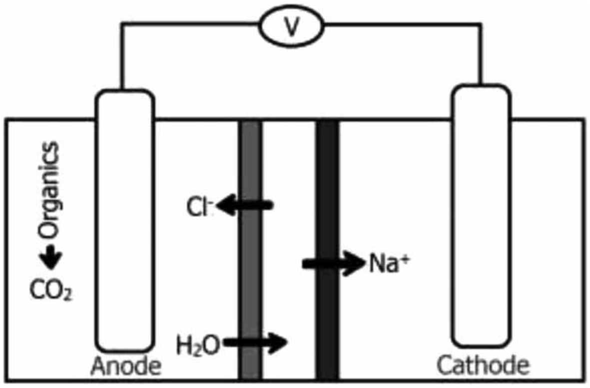

Figure 2 | oMDC Schematic Diagram [adapted from Al-Mamun *et al.* (2018)].

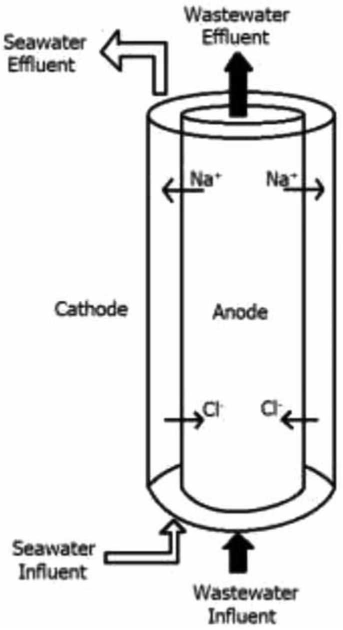

Figure 3 | UMDC Schematic Diagram [adapted from Jacobson *et al.* (2011a)].

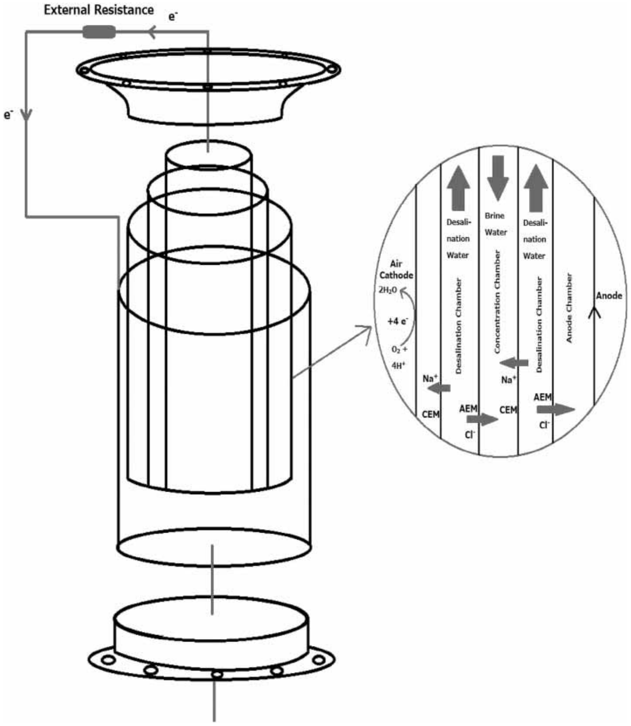

Figure 4 | USMDC Schematic Diagram [adapted from Wang *et al.* (2020)].

high-pressure pump) in the first chamber. The feed stream is initially pretreated to remove inorganic suspended solids to avoid the membrane clogging. The pretreated feed stream is then delivered to the first pressurized chamber. This forces the pure liquid to pass through the membrane and enter the second chamber. After the product liquid, referred to as 'permeate', is separated out, further treatment such as disinfection and pH adjustment may be required. The effluent stream, 'reject', containing water and impurities, is generally subjected to various treatment processes to remove residual toxicity before discharging it into the sea (Garud *et al.* 2011).

The membrane should typically be reasonably priced to allow for quick and easy replacements. It should also have a reliable lifetime and excellent salt rejection. The membrane is installed in the form of different RO modules such as spiral, hollow fiber, tubular and plate and frame modules. The spiral-wound module is the one most commonly used due to its affordability, high packing density and moderate high fouling resistance (Badruzzaman *et al.* 2019).

The pretreatment process is a very crucial step during the RO process as the extent of pretreatment can affect the efficiency of the RO process in both water recovery and energy requirement. Pretreatment is applied to specifically remove five varieties of foulants including the particulate foulants, colloidal foulants, mineral scale foulants, natural organic foulants and microbial foulants. Membrane fouling occurs as a direct consequence of one or more of such foulants (Badruzzaman *et al.* 2019).

Pretreatment setups consist of blocks of different processes such as Coagulation, Flocculation, Micro-Filtration (MF) and Dissolved Air Floatation (DAF), with various configurations, have been used broadly for several feed seawater compositions and salinity/impurity levels. The MDC technology has an extraordinary potential as the pretreatment section to the RO plants. They have been proven to possess very large water recovery capabilities while rejecting a large majority of organic matter and impurities (Elmekawy *et al.* 2014). The MDCS can also dilute the pretreatment water directed into the RO block, which would significantly reduce the amount of energy required for the water desalination. These properties would allow them to be easily integrated into the pretreatment block without modifying many of the currently used setups.

In 2008, the number of RO plants in the UAE was 18, making it among the most popular method of desalination. Due to the growing confidence of the GCC countries in using the RO method, the contribution of RO to the overall desalination capacity was predicted to increase in the coming years (The Cooperation Council for the Arab States of the Gulf (GCC) General Secretariat 2014).

MDC INTEGRATION WITH RO

Studies suggest that the MDCs technology could integrate very well with the RO technology as a pretreatment process in water desalination. A model setup was proposed by Jacobson *et al.* (2011a) where an UMDC was integrated as pretreatment to the RO process. A similar concept can be proposed when integrating other MDC configurations into the RO pretreatment process. There are several possible setups with respect to the integration structure and type of MDC, which will be explored in the next section. (Note that Figure 5 displays a generic MDC configuration, and does not account for IEM pairs as seen in SMDC setups).

