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Chapter 9

Microbial Desalination Cell: An Integrated Technology for Desalination, Wastewater Treatment and Renewable Energy Generation

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Abstract

Conversion of seawater to potable water is necessary to meet the demands of future generations. The energy-intensive and un-sustainable desalination technologies led to the development of bio-electrochemical systems called microbial desalination cells (MDCs). MDC configuration has been developed for a decade to overcome the challenges faced in operation and other phenomena. This chapter is aimed to discuss MDCs based on different types of cathodes chemical, air, and bio-cathode and their applications. The technical challenges such as pH imbalance in the anode, membrane fouling, electrode material selection and ohmic resistance are also included.

Keywords

Microbial Desalination Cell, Chemical Cathode, Air Cathode, Bio-Cathode

List of abbreviations

MDC-Microbial desalination cell

RO-reverse osmosis

GHG-green house gas

CEM-cation exchange membrane

AEM-anion exchange membrane

rMDC-recirculation microbial desalination cell

c-SMDC-S-separator coupled stacked circulation microbial desalination cell

M-MDC-multistage microbial desalination cell

PMDC-photosynthetic microbial desalination cell

CoTMPP-cobalt tetramethoxyphenylporphyrin

HRT-hydraulic retention time

PS-photosystems

NADP-nicotinamine adenine dinucleotide phosphate

MEDC-microbial electrolysis and desalination cell

MEDCC-microbial electrolysis desalination and chemical production cell

SMDC-submersible microbial desalination cell

CSTR- continuous stirred tank reactor

C-SMDC-non-separator coupled circulation stacked microbial desalination cell

UMDC-up flow microbial desalination cell

Contents

1. Introduction

Clean water represents 3% of the total water resources on earth of which only 1% is accessible and the rest 2% is locked under glaciers and icecaps. However, urbanization, industrial and population growth resulted in water deterioration and shortage. Hence there is a need to develop new sources of water to meet the increase in water demand. The water desalination technology is identified as a potential technology to overcome the water shortage problem, i.e., conversion of sea water into potable water, yet the present traditional techniques such as thermal desalination and reverse osmosis are energy consuming [1, 2]. For example, the pressure required for desalination of seawater by reverse osmosis process ranges from 55 to 82 bars and the energy consumption for the typical size of seawater reverse osmosis (RO) unit of 24000 m^3/day ranges from 4 to 6 kWh/m^3. More than 60% of the world's desalination plants utilise fossil fuels as the source for multi-stage flash distillation [3]. Thus, the present desalination processes contribute to the degradation of the environment by the emission of excessive heat, greenhouse gas (GHG) and high concentration of brine. Hence the challenges in the traditional process led to the development of a cheap, efficient and environmentally friendly method called microbial desalination cell technology for desalination of seawater.

1.1 Microbial desalination cell and its evolution

The new type of bio-electrochemical systems (BES) called microbial desalination cell (MDC) was developed by the integration of microbial fuel cell and electro-dialysis cell for desalination and wastewater treatment in a single reactor [4, 5]. The MFC consists of the anode for treating domestic and industrial wastewaters and the cathode separated by membranes such as cation exchange membranes (CEMs), anion exchange membrane (AEMs), bipolar membranes, and ultrafiltration. Insertion of the desalination chamber separated by AEM and CEM in the MFC led to the development of MDC. Cao et al. proposed a first small-scale setup of microbial desalination reactor with a salt water chamber volume of 3 mL [4]. It was further increased to 250 L to use at large scale by

Zuo et al. [6]. Effective selection of cathode electron accepter plays the vital role in the desalination process and bioelectricity generation. Many researchers utilized a chemical cathode called potassium ferricyanide during initial studies of microbial desalination cell. To overcome the toxic, expensive and non-sustainability nature of a chemical cathode, Mehanna et al., [1] used an air cathode and obtained substantial (43–67%) desalination of water using equal volumes of anode and salt solution. Expensive catalyst usage and high energy requirement to maintain dissolved oxygen led to the development of using aerobic microbes called bio-cathodes. Wen et al. suggested the use of an aerobic bio-cathode consisting of carbon felt and bacterial catalyst during their study that produced 609 mV of bioelectricity with bio-cathode which was 136 mV higher than that of the air cathode. The sustainable and effective desalination performance of the bio-cathode proved to be a promising technology when compared with the air cathode without catalyst and ferricyanide [7]. Another study reported utilizing algae, *Chlorella Vulgaris* as algae bio-cathode. The passive bio-cathodes performed better than the air cathode in desalination, COD removal and produced high-value products from biomass. [8]. Thereafter many studies concentrated on using bio-cathodes because of their sustainability and cost-effectiveness.

1.2 Microbial desalination cell construction and general principle

The basic configuration of MDC comprised of three compartments (anode, desalination chamber, and cathode) separated by using AEM and CEM and clamped by gaskets to inhibit the water flow between compartments. Fig 1 depicts the schematic representation of a MDC. The compartments are usually made with materials such as polymethyl methacrylate, borosil glass, plexi glass, polycarbonate, acrylic plates, etc. An AEM made of polystyrene cross-linked with divinylbenzene with quaternary ammonia as functional group separates the anode and middle desalination chamber. The CEM made of polystyrene gel cross-linked with divinylbenzene with sulphonic acid separates desalination chamber and cathode. The basic materials such as carbon felt, carbon cloth, carbon brush, graphite granule, graphite fiber granules, graphite rod, carbon fiber felt are generally used as electrodes in a MDC. The reactor can be operated in open circuit and also as a closed circuit by connecting an external resistance.

In the anode compartment, the multiplication of exoelectrogens form bio-films on the electrode material and breaks the organic matter into protons, electrons, and other by-products. The electrons produced by the oxidation of organic matter at the anode are transferred to the solid electrode and migrate to the cathode compartment through the external circuit. In the cathode chamber, the electrons and protons combine with the oxygen (terminal electron acceptor) and form clean water. The difference in potential

created across the electrodes of cathode and anode chambers generates electricity. The continuous oxidation of organic matter by exoelectrogens in the anaerobic environment leads to wastewater treatment. The desalination process is achieved by movement of ions such as anions (Cl^-, NO_3^-, and SO_4^{2-}) and cations (Na^+, Ca^{2+}, Mg^{2+}) across the AEM and CEM respectively. The transfer occurs to maintain electro-neutrality condition due to the release of electrons by the bioelectrochemical oxidation process at the anode that causes the transfer of anions. Similarly, the reduction reaction occurs at the cathode since oxygen accepts electrons and initiates the movement of cations into the cathode chamber. [4]. Thus the bio-electrochemical effect on MDC leads to simultaneous wastewater treatment, desalination, and electricity generation. The rate of desalination is the key factor in MDC function and depends on the initial salt concentration of the sample to be desalinated. The reaction taking place at anode and cathode chamber is given below:
At the anode:

$$(CH_2O)_n + nH_2O \rightarrow nCO_2 + 4ne^- + 4nH^+. \quad \text{Eq.1.}$$

At the cathode:

