Chapter 12
Microbial Desalination Cells: A Boon for Future Generations

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12.1 Introduction

As per the available information, the world's freshwater quantity has started decreasing tremendously due to the excess global warming, natural disasters, and also anthropogenic activities. Most of the water bodies are almost contaminated by our very own day-to-day events. Starting from our domestic waste to industrial waste such as effluents, pesticides, and radioactive waste have been continuously dumped into water bodies.

This has become a serious issue, as few of the countries have already started receiving alarming signals of water scarcity. This is the right time to implement these kinds of desalination technologies to receive a proper source of water.

The microbial fuel cell research has been extended in this field of desalination in the past 8 years. This is very much evident from the below graph depicting the number of articles published from 2010 to 2018 (Fig. 12.1). This contemporary change is due to many reasons like increased global warming, serious natural disasters, and immense water scarcity in parts of the world. These agitations have urged the researchers to find out alternative technology for desalinating the seawater. Comparative to the other technologies, microbe-driven desalination is a renewable one without any external power needed for the process. This can also provide a sufficient amount of bioelectricity. Although the conventional desalination serves the world with desalinated water, it consumes a huge amount of power.

MDCs have grabbed the attention of the imminent researchers due to its salient features such as non-expensive in terms of input energy, waste removal, desalinating water at a very economical way by combining MDCs and reverse osmosis (Yuan et al. 2015), and bio-restoring the heavy metal contaminated site (Ping et al. 2015).

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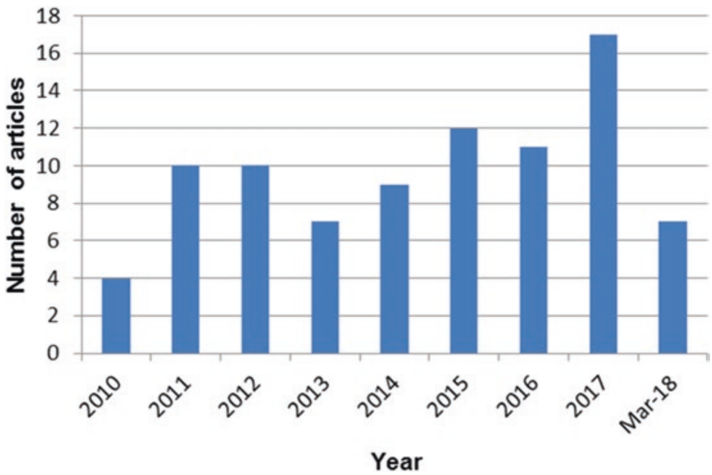

Fig. 12.1 Published articles in microbial desalination cell from 2010 to 2018 based on the keyword "microbial desalination cell" (Source: PubMed)

In order to improvise the technology in relation to desalination, stacked MDCs have been developed (Cao et al. 2009; Chen et al. 2011). Beyond these appreciable functions, they have their own constraints such as less possibility in concurrent organic removal and desalination in wastewater MDC (Zuo et al. 2013), desalination of only saltwater without any organics which is feasible (Lindstrand et al. 2000), and ineffective nitrogen removal from the anodic wastewater (Mehanna et al. 2010; Chen et al. 2012b).

12.1.1 Microbial Desalination Cell

Microbial desalination cell (MDC) is a technology where the microorganisms are fed with organic matter to produce bioenergy which in turn aids in desalinating the seawater. MDC is equipped with three chambers, anode, cathode, and a middle chamber filled with salt water. The anodic chamber is attached with anionic exchange membrane (AEM), and cathode is attached with cationic exchange membrane (CEM). During the oxidation of organic matter provided in the anode, protons are released into the anolyte, and positively charged species are prohibited from leaving the anode by the AEM. Meanwhile, the negatively charged particles from saltwater in the middle chamber are attracted toward the positive species in anode. The protons are disbursed in the cathodic chamber resulting in transfer of positively charged ions from the middle chamber to cathodic compartment. By this way, the ionic salts are eliminated from the middle chamber resulting in desalinated water. This process is free of physical or chemical methods (Cath et al. 2006). It is similar to electrodialysis process, but usage of energy is not engaged in MDC. The schematic representation of MDC has been given in Fig. 12.2.