The main feed into the MDC is saline water containing organic matter. The microorganisms in the MDC utilize this organic matter as a substrate. This leads to the formation of a biofilm on the anode (Saeed *et al.* 2015). The entire MDC process would fail if sufficient feed is not available to the microbes. Therefore, the initial step is to find a reliable source of organic matter as a feed to the anode compartment. One of the most economic candidates would be a municipal wastewater stream since it has a high concentration of organic matter and nutrients required for the growth of microorganisms. The MDC stage would partially treat the wastewater influent and produce useful products while integrating into the RO desalination process. The proposed integrated configuration, shown in Figure 5, consists of municipal wastewater being initially fed into an anaerobic digester (AD). The wastewater then goes through the process of anaerobic digestion, resulting in the production of acetate and biogas.

The effluent stream from the AD, which still contains organic matter, can satisfy the Chemical and Biological Oxygen Demands (COD and BOD) levels required for the microbial growth in the MDC. The partially treated effluent and seawater, as the second and main feeding streams, are then fed to the MDC compartment, as shown in Figure 5.

In the next step of the process, microorganisms on the anodic chamber utilize the organic matter in the feed stream as a substrate. Due to the presence of the FO membrane, this process facilitates a movement of water molecules through the membrane while leaving organic matter behind in the anodic chamber. Concurrently, the Cation Exchange Membrane (CEM) allows ions to move from the anodic side to the cathodic chamber, thereby producing electricity. The ions come from the salt present in the saline water feed, with the process resulting in the breakdown of the salt atoms into their constituent ions. This effectively desalinates the seawater fed into the configuration. The effluent stream from the MDC is subjected to further treatments to remove any harmful components and neutralize the pH before discharging into the sea.

Along with the MDC unit, pretreatment processes such as flocculation and microfiltration can be included in the setup. These can occur before or after the MDC process,

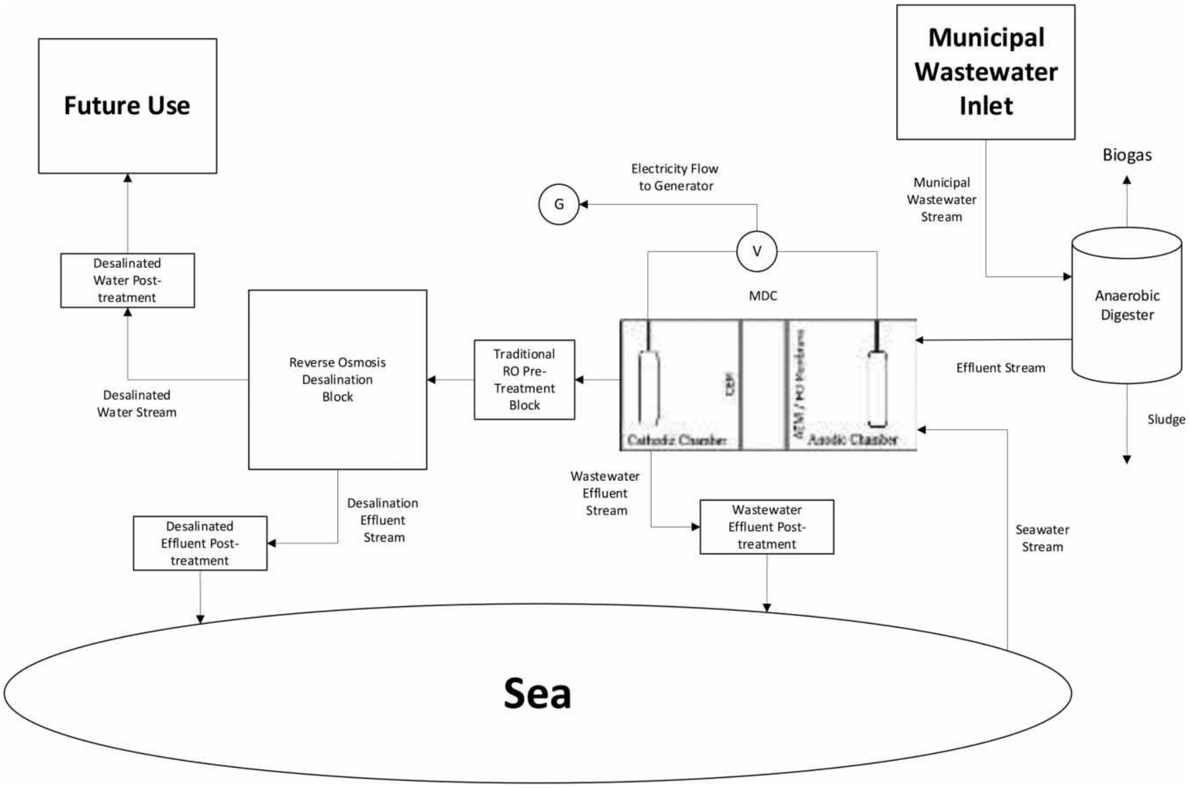

Figure 5 | Proposed configuration for the integration of MDC as RO pretreatment.

as needed, to ensure that the feed stream is ready for the RO block. After the completion of the pretreatment process, water is fed into the traditional RO chamber where the remaining salinity is removed. This configuration allows for desalination while consuming much less energy than of a stand-alone RO system as the MDC unit consumes no energy and reduces the number of RO passes. After this step, the desalinated water can be disinfected and neutralized to ensure that it is safe for further use.

ALTERNATIVE CASE STUDY

An ideal subject for the MDC integration would be the Fujairah 2 (F2) RO Desalination Plant.

The F2 RO Plant desalinates water using a combination of Multiple Effect Distillation and RO, with a capacity of 135,500 m^3/day for the RO section. It uses an average of 2000 MW/day for both sections and is one of the most efficient desalination plants in the world. In the plant's RO process, seawater first goes through flocculation, coagulation and DAF pretreatment processes in order to separate most of the organic matter, with special care given to algae removal. The water goes through a Dual Media Gravity Filtration for 40–60 hours in order to remove the accumulated flocs, which are then sent to a sludge treatment plant. The pretreated water is then transferred to an RO section where it goes through two RO passes, and after post-treatment, is pumped to a municipal water lines for domestic use (Veolia 2016).