$$O_2 + 4ne^- + 4nH^+ \rightarrow 2H_2O. \quad \text{Eq.2.}$$

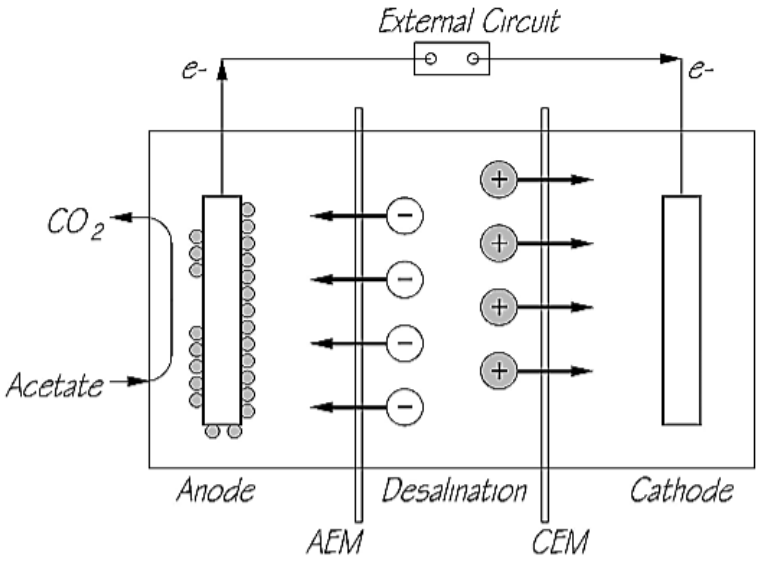

Figure 1. Schematic representation of Microbial Desalination Cell

Continuous research on MDC led to the development of different kinds of bio-electrochemical systems for integrated desalination and wastewater treatment. Table 1 represents the various design configurations with their advantages, special features and challenges to be tackled for a significant impact on the performance and efficiency (adapted from references 2, 9, 10)

Table1. Different configurations of MDC (adapted from 2, 9, 10)

MDC configuration	**Advantages**	**Challenges**	**Special features**	**Ref**
Air cathode MDC	High reduction potential in the cathode chamber	Rise in anolyte pH with time decreasing	Cathode exposed to O_2 as a terminal electron acceptor	[1] [11] [12]
Bio-cathode MDC	Self-generating and sustainable. Enhanced desalination with reduced start-up time.	A small reduction of cell potential during the batch mode of operation.	Enhanced reduction reactions with the help of microbes	[6] [7]
Stack structure MDC	Improved charge transfer efficiency, Increased energy recovery and improved desalination rate.	Increase in number of desalination chambers resulted in declined current and total desalination rate	Alternating IEMs (AEMs and CEMs)	[11] [13] [14]
Recirculation MDC (rMDC)	Increased separation of ion pairs from salt water and power efficiency. Reduction in the pH imbalance.	–	Sequential recirculation of electrolyte i.e. anolyte and catholyte across the chambers and low concentration of buffer used.	[5] [15]
Capacitive adsorption capability MDC (cMDC)	Reduction in the pH imbalance. No ion migration problem. Increased desalination rate.	The effect of increased ion concentration on anode biofilm activity and community on the electrode was not studied	Incorporating capacitive deionization, double layer capacitor on the surface of the electrode, acid-producing chamber and bipolar membrane.	[16] [17]

Upflow MDC	Increased desalination efficiency and power density. Efficient fluid mixing with the chamber. Easier to scale up.	Decrease in pH at a higher TDS removal rate	The tubular reactor containing two compartments and separated by IEMs. Continuous operation with improved performance in desalination and current production.	[18]
Osmotic MDC	Improved desalination efficiency and performance. Enhanced substrate removal from wastewater.	In-depth research is important to overcome challenges such as system scale-up, FO membrane fouling, reduced energy consumption	Forward Osmosis membrane replaced AEM, potassium ferricyanide used as a catalyst, increase water flux to dilute saltwater	[13] [19] [20]
Bipolar membrane MDC	High perm-selectivity. . Enhanced desalination efficiency and long time duration of bipolar membranes. Low water splitting voltage and electric resistance.	Membrane requires the additional voltage since that produced by the cell is not sufficient to the potentials needed to operate the membrane.	Four-chambered Bipolar MDC is formed by placing the bipolar membrane placed next to Anode Chamber; t anion and cation selective layers laminated together to make a Bipolar membrane.	[1] [13]
Decoupled MDC	Easy to scale up Easy to control liquid volume ratios Easy to repair and replace damaged parts	–	Electrodes are made from stainless steel mesh wrapped with carbon cloth, anode and cathode units placed directly in salt solution.	[21]
Separator coupled stacked circulation MDC (c-SMDC-S)	Check-in pH imbalance and improved Coulombic efficiency. No biofouling and smooth operation of the system for a longer period.	-	Glass fibre attached to water-facing one side of the cathode and acts as a separator	[22]

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Ion-exchange resin coupled MDC	Stabilised ohmic resistance Reduced energy consumption Enhances charge transfer efficiency and desalination rate.	–	Desalination chamber packed with mixed anions and cations exchange resins.	[22]
Microbial electrolysis desalination and chemical production	Higher desalination rate and low pH fluctuation	–	Involved an acid production chamber and a bipolar membrane	[14] [23] [24]
Submerged microbial desalination-denitrification cell	No bacterial leakage into groundwater. No additional energy treatment for nitrate	The whole process ended up with the depletion of nitrate and ionic strength of groundwater. The nitrogen species in the cathodic effluent required further treatment prior to discharge. Adapted external nitrification of anodic effluent was beneficial to the current generation and nitrate removal rate but total nitrogen removal not possible.	MDC integrated with denitrification system forms submerged microbial desalination-denitrification cell. Removal of nitrate ions from groundwater are for electricity generation	[25]

Multi-stage microbial desalination cell (M-MDC)	Simultaneous enhanced treatment and self-driven desalination of real domestic wastewater. Enhanced nitrogen removal due to coefficient biological nitrification/denitrification and electrical migration. Increased organics removal due to multi-stage anaerobic/ oxic conditions of the anode and cathode.	Partial desalination (43.4–75.7%). and relatively low current and desalination efficiency. Aeration of biocathode increases the cost and energy.	Two alternating anode and biocathode chambers, with AEM and CEM at opposite positions as in the conventional MDC. A concentrate chamber with deionized water with mixed ion exchange resins.	[7]
Photosynthetic microbial desalination cells (PMDCs)	Beneficial use of algae as a passive biocathode by *in- situ* oxygen generation and COD removal. Enhanced desalination and electricity production compared to chemical cathode	–	Microbial solar desalination cells supported by a photosynthetic microorganism, i.e., microalgae (*Chlorella Vulgaris* sp.), as a biocatalyst in the biocathode.	[8] [26]

2. Different types of MDC based on cathode electron acceptor

The desalination performance and bioelectricity generation of MDC greatly depend on the cathode and its potential to carry out reduction reaction enabling product formation. The rate of the reaction depends on the desired product formation at the cathode chamber by accepting electrons from the oxidation process at the anode via an external circuit. The different types of cathodes include chemical, air and bio-cathodes.