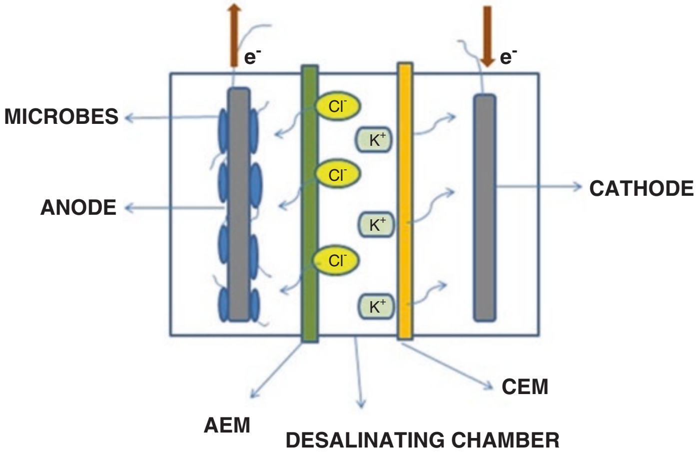

Fig. 12.2 Schematic representation of MDC

12.1.1.1 Materials: Electrodes, Anolyte, Separating Membrane

The electrodes in majority of the MDCs are of carbon nature such as carbon felt, carbon cloth, graphite felt, etc. Since carbon material has been proven to be the best material in microbial fuel cell with high performance, it has been used in MDC for increasing the efficiency. The type of MDC, electrode materials, anolytes, and electron exchange membrane along with their desalination efficiency has been listed in Table 12.1.

The anionic and cationic exchange membranes used in most of the studies are AMI7001/Membranes International and CMI7000/Membranes International, respectively. Depending upon the wastewater used in the anode, the substrate and anolyte type will vary.

12.1.1.2 Substrate/Anolyte/Catholyte

Substrate plays a vital role in the performance of MDC. Most the studies pertaining to microbial desalination employed sodium acetate as the anolyte. It turned out to be an efficient substrate in MDC, and by increasing its concentration, the desalination efficiency was improved (Cao et al. 2009; Kim and Logan 2011). Recent reports suggests that phosphate-buffered sodium acetate enhanced the salt removal (Jacobson et al. 2011). In photosynthetic MDC, synthetic wastewater with aerobic sludge acted as anolyte and microalgae as biocatalyst in cathode (Kokabian and Gude 2013). In a recent report, a stacked MDC was fortified with xylose (1 g/L) in 50 mM PBS. It was isolated as a waste product during the corn stover hydrolysis in biodiesel production has been used as a fermentable substrate (Qu et al. 2013).

Engine oil was used as an organic substrate which showed a considerable energy production and desalination in a recent MDC technology (Sabina et al. 2014).

Table 12.1 MDC configurations with its features

S. no.	MDC type	Electrodes	AEM	CEM	Anode solution	Desalination efficiency (%)	References
1	Three-chamber MDC	Anode and cathode carbon felt	DFI120/Tianwei Membrane	Ultrex CMI7000, Membrane International	Sodium acetate	90	Cao et al. (2009)
2	Biocathode MDC	Anode and cathode carbon felt	AMI-7001S/Membranes International	CMI7000S/Membranes International	Sodium acetate	92	Wen et al. (2012)
3	rMDC	Anode carbon graphite fiber brushes, air cathode carbon cloth	DF120/Tianwei Membrane	Ultrex CMI7000/Membrane International	Xylose	–	Qu et al. (2012)
4	PMDC	Anode and cathode graphite paper	AMI7001/Membranes International	CMI7000/Membranes International	Synthetic wastewater with aerobic sludge	40	Kokabian and Gude (2013)
5	Stacked MDC	Anode carbon felt, cathode carbon cloth	DF120/Tianwei Membrane	Ultrex CMI7000/Membrane International	Sodium acetate	99.4	Chen et al. (2011)
6	UMDC	Anode graphite granules, cathode carbon cloth	AMI7001/Membranes International	CMI7000/Membranes International	Synthetic wastewater (phosphate buffered sodium acetate)	>99	Jacobson et al. (2011)
7	cMDC	Anode graphite brush, cathode carbon cloth	CEM/ACC/Ni or Cu (CMXSB, Astom Corporation, Japan/ activated carbon cloth	Ni or Cu/ACC/CEM (Ni or Cu mesh current/activated carbon cloth/CMXSB, Astom Corporation	Phosphate buffered sodium acetate	88	Forrestal et al. (2012)

A multistage MDC (M-MDC) with two alternating anodes and cathodes was operated in two operating modes utilizing with domestic wastewater. In anode-anode-cathode-cathode mode, the wastewater has produced comparatively more current and desalination efficiency when compared to anode-cathode-anode-cathode mode (Zuo et al. 2016). Domestic wastewater has been utilized as the anolyte and phosphate-buffered ferricyanide as a catholyte in a MDC (Luo et al. 2012).

12.1.2 MDC Designs

The MDC has been developed in various designs such as biocathode, photosynthetic, stacked, ion-exchange resin packed, capacitive, recirculation, osmotic, submerged microbial desalination-denitrification cell, etc. Although these models have achieved a much performance, the operability in large scale has not been tested.