It would be very beneficial to use an MDC within the pretreatment process, as this has the capability to reduce the amount of time, energy, and possibly even the number of processes utilized in the pretreatment stage. Furthermore, the increased salinity dilution of the pretreated water might reduce the number of stages water needs to flow through the configuration. Further research and simulations are required to find the optimal operational conditions of water desalination.

PROPOSED SETUP CONFIGURATIONS

For such a potential integration process, there are several key parameters to consider, including the inoculum used in the anodic chamber, the ratio of wastewater to seawater introduced to the MDC, and the pretreatment processes that could accompany the MDC.

Inoculum

The key in the inoculum chosen pertains to the choice of whether to use mesophilic bacteria, which thrive in a temperature ranging between 20 and 45 °C, or whether to use thermophilic bacteria, which thrive in a range of 50–70 °C (Garip *et al.* 2007). The average temperature in the UAE is usually about 35 °C, but in the summer, may rise to 45 °C (Komuscu 2017). Therefore, it might be wise to prepare a medium with adaptive and proper inoculum where a transition and time lag may occur during the hot season in the UAE.

Another point to consider is the inoculum itself. Studies show that the most efficient type of inoculum used in MFCs for electricity generation include exoelectrogenic bacterial classes of *betaproteobacteria* and *gammaproteobacterial*, and affiliated species of *Acidovorax Avenae subs.* and *Aeromonas hydrophila* (Schaetzle *et al.* 2008). Research has also shown that *Acidovorax Avenae* strains tend to thrive at around 35 °C (Cavalcanti *et al.* 2005), which make them perfectly suitable for various seasons in the UAE. The species of *Aeromonas hydrophila* have also shown mesophilic behavior, thriving at around 35 °C. These species, although thriving around 35 °C, show temperature tolerances of up to 55 °C, which might make them suitable candidates for use in the case of any heat spikes in the environment (Rouf & Rigney 1971).

Studies have been conducted into the possible use of algae alongside bacteria in bioelectrochemical systems such as MDCs (Enamala *et al.* 2020). This could open up the possibility of hybrid MDCs that are more resistant to temperature and pH changes, as well as possible synergistic growth.

Wastewater-to-seawater ratio

The next essential parameter in the integration process is the ratio of municipal wastewater to seawater fed into the anodic chamber of the MDC. This ratio depends almost entirely on the amount of BOD of the wastewater and whether the inoculum is capable of breaking down the organic matter present in the wastewater. The complex organic compounds present in municipal wastewater serve as a source of substrate for the microbial consortium. Studies show that the presence of acetate in the wastewater helped significantly in the growth of the anodic inoculum (Das 2017). A possibly fruitful area of research would be into controlling the AD process to allow for more acetogenesis, and hence, greater levels of acetate in the effluent stream. In 2016, Abu Dhabi water statistics indicated that wastewater contains an average of 1074 mg/L of dissolved solids before treatment that could be broken down by bacteria (Moccae 2016). Specific genus of proteobacteria, *Geobacter*, was found to be a very good candidate for the inoculum due to its capability to oxidize complex organic compounds as well as some heavy metals. It was also found that some members of the *Geobacter* genus also exhibit thermophilic behavior, surviving in temperatures of around 55 °C (Kashe *et al.* 2003). This could make them ideal candidates for the high-temperature conditions in the UAE.

Jacobson *et al.* (2011a) proposed an integrated configuration of an UMDC and RO process with a wastewater-to-seawater ratio of 2.2:1.0. The large ratio of wastewater-to-seawater results in a better salt removal, sufficient organic matter for the inoculum and less salt accumulation in the MDC itself. It has also been observed that the high salt concentrations are not conducive to proper growth of bacteria such as *Acidovorax Avenae* (Cavalcanti *et al.* 2005). Studies would suggest that an approximate ratio of two parts wastewater to one-part of seawater might be a good ratio for the start-up. The actual ratio can be determined after further research and experimentation.

Pretreatment processes

The final configuration relates to the accompanying RO pretreatment processes and their placement within the integrated configuration. The main technologies used in such configuration are coagulation to remove polysaccharides with acidic groups, colloids and other organic matter, DAF to remove oil contaminants, Microfiltration and Ultrafiltration (MF and UF) to remove microorganisms, and flocculation to remove solid impurities (Sohn *et al.* 2011). The MDC would be best a reliable alternative served coming after the coagulation. This would help prevent any contaminants from interacting with the bacteria and would retain enough organic matter for the inoculum's usage. Since the presence of an MDC would effectively remove organic matters and solid contents, it might be possible to downsize the flocculation unit and allow for the upsizing of the other processes to ensure that the water is fully pretreated before the RO unit. Studies have also shown that integration of MECs can be used to remove metals such as lead from saline water. This might eliminate the requirement of metal treatment processes, and allow for a more efficient, compact process (Li *et al.* 2017).

Comparative look at different MDC setups

Due to the proposed setup being accommodable for different types of MDCs, it is important that a comparative numerical analysis of the different types of MDCs is done.