2.1 MDC with the chemical cathode

The chemical cathode such as ferricyanide is the commonly used catholyte as the electron acceptor in MDC studies. Fig 2 represents the schematic working mechanism of the chemical cathode. Ferricyanide reduces to ferrocyanide by accepting electrons from the anode. The reaction mechanism is as follows:

$$[Fe(CN)_6]^{3-} + e^- \rightarrow [Fe(CN)_6]^{4-} \quad \text{Eq. 3}$$

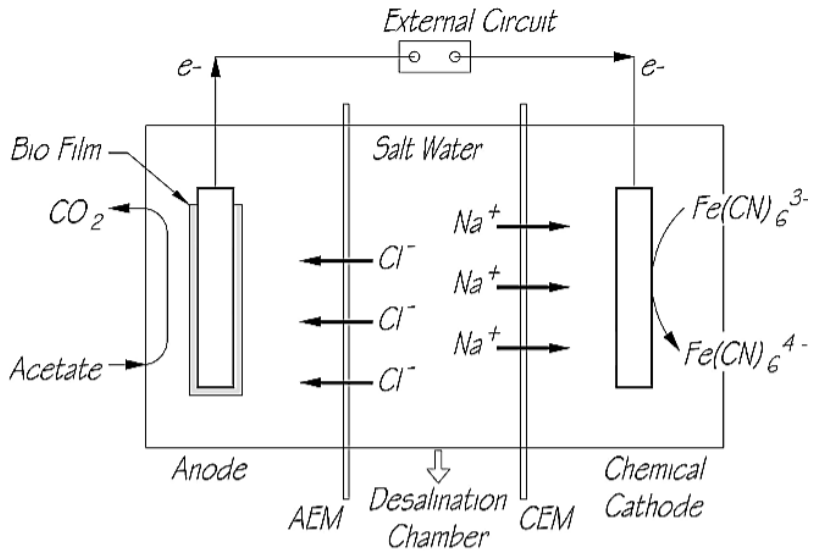

Figure 2. Schematic representation of MDC with the chemical cathode

Cao et al. [4] used ferricyanide as the catholyte because of its high cathodic potential and faster reduction kinetics. However, the significant disadvantage of using chemical catholyte is that it requires continuous replacement, expensive and toxic to the environment. Moreover, it is not sustainable for large-scale operation. Ferricyanides can be used for water softening process in MDC as tested by Brastad et al. [27]. In a study, MDC with $KFe(CN)_6$catholyte produced 1,532 ± 14 mW/m^3 for the first hour and decreased to 379 mW/m^3 after 10 h, while MDC with marine algae catholyte generated 384 ± 5 mW/m^3 during the first hour of operation. However, the stable voltage produced in algae catholyte was greater than for the chemical catholyte. Efficient desalination occurred by using algae catholyte when compared with chemical catholyte with lower power generation [28].

2.2 Microbial desalination cell with the Air cathode

The shortcomings of the chemical cathode led to the development of air cathodes. The air cathode can be defined as a cathode that utilizes oxygen as terminal electron acceptor. Pt, cobalt tetramethoxyphenylporphyrin (CoTMPP) and activated carbon are different types of air cathodes [29, 30]. Fig 3 illustrates the schematic diagram of MDC working with an air cathode. The oxygen combines with protons in the cathode chamber, and electrons generated by oxidation process from the anode chamber leads to the formation of clean water as shown in eq.2.

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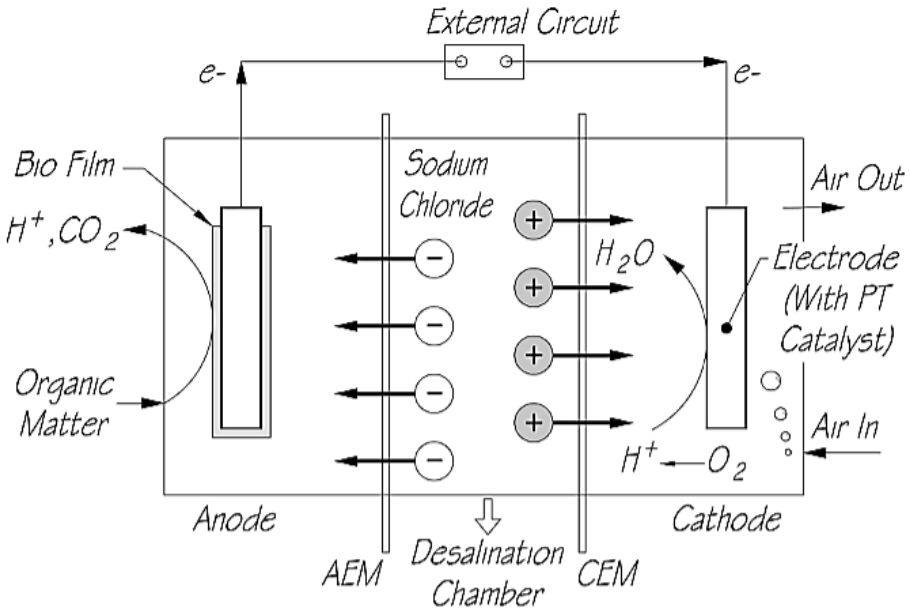

Figure 3. Schematic representation of MDC with air cathode

Oxygen is primarily used because of its high availability and high reduction potential. [31]. It is not toxic when compared with chemical catholytes. The significant disadvantage is that under ambient conditions, air cathodes undergo slow redox kinetics. To minimize the activation overpotential linked with oxygen reduction, expensive catalysts s (e.g. platinum) required. Another disadvantage is the utilization of mechanical equipment to maintain the necessary optimal dissolved oxygen concentration [16]. Thus, the high energy requirement increases the capital cost of the reactor. In another perspective, the reduction of oxygen to water requires four electrons which are not achieved. The decrease in oxygen at times forms hydrogen peroxide thus rendering only a two electron transfer reaction. Hydrogen peroxide is considered a strong oxidizer and results in electron or membrane degradation. It also acts as a disinfectant and inhibits the biofilm formation on the electrode.

Mehanna et al. [1] used air cathode and anolyte containing 2 g/L acetate in cubical shaped chambers, achieved desalination efficiency up to 63% and found superior to using ferricyanide as catholyte. Upflow microbial desalination cell with an air cathode containing platinum wire operated in a continuous mode reported to remove salt efficiently. The results showed that at a hydraulic retention time (HRT) of 4 days, more than 99% of NaCl removal from the initial salt concentration of 30 g TDS/L and current production of approximately 62 mA can be achieved. At 1 or 4 days HRT, the charge

transfer efficiencies were 98.6% or 81 % [18]. Zuo et al. fabricated a modularized filtration air cathode MDC (FMDC) using nitrogen-doped carbon nanotubes and Pt-carbon as filtration material and cathode. Salt removal efficiency and COD removal efficiencies were 93.6% and 97.3% respectively when real wastewater was circulated from anode to cathode and finally to the middle membrane stack. [32].

2.3 Microbial desalination cell with bio-cathode

The new research paved the way for the exploitation of microorganisms and their usage in the cathode chamber. Bio-cathodes called biological cathodes can be defined as microbial population present over the surface of the cheap electrode material or in the electrolyte that catalyzes the cathodic reaction. Microalgae and cyanobacteria are considered as potential bio-cathodes. Algal MDC is a new approach for environmentally sustainable desalination and bioelectricity generation method. Fig 4 portrays a schematic working model of MDC with a bio-cathode. Fig 5 denotes the fabricated image of a bio-cathode MDC [35]. The Oxygenic photosynthesis is carried out in algae that eliminate the mechanical aeration usage. Oxygenic photosynthesis requires three membrane-bound proteins such as Photosystems PSI, PSII, and cytochrome b6F complex for in electron transport from water to nicotinamide adenine dinucleotide phosphate (NADP). Plastoquinones and plastocyanins are small mobile molecules that help in the transportation of electrons between protein complexes thus leading to the photosynthetic energy conversion. [33].The advantages of bio-cathode include 1) enhanced desalination of water, 2) sustainable and self-generating by the production of oxygen in the cathode chamber and 3) reduction in start-up time [11]. Various by-products can also be obtained from the bio-cathode such as biofuels from algal biomass.