12.1.2.1 Biocathode MDC

Biocathode has turned out to be a sustainable electrode in promoting the performance by utilizing microbes as a catalyst. By using microbial catalyst, the biocathode MDC has reduced the construction price and been effective in producing valuable chemicals (Zhang et al. 2012). An aerobic biocathode MDC is more continuous and is inexpensive to operate than an abiotic cathode MDC. In a study done by Zhang et al. (2016), with biocathode MDC, it was observed that the salt removal, power density, and columbic efficiency were 44%, 77%, and 27%, respectively. Biofouling was found to be a major cause for the reduced performance. The researchers had the option of changing membranes after every cycle of MDC operation (Zhang et al. 2016).

12.1.2.2 Photosynthetic MDC

Another interesting research work based on algae powered MDC has thrown light in the area of biocathodes. This study has much emphasized on the use of biocathode to increase the system performance combined with reduced usage of the expensive catalysts. As similar to the environment, algae in PMDCs release oxygen as a terminal electron acceptor. Compared to other biocathodes, algae cathode has potential benefits such as the valuable products from the biomass after the process completion (Kokabian and Gude 2015). This is far better when compared to other MDCs where sludge formation takes place. Before utilizing algae in MDC, few factors such as carbon dioxide concentration, light availability, medium components, and other conditions have to be studied. Constant light source in lab level is achievable, but in large scale, it will increase the cost. It is clearly understood that light plays a major factor in the photosynthesis and actual growth of algae (Markou and Georgakakis 2011).

12.1.2.3 Stacked MDC

This type of MDC is made by placing multiple ion-exchange membranes in between the anode and cathode in order to achieve the maximum desalination. This will aid in increased charge transfer efficiency and salt removal via the membrane pairs (Gude et al. 2013). When compared to other MDCs, stacked MDC is an economical method to extract more energy. Stacked MDC had its own limitations like high saltwater – desalination and operable only in small scale. However, an attempt was made by Zuo et al. (2014) in order to scale up this technology. He used a >10 L stacked MDC packed with mixed ion-exchange resins with 0.5 g/L NaCl concentration and operated the system in batch mode. A desalination efficiency of 95.8% was achieved with 0.02 g/L of final effluent concentration (Zuo et al. 2014).

12.1.2.4 Supercapacitive MDC

Capacitive deionization (CDI) is based on exploitation of high surface area carbon materials at two electrodes. The potential difference applied between the anode and cathode in this MDC accelerates the consecutive process of adsorption and desorption by which the ions are detached from the saltwater (Suss et al. 2015; Anderson et al. 2010). The electrodes are self-polarized by the reduction-oxidation reactions, and thus the cathode acts as a positive electrode and anode acts as a negative electrode and of the internal supercapacitor. In supercapacitive microbial desalination cell (SC-MDC), CDI and MDC were combined to increase the power production. The conductivity of the solution and pH of the solution was observed with increase in time. An addition of capacitive electrode on the cathode side assisted the system to overcome the ohmic losses. To reduce the cost of the system, platinum was not used during the fabrication (Santoro et al. 2017).

12.1.3 Pros and Cons of MDC

pH plays a significant role in the process of desalination. The reduced pH hinders the microbial activity and thus results in a low current production. This can be eliminated by adding catholytes of pH (Lakshminarayanaiah 1969), recycling of anode solution (Chen et al. 2012a) and cultivating bacteria that would grow in low pH in anode (Ping and He 2013). Biofouling is one among the major limitation in MDC where the AEM is highly affected because of the biofilm formation over the membrane surface. It can be prevented by covering the membrane surface with some material that would not favor the microbial growth (Logan 2008).

12.1.4 Future of MDC

MDC has become a popular technology in terms of energy production, water softening, and desalinating saltwater. It has improvised on its own way in terms of different modes of operation, electrode materials, conjugated membranes, different biochemical pathways, MDC construction, etc. However, there are certain challenges that should be overcome for an effective operation. The performance of a microbial desalination cell is strongly influenced by the oxidation of organics by microbes and internal resistance. MDC has also expected to be applied in various fields such as bioremediation of industrial effluents, heavy metals, xenobiotic removal, etc. in the near future. Researchers are working toward a sustainable future for achieving 100% desalination efficiency with the maximum power production.

12.2 Summary and Conclusion

Microbial desalination cell has its own potential in desalinating saltwater apart from producing bioelectricity. In the future, this technology will surely lead us to a good path. The study of microbe's contribution in MDC is much understood. The microorganism's nature of degrading organic matter must be well studied before attempting the same in large scale. Improvisation of ion-exchange membranes with cost-effective materials, reduced membrane fouling, and catalyst addition will surely add a feather to the cap of commercial MDC applications.

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