The use of SMDCs

The SMDCs tend to have extremely high desalination capacities due to the multiple IEM pairs, allowing for large amounts of ion transfer. A study conducted by Chen *et al.* (2011) showed that after 18 hours of operation, the desalination capacity for a single-pair SMDC was as high as 99.4%. However, as the number of pairs was increased, the overall salinity removal started to decrease, with a two-pair SMDC having a salinity removal of 85.6% and a three-pair SMDC having a salinity removal of 72.1% after 18 hours of operation. As a trade-off, the Charge Transfer Efficiency (CTE) of the setup increased significantly as a result of adding IEM pairs. The study also reported that a CTE of 120, 233 and 283% for a single-pair, a two-pair and a three-pair SMDC are obtained, respectively. Another investigate parameter was ohmic resistance. Higher ohmic resistance decreases the current produced and, hence, it is preferred to keep it low. It was discovered that the ohmic resistance of the setup tended to increase as the desalination process continued. It was found that ohmic resistance increased at a slower rate when fewer pairs of IEMs were used (Chen *et al.* 2011). However, it has simultaneously discovered that using fewer pairs of IEMs resulted in a faster desalination. Therefore, to achieve a maximum and efficient desalination capacity, there needs to be a trade-off between desalination efficiency and desalination time. The downside of this strategy is that the IEMs are fairly expensive due to the high maintenance and replacement costs. In a study, Ziaedini *et al.* (2018) assessed the performance of SMDCs with internal parallel and series flow configurations. In the parallel flow configuration, the influent is passed through two IEM pairs parallelly, without them mixing. In the series flow configuration, the diluent from the first IEM pair is pumped into the second IEM pair as an influent. This study reported that in the parallel flow configurations, a decrease in distance between the membranes resulted in lower salinity removal and increased the Specific Desalination Rate (SDR). For the series flow configurations with low influent salt concentrations of around 1–2%, the desalination efficiency and intermembrane distance were inversely related. For the high influent salt concentrations of around 3%, the two parameters were directly related. For maximum salinity removal, the ideal setup was found to be a series flow configuration with the primary IEM pair having a large intermembrane distance, and the secondary pair having a low intermembrane distance. Simulations would need to identify whether the advantages of using SMDCs offsets the significant construction cost.

The use of oMDCs

These types of MDCs are significantly cost effective to construct and maintain, since the incorporated FO membranes are relatively inexpensive compared to the IEMs used in other MDC configurations. Zhang & He (2012) have indicated that the FO membranes used in the oMDC would cost $30 per square meter of membrane, whereas the AEMs used in a typical MDC would cost $97 per square meter of membrane. Kim & Logan (2013) have also mentioned that IEMs may cost up to an average of $150 per square meter of membrane, which accounts up to 80% of the construction cost. This contribution to the cost is exacerbated in SMDCs, which require multiple pairs of IEMs. This results in oMDCs being a reliable candidate for a start-up facility or a pilot-scale testing, ensuring that a large amount of capital is not lost in the initial process of constructing the MDC. However, since every technology comes with limits, the oMDCs tend to have far lower salinity removal and CTE compared to the SMDCs and UMDCs. Werner *et al.* (2013) found that for a stand-alone oMDC unit with one FO membrane, the salinity removal is around 35%, which is fairly low. In addition, the FO membranes are far more susceptible to biofouling compared to the typical IEMs. This necessitates additional maintenance and replacement costs for the FO membranes. Zhang & He (2013) coupled an oMDC with another MDC, similar to the aforementioned configuration of series-flow SMDCs. They observed that the desalination efficiency increased to 95.9%. However, this defeats the purpose of the setup, as it may require an additional MDC unit alongside the oMDC setup. Regarding the use of SMDCs, further investigation on the simulations and logistics is needed to determine whether a single oMDC or a coupled oMDC and SMDC would be more efficient in the final setup.

The use of UMDCs

An integrated setup using UMDCs was proposed in Jacobson *et al.* (2011b). This study used a liter-scale UMDC setup and obtained a desalination capacity of over 99%. Experiments in previous MDC studies were usually conducted with synthetic seawater. They were done with controlled saline water where the salinity level was a preset value. The results from controlled salinity were then extrapolated to match the salinity of seawater and, hence the efficiency of seawater desalination was approximated. In this UMDC setup, actual seawater was used as an influent, and the results showed a 20% decrease in desalination rate as compared to the synthetic seawater. It was concluded that if the UMDCs were integrated into the pretreatment process for the RO desalination, 30% of the initial total dissolved solids (TDS) could be removed. This integration resulted in a reduction of 2.9 kWh/m^3 in consumed energy in RO and saved 22% of energy compared to the solo RO desalination system. A downside of the UMDCs application is that the desalination rate tends to be inversely proportional to the power output. At high-current operations, high desalination levels are attainable, with a trade-off being a drastic drop in power output. However, when the power output is not critical and the focus is on the desalination process, the operation at the maximum current configuration is not disputable.

The use of USMDCs

Wang *et al.* (2020) proposed a novel integrated USMDC setup consisting of a fusion of SMDCs and UMDCs. The study found that the integrated USMDC would have an average desalination rate of almost 25% greater than that of the SMDC or UMDC setup. The desalination rate in this study remained at a stable average of 91.6% for 120 days. It also had twice the CTE of the UMDC, with barely any change in the pH of the system. Currently, due to the benefits provided by this combination, it would be a pertinent technology for further future researches. The downside of such setup would be a relatively expensive to construct, and due to the novelty of the idea, there is insufficient data to confirm whether this is the optimal configuration to be utilized in the RO pretreatment integration.

Overall MDC choice

The choice of the MDC is a very subjective question that can vary basically depended on the nature of the desalination plant. Regarding the Arabian Gulf region, studies have predicted an increase in hypersalinity of the water surrounding the region. This is attributed to the large evaporation rates combined with the rejection of brine waste streams back into the water bodies (Smith *et al.* 2007). As a result, in the future, it might require stronger desalination and more treatment (or reduction) of water streams. Hence, the optimal MDC used in the setup can vary.

Comparative data of all setups with regards to the different properties has been tabulated in Table 3.

LIMITATIONS

The limitations of the integrated setups are the same problems generally faced when using the MDCs.

Biofouling of the membranes

The membrane is undeniably one of the most crucial aspects of an MDC. A majority of the operational cost associated with using an MDC comes with the maintenance of its membrane. It is a caused by the formation of a biofilm on the

Table 3 | Consolidated comparison data of different MDC configurations

Configuration	Salinity of water (g/L)	Treatment rate of seawater (mL/min)	Salinity removal (%)	Maximum current generation for 1 m^2 of membrane (mA)	Power density (W/m^3)	References
Basic RO	–	(Dependent on size of facility)	99	N/A	N/A	Elmekawy *et al.* (2014)
SMDC (1 stack)	20	5	99.4	7.43	–	Chen *et al.* (2011)
oMDC	20	0.02	35	2.15	43	Werner *et al.* (2013)
oMFC + MDC	20	–	99.1	12.9	2.44	Zhang & He (2012)
UMDC	30	0.06	99	42	30.8	Jacobson *et al.* (2011a)
USMDC	25	5–17	99	294.1	32.91	Wang *et al.* (2020)

surface of the membrane. This biofilm is an eventual result groups of cells adhering to the membrane surface. These cell groups eventually form a thin film. The biofouling of the membrane is irreversible. It can occur on both the anodic and cathodic membranes, but the biofouling of the anodic membrane is the more common issue (Noori *et al.* 2019).