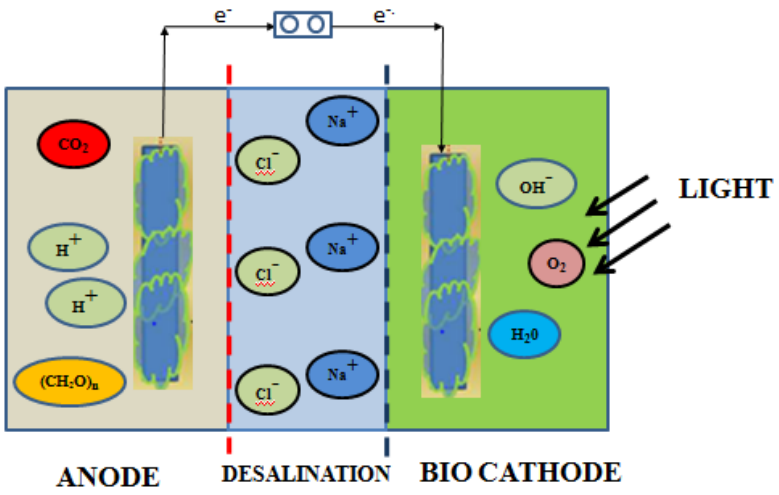

Figure 4. Schematic representation of MDC with bio- cathode

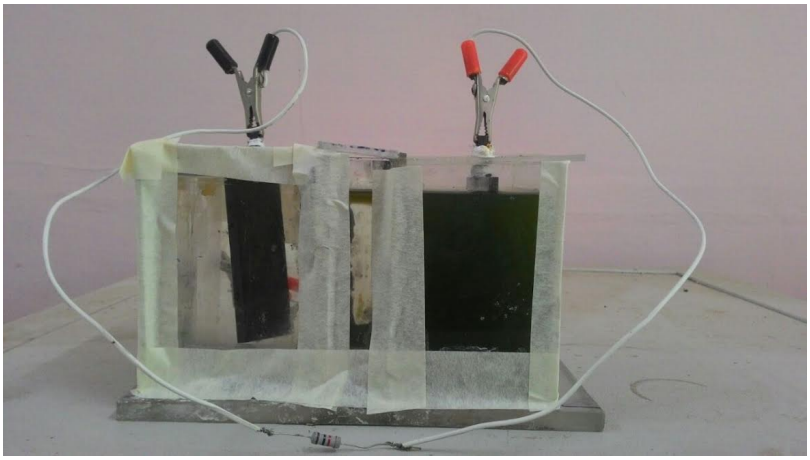

Figure 5. Fabricated image of Bio-cathode Microbial Desalination Cell [36]

The algae in the presence of light consume carbon dioxide and release oxygen and other by-products that help in the formation and growth of new cells. The oxygen produced combines with protons in the cathode chamber and with electrons from the oxidation process at the anode forms the clean water. The general mechanism using algae as bio-cathode is as follows:

Carbon dioxide + water + light energy → Carbohydrates + oxygen+ new cells

The reaction mechanism at the cathode is as shown in e.q.2.

Wen et al. [7] first proposed the use of the bacterial catalyst in the cathode chamber of microbial desalination cells. The study produced maximum voltage, Columbic efficiency, desalination performance for the bio-cathode when compared with the air cathode. During the aerobic metabolic process, more hydrogen ions and electrons were consumed and resulted in higher removal of salt and substrate. The photosynthetic microbial desalination cell led to the utilization of microalgae *Chlorella vulgaris* as passive bio-cathode. The study produced the power density of 151 mW/ m^3 and 40% desalination performance with 0.9:1:0.5 volumetric ratios of the anode, desalination chamber, and cathode. Bio-cathodes catalyzed by microbes produced steady output voltage when compared with the chemical catholytes [8]. Zamanpour et al. also reported simultaneous desalination and the power generation using microalgae *Chlorella vulgaris* as bio-cathode and dairy wastewater in the anode chamber. The results showed that MDC with a salinity of 35 g/L had a removal rate of 0.341 g/L/day which was 1.5 times greater than MDC

with the saline concentration of 15 g/L. Higher algal growth (38%) in 35 g/L saline water proved that higher saline concentration positively increases the desalination performance. [34]. Microalgae *Scenedesmusabundans* also had the positive effect of desalination coupled with petroleum wastewater treatment and bioelectricity generation. [35].

Although MDCs with the chemical and air cathodes have their respective advantages; MDCs with bio-cathodes are found to be sustainable and efficient in enhancing the desalination process. Table 2 summarises the different types of cathodes used in MDCs along with their advantages and disadvantages.

Table2. Summary of different types of MDC cathodes

MDC Configurations	**Materials used**	**Advantages**	**Disadvantages**
Chemical cathode MDC	• Ferricyanide • Phosphate buffer solution	• High cathodic potential • Faster reduction kinetics	• The need for continuous replacement • Expensive • Toxic to the environment
Air cathode MDC	• Oxygen with Platinum catalyst • Cobalt tetramethoxyphenyl porphyrin (CoTMPP • Activated carbon	• Easy availability • High reduction potential • Not Toxic	• Utilization of expensive catalyst, • High energy requirement • Formation of hydrogen peroxide
Bio-cathode MDC	• Microalgae such as *Chlorella vulgaris, Scenedesmus abundance* etc • Cyanobacteria	• Enhanced desalination of water • Sustainable and self-generating • Reduction in start-up time	• Maintenance of essential growth conditions

3. Applications of microbial desalination cell

The important application of MDC is desalination. Further, it carries out the following diversified applications instead of desalination.

3.1 Water softening

The available groundwater is probably hard due to the presence of positively charged multivalent ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). [36]. The most commonly used method for water softening is ion exchange. The major disadvantage of the process is a generation of large amount of concentrated solutions of acids and salts that cause a problem during the regeneration process. [37][38].The other frequently used softening process accepted by US EPA is chemical precipitation, i.e., lime softening. [39] Other softening methods include carbon nanotubes, nanofiltration, capacitive deionization, electrodialysis and reverse osmosis which involve energy and are cost intensive. [40]

Kristein et al. [27] reported the first bench scale laboratory experiment to study the effectiveness of using MDC in the water softening process. It was found that MDC removed more than 90% of hardness in tested samples and also 89% of the arsenic, 97% of the copper, 99% of the mercury, and 95% of the nickel at the testing concentrations in a synthetic solution. Since it is the first study on water softening, it has some drawbacks to be considered such as membrane fouling, scaling, retention period and economics of the study. The enzymatic mode of MDC was developed for water softening process. [41]. Enzymatic oxidation of glucose by glucose dehydrogenase generates bioelectricity and removes 46% of hardness. The removal efficiency was decreased by the composition of hard waters. The performance of the enzymatic MDC can be enhanced by improving the current generation and bio-anode stability. Hemalatha et al. also proposed MDC as an alternative technique for ground and surface water treatment. [42].