Membrane biofouling can lead to a lot of performance issues for the MDC, including the reduction of proton transfer from the anodic side to the cathodic side. This can lead to a reduction in pH in the anodic side (Xu *et al.* 2012). This reduced pH can lead to the death of the inoculum present in the chamber, since many inoculums require very specific pH conditions. It also increases the ohmic resistance, leading to lower current generation (Noori *et al.* 2019).

Biofouling on the cathodic side is generally a less-common issue. But there are major disadvantages to it occurring. These include reduced reduction due to lower oxygen transfer (An *et al.* 2011) and lower proton transfer through the membrane (Ma *et al.* 2014).

Biofouling is altered by multiple factors such as temperature, tidal forces, humidity and sunlight which essentially affect the growth of microorganisms in seawater (Maddah & Chogle 2017).

In general, FO membranes tend to foul much more easily than the IEMs. This leads to greater maintenance requirements on the oMDCs when compared to three-chambered MDCs and SMDCs. The benefit of the oMDC is that that FO membranes are more cost effective than the IEMs.

Biofouling also requires extensive and frequent cleaning operations. These cleaning processes also heavily impact on water production since the desalination process needs to be ceased in order to conduct the cleaning process. This is a large issue in the Middle East, considering that a majority of domestically used water produces from desalination process. The seawater in the region contains a large amount of dissolved solids which results in a rapid biofouling being and a flux reduction in the Sea Water Reverse Osmosis (SWRO) plants of the region (Maddah & Chogle 2017).

Extensive research has been conducted in order to find better ways of preventing biofouling, and to find membranes with high resistance to fouling. Xu *et al.* (2017) put forth the idea of incorporating Graphene Oxide (GO) nanosheets into the FO membranes as they were found to improve output water quality and increase membrane selectivity. One benefit of using the oMDCs is that the FO membranes are generally far more economically viable as compared to AEMs. This greatly reduces the maintenance expenses.

(Koók *et al.* 2019) noted that the biofouling of membranes was an eventuality that cannot be avoided. Hence the best option would be to conduct further research in membrane technology to create longer-lasting membranes. The operating time for the MDC would vary depending on the situation. It was generally observed that increasing the operating time led to an increase in biofouling rate (Miskan *et al.* 2016). Hence it would also be pertinent to find a method to increase the lifetime of the membrane without changing the membrane itself. An example would perhaps be by using different ratios of liquids in the chambers.

Mitigation methods for biofouling of cathodes include regenerating and refabricating cathodes that have fouled, use of bifunctional catalysts with cathodes that are anti-fouling and using anti-fouling chemicals (Noori *et al.* 2019).

Scaling up of MDCs

Scaling up of MDC's to use in practical real-life scenarios has always been a point of challenge. Since biofouling is such a major issue even in the laboratory scale of MDCs, the difficulty in cleaning and maintaining them increases multifold once it is scaled up. Another issue is that constructing a single MDC handling the load of an entire SWRO plant would likely be extremely expensive and in sometimes impractical (Elmekawy *et al.* 2014). A possible solution would be a configuration of multiple smaller MDCs acting in parallel or having part of the load of the whole SWRO plant handled by the MDC configuration. This would allow for the construction of a smaller MDC while still lowering the total load of seawater.

Another issue caused as a direct result of the scaling up would be the controlling of pH in the anodic chamber. Since microbes are extremely pH sensitive, if the pH becomes too acidic or too alkaline, it can result in biomass destruction and would necessitate a fresh inoculum as well as cleaning operations to remove the perished microbes and avoid the creation of biofoulants. It is very difficult to control the overall pH in large scale MDC chambers, since the pH depends almost on the feeding sludge and seawater into the anodic chamber. The pH of these two feeds cannot be easily controlled. The best way to resolve this would be to adjust the pH of the sludge beforehand and ensure that it is at an acceptable neutral level before entering the MDC compartment. Research has also been done to implement acidophilic bacteria, which can thrive in acidic pH and will not hamper as a result of low pH (Das 2017). Currently, the largest MDC that has been employed in tests is an SMDC of about 3,800 mL capacity (Kim & Logan 2013). Further studies on scaling up of MDCs would be a pertinent research area.

Low efficiency of MDC setups

As it stands, different types of MDC would have different efficiencies. The SMDCs with multiple pairs of IEMs tend to have a high efficiency regarding both the CTE and desalination capacity which reaching the salinity removal percentages up to 99.4%. As the number of stacks in the body increases the salinity removal percentage decreases while conversely the ion transfer increases (Chen *et al.* 2011). Certain studies observed the UMDCs desalination capacities of up to 99% (Jacobson *et al.* 2011b). However, due to inadequate researches conducted on oMDCs, the desalination capacity data are limited. Since the key function of the oMDC is that of water recovery, and not electricity generation, a key problem is the lower efficiency of the oMDCs as compared to other MDCs. In a study conducted by Werner *et al.* (2013), the oMDCs was incorporated with a single FO membrane splitting the anodic and middle chamber achieved 35% salinity removal. Studies have shown that coupling an Osmotic MFC with another MDC that uses IEMs would increase the salt removal capacity to over 90% (Zhang & He 2013). Studies show that adding more chambers in the oMDC, separated by Ion Exchange membranes (IEM), can improve the desalination efficiency but at higher construction and maintenance costs (Elmekawy *et al.* 2014). The coupling of oMDCs with air-cathode MDCs has also been investigated and the results showed better wastewater treatment and desalination efficiency (Werner *et al.* 2013). Optimization needs to be done to confirm the overall expenses saved on energy on the direct RO versus the additional expenses accrued by utilizing the MDC configuration.

OPPORTUNITIES AND FURTHER RESEARCH

There are many areas of research that could significantly benefit the integration of MDCs into RO desalination.

The first major area of research would be membrane technology. Since biofouling is a major concern in MDCs, development of membranes that are more resistant to the fouling would be very useful. This extends to both the FO and IE membranes. Membranes with higher biofouling resistance would not need to be replaced as frequently and would require less maintenance time. Firouzjaei *et al.* (2020) looks into recent innovations in FO membranes, and compares their biofouling tendency, their electricity generation, and their salt removal capacity. Moruno *et al.* (2018) proposed a sulphonated sodium poly (ether ketone) CEM, which showed greater power generation and improved dilution capacity. The study found that flatter membranes led to greater power generation and dilution capacity. Herzberg *et al.* (2019) investigated into the biofouling of IEMs, including the differential bacterial biofoulants, as well as the difference in biofouling of AEMs versus CEMs.

A pertinent area of research would be better methods to control the pH inside an MDC. As it stands, there are not many methods that exist that consistently help control pH. It would be extremely beneficial to design a control system that can accurately measure and control pH. A possible solution could be a system that injects trace amounts of acid or base, as required, in order to keep the pH stable. (Jafary *et al.* 2020) proposed a novel MDC setup that could handle bioelectricity production, wastewater treatment and desalination. It possessed a self-generated pH control that prevented the accumulation of hydrogen and hydroxide ions to help mitigate pH imbalance.

Another area of research that would be worth looking into would be the integration of anaerobic inoculum into MDCs. As of this moment, there have not been many studies conducted with their utilization in MDCs. A few studies have been conducted using MFCs, such as the setup proposed in Rhoads *et al.* (2005). It would be worth exploring since it could lead to the discovery of a new applicable subset of MDCs which could operate under different conditions rather than the conventional ones. This would allow MDCs to be utilized in the regions where the conventional MDCs are not typically used.

Similar to the USMDC configuration, it might be a good idea to investigate other possible combinations of MDCs that would allow to significantly overcome the limits of every single unit.

Another area of research would be the incorporation of MDC technology into areas not related to water treatment. Khazraee Zamanpour *et al.* (2017) looked into the possibility of cultivating microalgae within a biocathode MDC. The setup showed the possibility of simultaneous desalination and algae growth in a bioelectrochemical system. Although no studies have yet been done on it, the usage of MDCs in the process of medical dialysis, such as kidney dialysis, might be an interesting field to explore.

Given the current plastic and waste problems plaguing the world, it would also be a good idea to research into the use of renewable or recoverable materials in the construction or operation of MDCs. Sophia & Bhalambaal (2015) have studied the application of coconut shell carbon as an electrode in the anode compartment of the MDC. The results revealed the possibility of using activated carbon from biomass waste (such as coconut shells) as electrode material.

CONCLUSIONS

With the advent of a large freshwater scarcity across the world, desalinated water is quickly becoming one of the major ways to obtain clean water for domestic use. The most commonly used process to desalinate water is the RO process. This method is hampered by extremely large energy requirements. MDCs are a technology that show immense potential to reduce energy and economic loads on the RO desalination process. MDCs have the potential to be integrated into the RO pretreatment process due to their high-water recovery and dilution capacity. Countries like the United Arab Emirates, which depend heavily on desalinated water for domestic use, could benefit heavily from integrating MDCs into the RO desalination process. There still needs to be a significant amount of research done in order to combat the many drawbacks and limitations involved in the MDC integration, such as the biofouling of the membranes and the scaling up of the integration. Research should also be done in order to look at ways to best optimize the integration, such as by improving the efficiency of the MDCs, or better integrating other pretreatment processes into the process. However, once resolved, MDCs could open the path for a significantly more sustainable process to obtain potable water, both in terms of energy and resources utilized.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Al-Mamun, A., Ahmad, W., Baawain, M. S., Khadem, M. & Dhar, B. R. 2018 A review of microbial desalination cell technology: configurations, optimization and applications. *Journal of Cleaner Production* **183**, 458–480. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2018.02.054.

An, J., Jeon, H., Lee, J. & Chang, I. S. 2011 Bifunctional silver nanoparticle cathode in microbial fuel cells for microbial growth inhibition with comparable oxygen reduction reaction activity. *Environmental Science and Technology* **45** (12), 5441–5446. https://doi.org/10.1021/es2000326.

The Cooperation Council for the Arab States of the Gulf (GCC) General Secretariat 2014 Desalination in the GCC: The History, the Present & the Future. *Report Prepared by Desalination Experts Group, Originating from the Water Resources Committee*. https://doi.org/10.3878/j.issn.1006-9585.2014.13112.

Badruzzaman, M., Voutchkov, N., Weinrich, L. & Jacangelo, J. G. 2019 Selection of pretreatment technologies for seawater reverse osmosis plants: a review. *Desalination* **449**, 78–91. https://doi.org/10.1016/j.desal.2018.10.006.

British Petroleum Company 2019 *Statistical Review of World Energy*. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Cavalcanti, M. T., Silveira, E. B. da., Mariano, R. de Lima Ramos & Viana, I. O. 2005 Growth of Acidovorax avenae subsp. citrulli under different variable temperature, pH, sodium chloride concentrations and carbon sources. *Ciência Rural* **35**, 1313–1318. https://doi.org/10.1590/S0103-84782005000600013.

Chen, X., Xia, X., Liang, P., Cao, X., Sun, H. & Huang, X. 2011 Stacked microbial desalination cells to enhance water desalination efficiency. *Environmental Science and Technology* **45** (6), 2465–2470. https://doi.org/10.1021/es103406 m.

Das, D. (ed.) 2017 *Microbial Fuel Cell: A Bioelectrochemical System That Converts Waste to Watts*. Springer. https://doi.org/10.1007/978-3-319-66793-5.