3.2 Production of chemicals and gases

Integrated BES system called microbial electrolysis and desalination cell (MEDC) helps in the production of hydrogen, desalination of sea water and wastewater treatment in a single reactor. Lab scale study achieved 1.6 ml/h of hydrogen production from the cathode chamber with the application of 0.8V potential difference and concurrently desalinated 10 g/L NaCl in the middle chamber with removal efficiency of 98.8 % [43]. A new set up called microbial electrolysis desalination and chemical production cell (MEDCC) was developed from MEDC by the insertion of acid production chamber and a bipolar membrane. The MEDCC simultaneously produced HCl and NaOH in the cell along with desalination rates of 46-86% within 18 h using 10 g NaCl/L in the middle chamber with 1.0 V applied voltage [24]. Stack construction of MEDCC enhanced the desalination rates and chemical production when compared with MEDCC. Desalination rate of 0.58 ± 0.02 mmol/h was achieved in the four desalination chamber MEDCC with the AEM and CEM stack structure, which was 43% higher than MEDCC. Maximum acid

and alkali production rates were 46 and 8% higher than MEDCC respectively [23]. Although system scaling up poses an important challenge, MEDCC concept effectively recovers high-value chemicals.

3.3 Remediation of contaminated water and nutrients recovery

In general, groundwater remediation employs active or passive methods to remove contaminants. Groundwater possess a high concentration of nitrates due to improper discharge of untreated wastewater with increased use of fertilizers [44]

Zhang et al. developed a novel technique called microbial desalination denitrification cell (SMDCC) to *in-situ* removal of nitrate from groundwater and simultaneous energy production and wastewater treatment. The SMDCC with 12 h wastewater retention time and 10 Ω external resistances produced 3.4 A/m^2 of current density and removed 90.5% nitrate from groundwater [25]. Another study concentrated on the development of an innovative method to remove ammonia in a continuous stirred tank reactor (CSTR) by submersible desalination cell (SMDC) to recover ammonia. In the batch experiment, the average ammonia recovery rate of 80 g-N/m^2/d and the maximum power density of 0.71± 0.5 W/m^2 generated at 2.85 A/m^2 during 30 days of operating time was achieved. The mechanisms responsible for the ammonia transportation in this study were due to current driven NH_4^+ migration and free NH_3 diffusion. [45]. A microbial nutrient recovery cell has been developed to purify wastewater and the recovery of nutrient ions by taking the advantage of energy present in the wastewater. The removal efficiencies were > 82% for COD, >96% for NH_4^+-N, and >64% for PO_4^{3-}-P in all the operational cycles. [46]. Thus, the above novel and cost-efficient techniques were beneficial in nutrients recovery and renewable energy production.

4. Parameters affecting the performance of microbial desalination cell in desalination

Effective performance of a process or technology can be made only by means of controlling certain factors. The performance of MDC reactor is essentially influenced by several factors such as reactor configurations, mode of operation, operational conditions, volumetric ratios of chambers, substrate concentration, bacteriological media, initial salt concentration, conductivity, charge transfer efficiency, internal and external resistances, electrode materials, membrane and intermembrane distance, resin packing, hydraulic retention time, pH imbalance and electrolyte recirculation rate. The important parameters are discussed below in detail.

4.1 Mode of microbial desalination cell operation

Different modes of MDC operation such as batch, cyclic batch and continuous mode affect MDC performance and stability. For example, four microbial desalination cells operated under continuous flow conditions showed total NaCl removal efficiency of 97 ± 1% at an HRT for 2 days. The continuous flow study eliminated substantial pH change and hence increased the desalination rate when compared with the single reactor. [47]. In UMDC continuous mode of operation, uniform substrate distribution enhanced current distribution thus increasing desalination efficiency [48] and produced the maximum power density of 30.8 $W.m^{-3}$ in the study carried out by Jacobson et al. [18]. In batch mode, the increase in internal resistance due to low electrolyte conductivity decreased MDC performance [49]. Atieh Ebrahimi et al. compared batch and continuously operated MDC in terms of power generation and salt removal efficiency. The batch MDC generated the maximum power density of 13.9 W/m^3 and salt removal rate of 68.1% whereas continuously operated MDC produced the maximum power density of 15.9 W/m^3 and average salt removal of 80%. [12].

4.2 Substrate concentration

The substrate as the fuel of microbial desalination cell affects the performance of MDCs. Anolyte and catholyte are the sources of the nutrient, organic matter and reservoir for ion species. [8] Different substrates such as acetate [1, 4], phosphate buffer solution [5], cellulose degrading rumen microbial consortium [26], synthetic wastewater containing acetate [18], wastewater [12, 51], and dewatered sludge [52] have been used by many researchers in their studies to enhance the exoelectrogenic bacteria activity in the anode chamber. Meanwhile, ferricyanide [4], PBS with NaCl [53], bio-cathode inoculation from the topsoil with the solution [52], *Chlorella vulgaris* as biocathode [8], *Scenedesmus abundance* as biocathode [35] and many more have been used as catholyte substrates. These studies have revealed that concentration losses due to the nutrient gradient in the substrate which significantly influenced the MDC performance and efficiency. In a study, MDCs were acclimated to different acetate concentrations (1-2 g/L) in a fed-batch cycle. In lower substrate concentration, 43 % reduction in NaCl conductivity was observed. Current density with 1 g/L of acetate was high (2.80 Am^2) when compared with 2 g/L (less than 1.00 Am^2). Higher substrate concentration reported inhibiting the anode performance [1]. Luo et al. [15] observed that the power output from the MDC was four times higher than the control MFC without desalination function when wastewater was used as a sole substrate. Increase in conductivity by 2.5 times and stability in anolyte pH maintained the microbial activity in the anode.

4.3 Salt concentration

Generally, desalination efficiency depends on the effect of initial salt concentration. The desalination performance is basically measured as conductivity change in the desalination chamber. The desalination efficiency increases with increase in salinity of saline solution i.e., a higher concentration between the desalination chamber and electrode containing chamber. Due to increased internal resistance and lower electrical conductivity, low salt concentration leads to lower desalination efficiency. Yang et al. [54] compared the results of MDCs having different initial salt concentrations and MFC with no desalination chamber. When the initial NaCl concentration was increased from 5 to 30 g/L, the current and power density generation increased from 2.82 mA and 158.2 mW/m^2 to 3.17 mA and 204.5 mW/m^2 respectively in MDC whereas the internal resistances decreased from 2432.0 to 2328.4Ω. The junctional potential i.e., the passage of ions across AEM and CEM increased in MDC with the increase in initial NaCl concentration. In a study conducted by Mehanna et al., [1], the desalination performance of osmotic MDC and control MDC for three different initial saline concentrations (2, 10 and 20 g/L) were investigated. Control MDC showed lower removal efficiency when compared with osmotic MDC at all the variable salinities. The changes occurred due to the difference in osmotic pressure that contributed to the desalination of water.

4.4 pH imbalance

In MDC operation, pH variation is considered as a universal phenomenon. The reaction between protons released by the oxidation of bio-pollutants and the anions in the desalination chamber results in a pH drop (acidic) over a period. Meanwhile, an oxygen reduction reaction in the cathode chamber leads to accumulation of hydroxide ions thus increasing pH within the cathode chamber. [4, 18, 55]. Researchers tackled the pH imbalance based on different perspectives such as adding acids or bases [4, 18, 14] or increasing the anolyte volume [4]. Alternatively, the recirculation of the solutions between anode and cathode to avoid the inhibition of bacterial metabolism was found to be a promising method. Maximum power density was 931 ± 29 mW/m^2 with a 50 mM phosphate buffer solution (PBS) and 776 ± 30 mW/m^2 with 25 mM PBS with recirculation process. The power densities obtained were higher than those achieved without recirculation. [5]. The above recirculation technique was found to eliminate the pH imbalances effectively. Youpeng Qu et al. [47] reported that hydraulic flow through the desalination cells, i.e., anode solution from the first reactor flowed into the cathode and then to the anode of the next reactor, connected can avoid pH fluctuations. But, the transfer of organic matter and microbes during recirculation stimulated the growth of biofilm on the cathode thus reducing the catalytic activity. The new concept called

separator coupled circulation stacked microbial desalination cell (c-SMDC-S) to avoid the bio-film growth in the cathode and increase desalination efficiency. The performance of c-SMDC-S was compared with other configurations such as non-separator coupled circulation stacked microbial desalination cell (c-SMDC) and the regular SMDC. It was found that the operation lasted for two months with mild pH variation of 6.8 to 7.9 with desalination efficiency of 65-37% [24] [23][21]. Another technology to overcome pH fluctuation problem was addressed by microbial capacitive desalination cell (MCDC). Insertion of specially designed membrane assembly consisting of cation exchange membrane and layers of activated carbon cloth (ACC) in the set up effectively increased the desalination efficiency, 7 to 25 times than the traditional capacitive deionization process [16]. In another study, pH variation was decreased by 54% by dividing the desalination chamber into upper and lower compartments. The upper part was used for desalination, and lower compartment acted as a medium for proton transfer [56].

4.5 External resistance

External resistance is one of the essential factors that affect the performance of microbial desalination cells. The circuit is usually closed through external resistance. The external resistance controls the flow of electrons from the anode to the cathode affecting the cell potential and current outputs of the microbial desalination cell according to Ohm's Law ($V=I\ R_{ext}$). The approximate total internal resistance of the cell can be obtained by the polarisation curve with variable external resistances. [57]. Sevda et al. [55] reported that COD removal and desalination efficiency were directly dependent on external resistance. At very high resistance (5000-10000 Ω), the flow of electrons was less, and hence upflow microbial desalination cell (UMDC) behaved near to open circuit thus leading to the reduction in COD removal. Higher COD removal was obtained when the reactor was operated at the high resistance (100-1000 Ω) and higher desalination efficiency obtained under lower resistance (0.1 to 1 Ω). Chen et al. [14] proposed that low external resistance (<10 Ω) could cause the unstable behaviour of exoelectrogenic bacteria and a decrease in production of electrons. Maximum power production was recorded at 10 Ω in this study. With the above results, conclusions can be drawn that important factors such as desalination rate, current generation, power density, COD removal depend on external resistance.

5. Challenges and future prospects

Despite many advantages such as lower energy or chemical consumption and the added benefit of wastewater treatment, bioelectricity production, and production of high-value by-products, MDC suffers few limitations. It is crucial to overcoming the barriers of

MDC to use as a pre-treatment process for the energy-intensive technologies. The important restriction is the constructive reactor design. The innovation in reactor configuration, selection of prominent materials, and thorough knowledge about biochemical mechanisms ensure the high level of mutual benefits such as power amplification and reduction in capital cost of desalination. The MDCs power densities can be enhanced by reducing the electrochemical losses such as ohmic losses, activation overpotential, and mass transfer limitations. The losses at the cathode can also be minimized by low electrode spacing, large anode surface area (m^2/m^3), and usage of the efficient chemical catalyst. Anolyte and catholyte pH should be taken care of, as the pH fluctuations inhibit the biofilm formation and growth. Chloride ions alter crossing AEM combine with protons in the anode to form hydrochloric acid and thus make the medium acidic. Meanwhile, sodium ions combine with hydroxide ions forming sodium hydroxide in the cathode chamber thus increasing the alkalinity in the cathode chamber. Hence extensive buffering is essential to avoid the pH changes.

Another drawback is the increase in ohmic resistance which occurs due to a decrease in conductivity and salinity, limiting the desalination performance and bioelectricity production. The above scenario is particularly seen in low salinity solutions. The sustainability of MDC operation is affected majorly by another parameter called membrane fouling/biofouling. Deposition of soluble cations such as Mg^{2+} and Ca^{2+} cause scaling phenomenon resulting in amplification of MDC's external resistance. Additionally, the ions react with natural organic matter in water and form scales on the membrane. [58, 59]. Hence, modification in the ion exchange membrane is essential to overcome the scaling problems.

Another issue to be sorted out is scale-up of MDC. The liquid volume ranges from hundreds to thousands. A large-scale MDC holding 105 L liquid volume was tested and found to produce bio-electricity of 2000 mA and the removal of 9.2 $kg/m^3/d$ salt. [60]. The system efficiency was mainly affected by fluctuations in environmental conditions such as temperature, pH, membrane fouling, etc. and also the scale-up faced difficulty due to the usage of a significant amount of pH buffers in the reactor.

MDC can be used as a pre-treatment for the RO process, or it can be used as a stand-alone process for treatment of brackish water. MDC technology can also be used as a water softening process for sustainable treatment of wastewater. Use of MDC as a pre-treatment to RO can decrease the impact of membrane-related issues and other operational costs. Hence significant research is necessary to understand the loopholes of technology to improve the overall system's efficiency.

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Conclusion

The general concepts about various aspects of MDC have been discussed in this chapter. In-depth researches on MDCs have led to the development of various reactor configurations and utilization of different forms of cathodes. Finally, the photosynthetic MDC is declared as an efficient technology utilizing biological cathodes such as microalgae. Usage of bio-cathodes increased because of their sustainable nature, increased desalination efficiency, reduction in start-up time and production of valuable biomass. The ability of bio-cathodes can be improved with the recent molecular biology and bioinformatics techniques. Identification of better bacterial and algal species can improve the overall efficiency of bio-cathode microbial desalination cells.

Other than desalination process, MDC plays a vital role in other valuable applications such as water softening process, production of chemicals, acids and bases, hydrogen gas production, remediation of contaminated water and also helps in recovery of nutrients.

A process is considered efficient only after controlling defined operational parameters. The continuous mode of MDC operation, selection of effective anode and cathode substrates, pH balance, initial salt concentration, usage of lower external resistance are some of the important changes that can be done to enhance the working of MDC process.

MDC technology came into existence less than a decade and had multiple outcomes from a single reactor. Further development in reactor configurations, selection of better electrode materials, and optimization of other operational parameters can extensively increase the integrated process of desalination performance, wastewater treatment, and electricity generation.

Hence MDC is found to be a new, green, environmentally friendly, efficient and sustainable technology.