Elmekawy, A., Hegab, H. M. & Pant, D. 2014 The near-future integration of microbial desalination cells with reverse osmosis technology. *Energy and Environmental Science* **7**, 3921–3933. https://doi.org/10.1039/c4ee02208d.

Enamala, M. K., Dixit, R., Tangellapally, A., Singh, M., Dinakarrao, S. M. P., Chavali, M., Pamanji, S. R., Ashokkumar, V., Kadier, A. & Chandrasekhar, K. 2020 Photosynthetic microorganisms (algae) mediated bioelectricity generation in microbial fuel cell: concise review. *Environmental Technology & Innovation* **19**, 100959. https://doi.org/10.1016/j.eti.2020.100959.

Firouzjaei, M. D., Fatemeh Seyedpour, S., Aktij, S. A., Giagnorio, M., Bazrafshan, N., Mollahosseini, A., Samadi, F., Ahmadalipour, S., Firouzjaei, F. D., Esfahani, M. R., Tiraferri, A., Elliott, M., Sangermano, M., Abdelrasoul, A., McCutcheon, J. R., Sadrzadeh, M., Esfahani, R. A. & Rahimpour, A. 2020 Recent advances in functionalized polymer membranes for biofouling control and mitigation in forward osmosis. *Journal of Membrane Science* **596**, 117604. https://doi.org/10.1016/j.memsci.2019.117604.

Garip, S., Bozoglu, F. & Severcan, F. 2007 Differentiation of mesophilic and thermophilic bacteria with Fourier transform infrared spectroscopy. *Applied Spectroscopy* **61** (2), 186–192. https://doi.org/10.1366/000370207779947486.

Garud, R. M., Kore, S. V., Kore, V. S. & Kulkarni, G. S. 2011 A short review on process and applications of reverse osmosis. *Universal Journal of Environmental Research and Technology* **1** (3), 233–238.

Herzberg, M., Pandit, S., Mauter, M. S. & Oren, Y. 2019 Bacterial biofilm formation on ion exchange membranes. *Journal of Membrane Science* **596**, 117564. https://doi.org/10.1016/j.memsci.2019.117564.

Jacobson, K. S., Drew, D. M. & He, Z. 2011a Efficient salt removal in a continuously operated upflow microbial desalination cell with an air cathode. *Bioresource Technology* **102** (1), 376–380. https://doi.org/10.1016/j.biortech.2010.06.030.

Jacobson, K. S., Drew, D. M. & He, Z. 2011b Use of a liter-scale microbial desalination cell as a platform to study bioelectrochemical desalination with salt solution or artificial seawater. *Environmental Science and Technology* **45** (10), 4652–4657. https://doi.org/10.1021/es200127p.

Jafary, T., Al-mamun, A., Alhimali, H., Said, M., Rahman, S., Tarpeh, W. A., Ranjan, B. & Hong, B. 2020 Novel two-chamber tubular microbial desalination cell for bioelectricity production, wastewater treatment and desalination with a focus on self-generated pH control. *Desalination* **481** (February), 114358. https://doi.org/10.1016/j.desal.2020.114358.

Kashe, K., Holmes, D. E., Baross, J. A. & Lovley, D. R. 2003 Thermophily in the Geobacteraceae: Geothermobacter ehrlichii gen. nov., sp. nov., a novel thermophilic member of the Geobacteraceae from the 'Bag City' hydrothermal vent. *Applied and Environmental Microbiology* **69** (5), 2985–2993. https://doi.org/10.1128/AEM.69.5.2985.

Khazraee Zamanpour, M., 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. https://doi.org/10.1016/j.jece.2016.12.045.

Kim, Y. & Logan, B. E. 2013 Microbial desalination cells for energy production and desalination. *Desalination* **308**, 122–130. https://doi.org/10.1016/j.desal.2012.07.022.

Komuscu, A. U. 2017 Long-term mean monthly temperatures trends of the United Arab Emirates. *International Journal of Global Warming* **11** (1), 1–22. https://doi.org/10.1504/IJGW.2017.080987.

Koók, L., Bakonyi, P., Harnisch, F., Kretzschmar, J., Chae, K. J., Zhen, G., Kumar, G., Rózsenberszki, T., Tóth, G., Nemestóthy, N. & Bélafi-Bak, K. 2019 Biofouling of membranes in microbial electrochemical technologies: causes, characterization methods and mitigation strategies.

Bioresource Technology **279**, 327–338. https://doi.org/10.1016/j.biortech.2019.02.001.

Li, Y., Styczynski, J., Huang, Y., Xu, Z., McCutcheon, J. & Li, B. 2017 Energy-positive wastewater treatment and desalination in an integrated microbial desalination cell (MDC)-microbial electrolysis cell (MEC). *Journal of Power Sources* **356**, 529–538. https://doi.org/10.1016/j.jpowsour.2017.01.069.

Ma, J., Wang, Z., Suor, D., Liu, S., Li, J. & Wu, Z. 2014 Temporal variations of cathode performance in air-cathode single-chamber microbial fuel cells with different separators. *Journal of Power Sources* **272**, 24–33. https://doi.org/10.1016/j.jpowsour.2014.08.053.

Maddah, H. & Chogle, A. 2017 Biofouling in reverse osmosis: phenomena, monitoring, controlling and remediation. *Applied Water Science* **7** (6), 2637–2651. https://doi.org/10.1007/s13201-016-0493-1.

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 and Environmental Science* **3** (8), 1114–1120. https://doi.org/10.1039/c002307 h.

Miskan, M., Ismail, M., Ghasemi, M., Jahim, J. M., Nordin, D. & Bakar, M. H. A. 2016 Characterization of membrane biofouling and its effect on the performance of microbial fuel cell. *International Journal of Hydrogen Energy* **41** (1), 543–552. https://doi.org/10.1016/j.ijhydene.2015.09.037.

Moccae 2016 Water statistics. *Abu Dhabi Water Statistics* 1–8 www.moccae.gov.ae.