References

[1] M. Mehanna, T. Saito, J. Yan, M. Hickner, X. Cao, X. Huang, B.E. Logan, Using microbial desalination cells to reduce water salin¬ity prior to reverse osmosis, Ener. Environ. Sci. 3 (2010) 1114. https://doi.org/10.1039/c002307h

[2] A. Carmalin Sophia, V.M. Bhalambaal, E.C. Lima, M. Thirunavoukkarasu, Microbial desalination cell technology: Contribution to sustainable waste water treatment process, current status and future applications, J. Environ. Chem. Eng. 4 (2016) 3468–3478. https://doi.org/10.1016/j.jece.2016.07.024

[3] V.G. Gude, N. Nirmalakhandan, S. Deng, Renewable and sustainable approaches for desalination. Renew. Sustain. Energy Rev. 14 (2010) 2641-2654. https://doi.org/10.1016/j.rser.2010.06.008

[4] X. Cao, X. Huang, P. Liang, K. Xiao, Y. Zhou, X. Zhang, B.E. Logan, A new method for water desalination using microbial desalination cells, Environ. Sci. Technol. 43 (2009) 7148–7152. https://doi.org/10.1021/es901950j

[5] Y. Qu, Y. Feng, X. Wang, J. Liu, J. Lv, W. He, B.E. Logan, Simultaneous water desalination and electricity generation in a microbial desalination cell with electrolyte recirculation for pH control, Bioresour. Technol. 106 (2012) 89–94. https://doi.org/10.1016/j.biortech.2011.11.045

[6] K. Zuo, F. Liu, S. Ren, X. Zhang, P. Liang, X. Huang, A novel multi-stage microbial desalination cell for simultaneous desalination and enhanced organics and nitrogen removal from domestic wastewater, Environ. Sci. Water Res. Technol. 2 (2016) 832–837. https://doi.org/10.1039/C6EW00196C

[7] Q. Wen, H. Zhang, Z. Chen, Y. Li, J. Nan, Y. Feng, Using bacterial catalyst in the cathode of microbial desalination cell to improve wastewater treatment and desalination. Bioresour. Technol. 125 (2012) 108–113 https://doi.org/10.1016/j.biortech.2012.08.140

[8] B. Kokabian, V.G. Gude, Photosynthetic microbial desalination cells (PMDCs) for clean energy, water and biomass production. Environ. Sci.: Processes Impacts, 15 (2013) 2178. https://doi.org/10.1039/c3em00415e

[9] H.M. Saeed, G.A. Husseini, S. Yousef, J. Saif, S. Al-Asheh, A. Abu Fara, S. Azzam, R. Khawaga, A. Aidan, Microbial desali¬nation cell technology: A review and a case study, Desalina¬tion. 359 (2015) 1–13.

[10] H. Jingyu, D. Ewusi-Mensah, EyramNorgbey, Microbial desalination cells technology: a review of the factors affecting the process, performance and efficiency, Desal. Water Treat. 87 (2017) 140–159.

[11] G. Gude, B. Kokabian, V. Gadhamshetty, Beneficial bioelectrochemical systems for energy, water, and biomass production, Microb. Biochem. Technol. 6 (2013) 1–14.

[12] X. Zhang, W. He, L. Ren, J. Stager, P.J. Evans, B.E. Logan, COD removal characteristics in air-cathode microbial fuel cells, Bioresour Technol. 176 (2015) 23–31 https://doi.org/10.1016/j.biortech.2014.11.001

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

[14] X. Chen, X. Xia, P. Liang, X. Cao, H. Sun, X. Huang, Stacked microbial desalination cells to enhance water desalination effi¬ciency, Environ. Sci. Technol. 45 (2011) 2465–2470. https://doi.org/10.1021/es103406m

[15] H. Luo, P. Xu, T.M. Roane, P.E. Jenkins, Z. Ren, Microbial desalination cells for improved performance in wastewater treatment electricity production, and desalination, Bioresour. Technol. 105 (2012) 60–66. https://doi.org/10.1016/j.biortech.2011.11.098

[16] C. Forrestal, P. Xu , Z. Ren, Microbial desalination cell with capacitive adsorption for ion migration control, Bioresour. Technol. 120 (2012) 332–336. https://doi.org/10.1016/j.biortech.2012.06.044

[17] L. Yuan, X. Yang, P. Liang, L. Wang, Z.H. Huang, J. Wei, X. Huang, Capacitive deionization coupled with microbial fuel cells to desalinate low-concentration salt water, Bioresour. Technol. 110 (2012) 735–738. https://doi.org/10.1016/j.biortech.2012.01.137

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

[19] C. Huang, T. Xu, Electrodialysis with bipolar membranes for sus¬tainable development, Environ. Sci. Technol. 40 (2006) 5233–5243. https://doi.org/10.1021/es060039p

[20] B. Zhang, Z. He, Improving water desalination by hydrauli¬cally coupling an osmotic microbial fuel cell with a microbial desalination cell, J. Membr. Sci. 441 (2013) 18–24. https://doi.org/10.1016/j.memsci.2013.04.005

[21] X. Chen, P. Liang, Z. Wei, X. Zhang, X. Huang, Sustainable water desalination and electricity generation in a separator coupled stacked microbial desalination cell with buffer free electrolyte circulation, Bioresour. Technol. 119 (2012) 88-93. https://doi.org/10.1016/j.biortech.2012.05.135

[22] A. Morel, K. Zuo, X. Xia, J. Wei, X. Luo, P. Liang, X. Huang, Microbial desalination cells packed with ion-exchange resin to enhance water desalination rate, Bioresour. Technol. 118 (2012) 43–48. https://doi.org/10.1016/j.biortech.2012.04.093

[23] S. Chen, G. Liu, R. Zhang, B. Qin, Y. Luo, Y. Hou, Improved performance of the microbial electrolysis desalination and chemical-production cell using the stack structure, Bioresour. Technol. 116 (2012b) 507-511. https://doi.org/10.1016/j.biortech.2012.03.073

[24] S. Chen, G. Liu, R. Zhang, B. Qin, Y. Luo, Development of the microbial electrodialysis and chemical-production cell for desalination as well as acid and alkali productions, Environ. Sci. Technol. 46 (2012) 2467–2472. https://doi.org/10.1021/es203332g

[25] Y. Zhang, I. Angelidaki, A new method for in situ nitrate removal from groundwater using submerged microbial desalination edenitrification cell (SMDDC), Water Res. 47 (2013)1827-1836. https://doi.org/10.1016/j.watres.2013.01.005

[26] G.M. Girme, Algae powered microbial desalination cells, 58. MSc Thesis, Graduate School of the Ohio State Uni¬versity, Ohio. (2014)

[27] S. Kristen Brastad, Zhen He, Water softening using microbial desalination cell technology, Desalination. 309 (2013) 32–37 https://doi.org/10.1016/j.desal.2012.09.015

[28] D. BeenishSaba, A. Christy, Z. Yu, C.A. Co, A. Park, Simultaneous power generation and desalination of microbial desalination cells using nannochloropsissalina (marine algae) versus potassium ferricyanide as catholytes, Environ. Eng. Sci. 34 (2017).

[29] S. Cheng and B. E. Logan, Evaluation of catalysts and membranes for high yield biohydrogen production via electrohydrogenesis in microbial electrolysis cells

(MECs), Water Sci. Technol. 58 (2008) 853–857. https://doi.org/10.2166/wst.2008.617

[30] F. Zhang, S. Cheng, D. Pant, G. V. Bogaert and B. E. Logan, Power generation using an activated carbon and metal mesh cathode in a microbial fuel cell Electrochem. Commun. 11 (2009) 2177–2179. https://doi.org/10.1016/j.elecom.2009.09.024

[31] S.M. Rismani-Yazdi, A.D. Carver, O.H. Christy, Tuovinen, Cathodic limitations in microbial fuel cell: An overview, J. Power Sour. 180 (2008) 683-694. https://doi.org/10.1016/j.jpowsour.2008.02.074

[32] K. Zuo, Z. Wang, X. Chen, X. Zhang, J. Zuo, P. Liang, X. Huang, Self-driven desalination and advanced treatment of wastewater in a modularized filtration air cathode microbial desalination cell, Environ. Sci. Technol. 50 (2016) 7254–7262. https://doi.org/10.1021/acs.est.6b00520

[33] L. Taiz, E. Zeiger, Plant Physiology, Sinauer Associate (2010).