Moruno, F. L., Rubio, J. E., Atanassov, P., Cerrato, J. M., Arges, C. G. & Santoro, C. 2018 Microbial desalination cell with sulfonated sodium poly(ether ether ketone) as cation exchange membranes for enhancing power generation and salt reduction. *Bioelectrochemistry* **121**, 176–184. https://doi.org/10.1016/j.bioelechem.2018.02.004.

Noori, M. T., Ghangrekar, M. M., Mukherjee, C. K. & Min, B. 2019 Biofouling effects on the performance of microbial fuel cells and recent advances in biotechnological and chemical strategies for mitigation. *Biotechnology Advances* **37** (8), 107420. https://doi.org/10.1016/j.biotechadv.2019.107420.

Ping, Q., Abu-Reesh, I. M. & He, Z. 2015 Boron removal from saline water by a microbial desalination cell integrated with donnan dialysis. *Desalination* **376**, 55–61. https://doi.org/10.1016/j.desal.2015.08.019.

Qasim, M., Badrelzaman, M., Darwish, N. N., Darwish, N. A. & Hilal, N. 2019 Reverse osmosis desalination: a state-of-the-Art review. *Desalination* **459**, 59–104. https://doi.org/10.1016/j.desal.2019.02.008.

Rhoads, A., Beyenal, H. & Lewandowski, Z. 2005 Microbial fuel cell using anaerobic respiration as an anodic reaction and biomineralized manganese as a cathodic reactant. *Environmental Science and Technology* **39** (12), 4666–4671. https://doi.org/10.1021/es048386r.

Rouf, M. A. & Rigney, M. M. 1971 Growth temperatures and temperature characteristics of *Aeromonas*. *Applied Microbiology* **22** (4), 503–506.

Saeed, H. M., Husseini, G. A., Yousef, S., Saif, J., Al-Asheh, S., Fara, A. A., Azzam, S., Khawaga, R. & Aidan, A. 2015 Microbial desalination cell technology: a review and a case study. *Desalination* **359**, 1–13, https://doi.org/10.1016/j.desal.2014.12.024.

Schaetzle, O., Barrière, F. & Baronian, K. 2008 Bacteria and yeasts as catalysts in microbial fuel cells: electron transfer from micro-organisms to electrodes for green electricity. *Energy and Environmental Science* **1** (6), 607–620. https://doi.org/10.1039/b810642 h.

Smith, R., Purnama, A. & Al-Barwani, H. H. 2007 Sensitivity of hypersaline Arabian Gulf to seawater desalination plants. *Applied Mathematical Modelling* **31** (10), 2347–2354. https://doi.org/10.1016/j.apm.2006.09.010.

Sohn, J., Valavala, R., Han, J., Her, N. & Yoon, Y. 2011 Pretreatment in reverse osmosis seawater desalination: a short review. *Environmental Engineering Research* **16** (4), 205–212. https://doi.org/10.4491/eer.2011.16.4.205.

Sophia, A. C. & Bhalambaal, V. M. 2015 Utilization of coconut shell carbon in the anode compartment of microbial desalination cell (MDC) for enhanced desalination and bio-electricity production. *Journal of Environmental Chemical Engineering* **3** (4), 2768–2776. https://doi.org/10.1016/j.jece.2015.10.026.

Veolia 2016 Fujairah 2 reverse osmosis desalination plant. *Paristokyo* **2** (1), 12. Available from: http://www.veolia.com/middleeast/sites/g/files/dvc171/f/assets/documents/2017/03/Fujairah_II_Brochure.pdf.

Wang, Y., Xu, A., Cui, T., Zhang, J., Yu, H., Han, W., Shen, J., Li, J., Sun, X. & Wang, L. 2020 Construction and application of a 1-liter upflow-stacked microbial desalination cell. *Chemosphere* **248**, 126028. https://doi.org/10.1016/j.chemosphere.2020.126028.

Wen, Q., Zhang, H., Yang, H., Chen, Z., Nan, J. & Feng, Y. 2014 Improving desalination by coupling membrane capacitive deionization with microbial desalination cell. *Desalination* **354**, 23–29. https://doi.org/10.1016/j.desal.2014.09.027.

Werner, C. M., Logan, B. E., Saikaly, P. E. & Amy, G. L. 2013 Wastewater treatment, energy recovery and desalination using a forward osmosis membrane in an air-cathode microbial osmotic fuel cell. *Journal of Membrane Science* **428**, 116–122. https://doi.org/10.1016/j.memsci.2012.10.031.

Xu, W., Chen, Q. & Ge, Q. 2017 Recent advances in forward osmosis (FO) membrane: chemical modifications on membranes for FO processes. *Desalination* **419** (March), 101–116. https://doi.org/10.1016/j.desal.2017.06.007.

Xu, J., Sheng, G. P., Luo, H. W., Li, W. W., Wang, L. F. & Yu, H. Q. 2012 Fouling of proton exchange membrane (PEM) deteriorates the performance of microbial fuel cell. *Water Research* **46** (6), 1817–1824. https://doi.org/10.1016/j.watres.2011.12.060.

Zhang, B. & He, Z. 2012 Integrated salinity reduction and water recovery in an osmotic microbial desalination cell. *RSC Advances* **2** (8), 3265–3269. https://doi.org/10.1039/c2ra20193c.

Zhang, B. & He, Z. 2013 Improving water desalination by hydraulically coupling an osmotic microbial fuel cell with a microbial desalination cell. *Journal of Membrane Science* **441**, 18–24. https://doi.org/10.1016/j.memsci.2013.04.005.

Zhang, F., Brastad, K. S. & He, Z. 2011 Integrating forward osmosis into microbial fuel cells for wastewater treatment, water extraction and bioelectricity generation. *Environmental Science and Technology* **45** (15), 6690–6696. https://doi.org/10.1021/es201505t.

Ziaedini, A., Rashedi, H., Alaie, E. & Zeinali, M. 2018 Performance assessment of the stacked microbial desalination cells with internally parallel and series flow configurations. *Journal of Environmental Chemical Engineering* **6** (4), 5079–5086. https://doi.org/10.1016/j.jece.2018.07.051.

First received 14 October 2020; accepted in revised form 11 December 2020. Available online 21 December 2020