[34] M.K. Zamanpour, H.R. Kariminia, M. Vosoughi, Electricity generation, desalination and microalgae cultivation in a biocathode-microbial desalination cell, J. Environ. Chem. Eng. 5 (2017) 843–848. https://doi.org/10.1016/j.jece.2016.12.045

[35] V.R.V. Ashwaniy, M. Perumalsamy, Reduction of organic compounds in petro-chemical industry effluent and desalination using Scenedesmus abundans algal microbial desalination cell, J. Environ Chem. Eng. 5 (2017) 5961-5967. https://doi.org/10.1016/j.jece.2017.11.017

[36] Water Quality Research Council, What makes water hard & how can it be improved, Water Rev. 5 (1990) 1–2

[37] M.A. Burris, in: Soft Water, Hard Choice? Government Engineering, (2004) 20–21.

[38] S.R. Maguin, P.C. Martyn, in: Notification of the Continued Prohibition on Brine Discharges from Self-Regenerating Water Softeners and the Imposition of New Chloride Discharge Requirements at Santa Clarita Valley Businesses, 2 (2010).

[39] R.A. Bergman, Membrane softening versus lime softening in Florida: a cost comparison update, Desalination 102 (1995) 11–24. https://doi.org/10.1016/0011-9164(95)00036-2

[40] M.A. Tofighy, T. Mohammadi, Permanent hard water softening using carbon nanotube sheets, Desalination 268 (2011) 208–213. https://doi.org/10.1016/j.desal.2010.10.028

[41] M.A. Arugula, K.S. Brastad, S.D. Minteer, Z. He, Enzyme catalyzed electricitydriven water softening system. Enzyme Microb. Technol. 51 (2012) 396-401. https://doi.org/10.1016/j.enzmictec.2012.08.009

[42] M. Hemalatha, S.K. Butti, G. Velvizhi, S. Venkata Mohan, Microbial mediated desalination for ground water softening with simultaneous power generation. Bioresour. Technol. 242 (2017) 28-35. https://doi.org/10.1016/j.biortech.2017.05.020

[43] H. Luo, P.E. Jenkins, Z. Ren, Concurrent desalination and hydrogen generation using microbial electrolysis and desalination cells. Environ. Sci. Technol. 45 (2010) 340-344. https://doi.org/10.1021/es1022202

[44] J.N. Galloway, J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, B.J. Cosby, The nitrogen cascade, Bioscience 53 (2003) 341–356 https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

[45] Y. Zhang, I. Angelidaki, I, Submersible microbial desalination cell for simultaneousammonia recovery and electricity production from anaerobic reactorscontaining high levels of ammonia. Bioresour. Technol. 177 (2015) 233-239. https://doi.org/10.1016/j.biortech.2014.11.079

[46] X. Chen, D. Sun, X. Zhang, P. Liang, X. Huang, Novel self-driven microbial nutrient recovery cell with simultaneous wastewater purification, Scientific Reports 5 (2015) 15744. https://doi.org/10.1038/srep15744

[47] Y. Qu, Y. Feng, J. Liu, W. He, X. Shi, Q. Yang, J. Lv, B.E. Logan, Salt removal using multiple microbial desalination cells under continuous flow conditions, Desalination 317 (2013) 17–22. https://doi.org/10.1016/j.desal.2013.02.016

[48] K.S. Jacobson, D.M. Drew, Z. He, Use of a liter-scale microbial desalination cell as a platform to study bioelectrochemical desalination with salt solution or artificial seawater, Environ. Sci. Technol. 45 (2011) 4652–4657. https://doi.org/10.1021/es200127p

[49] Q. Ping, B. Cohen, C. Dosoretz, Z. He, Long-term investigation of fouling of cation and anion exchange membranes in microbial desalination cells, Desalination 325 (2013) 48–55. https://doi.org/10.1016/j.desal.2013.06.025

[50] D.A. Ebrahimi, G.N. Kebria, D. Youse, Effect of batch vs. continuous mode of operation on microbial desalination cell performance treating municipal wastewater, Iranian Journal of Hydrogen & Fuel Cell 4 (2016) 281-290.

[51] A. Aidan, G.A. Husseini, H. Yemendzhiev, V. Nenov, A. Rash¬eed, H. Chekkath, Y. Al-Assaf, Microbial desalination cell (MDC) in the presence of activated carbon, Adv. Sci, Eng. Med¬. 6 (2014) 1100–1104.

[52] F. Meng, J. Jiang, Q. Zhao, K. Wang, G. Zhang, Q. Fan, L. Wei, J. Ding, Z. Zheng, Bioelectrochemical desalination and electricity generation in microbial desalination cell with dewatered sludge as fuel, Bioresour Technol. 157 (2014) 120–126 https://doi.org/10.1016/j.biortech.2014.01.056

[53] G.C. Gil, I.S. Chang, B.H. Kim, M. Kim, J.K. Jang, H.S. Park, H.J. Kim, Operational parameters affecting the performance of a mediator-less microbial fuel cell., Biosens. Bioelectr.,18 (2003) 327–334. https://doi.org/10.1016/S0956-5663(02)00110-0

[54] 1Euntae Yang, Mi-Jin Choi, Kyoung-Yeol Kim, Kyu-Jung Chae, In S. Kim (2014): Effect of initial salt concentrations on cell performance and distribution of internal resistance in microbial desalination cells, Environmental Technology 36 (2015) 852-860. https://doi.org/10.1080/09593330.2014.964333

[55] S. Sevda, H. Yuan, Z. He, I.M. Abu-Reesh, Microbial desalina¬tion cells as a versatile technology: Functions, optimization and prospective, Desalination. 371 (2015) 9–17. https://doi.org/10.1016/j.desal.2015.05.021

[56] E. Yang, M.J. Choi, K.Y. Kim, I.S. Kim, Improvement of biohydrogen generation and seawater desalination in a microbial electrodialysis cell by installing the direct proton transfer pathway between the anode and cathode chambers, Desalination Water Treat. 51 (2013) 6362-6369. https://doi.org/10.1080/19443994.2013.780997

[57] T.A. Bower, A.D. Christy, O. Tuovinen, L. Zhao, Voltage Self-Amplification and Signal Conditioning for Enhanced Microbial Fuel Cell Performance, Ohio, 2013.

[58] L. Bazinet, M. Araya-Farias, Effect of calcium and carbonate concentrations on cationic membrane fouling during electrodialysis, J. Colloid Interface Sci. 281 (2005) 188–96. https://doi.org/10.1016/j.jcis.2004.08.040

[59] C. Casademont, G. Pourcelly, L. Bazinet, Effect of magnesium/calcium ratio in solutions subjected to electrodialysis: Characterization of cation-exchange membrane fouling, J. Colloid Interface Sci. 315 (2007) 544–54. https://doi.org/10.1016/j.jcis.2007.06.056

[60] F. Zhang, Z. He, Scaling up microbial desalination cell system with a post-aerobic process for simultaneous wastewater treatment and seawater desalination, Desalination 360 (2015) 28–34 https://doi.org/10.1016/j.desal.2015.01.009