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# Microbial desalination cells technology: a review of the factors affecting the process, performance and efficiency

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**ABSTRACT**

The concept microbial desalination cells (MDC) evolved from microbial fuel cells (MFC) technology. MDCs have been used in a wide range of applications since its introduction in 2009 including various configuration introduced by different researchers to solve some challenges in the operation of the reactor. Some of these applications include; seawater desalination, brackish water desalination, water softening, hydrogen and chemical production and groundwater remediation. Performance and efficiency of this technology is influenced by many factors just as any other technology, this review enlightens the varying impact of reactor configuration, pH imbalance/fluctuation, operational conditions, microbial conditions, substrate, materials and dimensions, electrode materials, resistance, hydraulic retention time (HRT) and conductivity on the performance of the MDC rector in terms of electricity production, desalination and wastewater treatment (COD removal). The study also identifies and demonstrates the factors other studies have compared over the years till date classified under technical topics, theoretically showing their significance to enhance the improvement of MDC for future extension of its application. The study as well shows the relationship between the individual factors along with how these factors contribute to the performance and efficiency of the MDC reactor, its processing (operation) and the way forward.

*Keywords:* MDC performance; Microbial desalination cells; Sustainability; Water desalination

## 1. Introduction

Lots of technologies, such as thermal desalination and reverse osmosis, have been introduced over the years for desalination of saline water but these technologies are energy and cost intensive using approximately 3–68 kWh to desalinate 1 $m^3$ of saltwater from the sea [1–5] but any reduction of salinity will benefit the energy efficiency of a downstream reverse osmosis (RO). In spite of such challenges the demand for freshwater, which forms only 3% of world water, is very high due to the rapid increase in its utility as a result of the exponential population growth [6]. For that reason, the concept of generating electricity stored in wastewater and simultaneously restore freshwater in the same device could be considered a significant and sustainable approach. Microbial electrochemical technologies (METs), emerging from the concept of microbial electrochemistry, deals with the interactions between microorganisms and conductive electrodes through the oxidation of organic matter to produce electricity (bioenergy), clean water and desalinate seawater [7]. Bioenergy since its introduction has proved to be a promising green source of energy generated from organic wastes. It has recently been applied in diverse ways including desalination of which microbial fuel cell (MFC) emerged from [8,9].

Since the discovery of electrochemically active bacteria, MFC and its related technologies have won the interest of many researchers because of its potentials [10]. Another METs which evolved from MFC that can simultaneously desalinate water, treat wastewater and produce energy

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is microbial desalination cell (MDC) [11]. Its concept of operation is similar to water electrodialysis but instead of applying an external source of energy, the MDC uses the electrical energy produced by the bacteria. As the bacteria respire, electrons are produced and transferred to the negative terminal (anode) within the anode chamber, which flow through a conductive material (wire) containing a resistor or a load to the positive terminal (cathode) thereby producing electricity [12].

For the past decade, MDC's configuration and performance have improved in terms of volume and power density from few microliters to more than 250 L and up to 3.3 W/m$^2$, respectively [13,14]. With MDC's gradual growth in application, environmental benefits have been maximized as well as sustainability and generation of energy from wastes prior to discharge back into nature and integrating waste treatment with desalination [8,15]. It has been applied in the treatment of many different types of impaired water including industrial and domestic wastewater, brackish water, landfill leachate and seawater [16]. Recent researches have proven that MDCs can be applied in reducing feed water salinity and energy demand either as a stand-alone process for decentralized water treatment and reuse or combined with conventional desalination processes, such as membrane-based reverse osmosis (RO) and thermal-based distillation [1,8]. The reactor requires little or no energy input to treat wastewater, and produce fresh water up to 99% salt removal and over 70% COD removal [17]. It can additionally produce a current density of about 8.4 A/m$^2$ from renewable sources which is essential for sustainable energy production and global water infrastructure [18].

Reviews articles of MDC have considered the working principle, different configurations together with their merits and demerits and proposed an MDC integrated wastewater treatment design [19]. Others have reviewed the systematic, qualitative and quantitative literature of MDC including the limitations and future applications [2] as well as suggestions of MDCs potentials in municipal and industrial wastewater treatment [17]. Though these studies propose important future focus for this technology, they lack critical study and analysis of factors influencing MDC's performance impeding the future applications they propose. Eventually, studies which considered factor-study compared few factors in their research. Consequently, in spite the numerous studies that have been carried out, MDC is still struggling to be applied outside the laboratory and on a larger scale due to challenges facing its performance. Most studies have encountered varying efficiency of the MDC's output which is attributed to varying conditions (factors) in which they operate. A thorough study and analysis of these factors and their relationship with each other against performance with sustainable solutions will enhance MDC real life application on a larger scale.

This review looks into details, if not all, a wide number factors that affect and influence the performance and efficiency of the MDC reactor. We review the factors various researchers have compared over the years till date classified under technical topics, theoretically showing their relations. The study also shows the relationship between the factors as well as how these factors significantly influence the performance and efficiency of the MDC reactor.

## 2. MDC basic concept

MDCs differ from MFCs in that, they employ an additional chamber, or chambers, between the anode and the cathode that contains saline water. MDC utilizes the potential difference generated from oxidation by anodic bacteria to drive the migration and accordingly desalination of salt ions, as shown in Fig. 1. With time, the bacteria consume the organic matter in the wastewater thereby cleaning it, generate electricity and desalinate water simultaneously [9,11,12,17]. MDC's performance in terms of its application has been measured by its desalination efficiency/salt removal [8], total desalination rate [20], specific desalination rate (SDR) [20], current production/power density [8,21], COD removal, nitrogen ($NH_4^+$-N, and TN) removal [13,22], Coulombic/current/Faradaic efficiency [13], removal of organic matter [23], effluent pH, and anode microbial community [21] as Table 1 described into details. Several researchers are altering configuration and factors in order to improve this promising technology for practical applications.

## 3. Factors affecting process performance and efficiency

Performance and output efficiency of every technology is being controlled by the magnitude and conditions of certain factors before, during and after the operation. MDC's performance is influenced significantly by reactor configuration, operational conditions, the substrate (Anolyte and catholyte), conductivity, charge transfer efficiency, electrode materials, resistance, hydraulic retention time (HRT), pH imbalance and membrane. Details of the mechanism, how they affect performance and their relationship with each other are explained into details under Sections 3.1–3.10.

### *3.1. Reactor configuration*

A variety of configuration of MDCs has been introduced in various studies, mostly to solve one or more setbacks in the use of MDCs. Table 2 summarizes some configuration of MDC together showing theirs set-backs, special features along with the influence those configurations have on performance. MDC configurations come with diverse and peculiar dimensions, materials, operating conditions and other features which have a significant influence on reactor performance and efficiency as described in details below. The trend in the advantages, challenges and features in Table 2 proves that configuration or design of reactor has a significant impact on the performance and efficiency, therefore further studies on how to improve configuration to suit MDC application without challenges will be significant to this technology.

#### *3.1.1. Materials property and dimensions*

Precise dimensions and specific materials used in reactor construction and processes have shown important influence on performance. Forrestal et al. in their research proved that material choice in capacitive adsorption capability MDC (cMDC) construction affects desalination rate as their

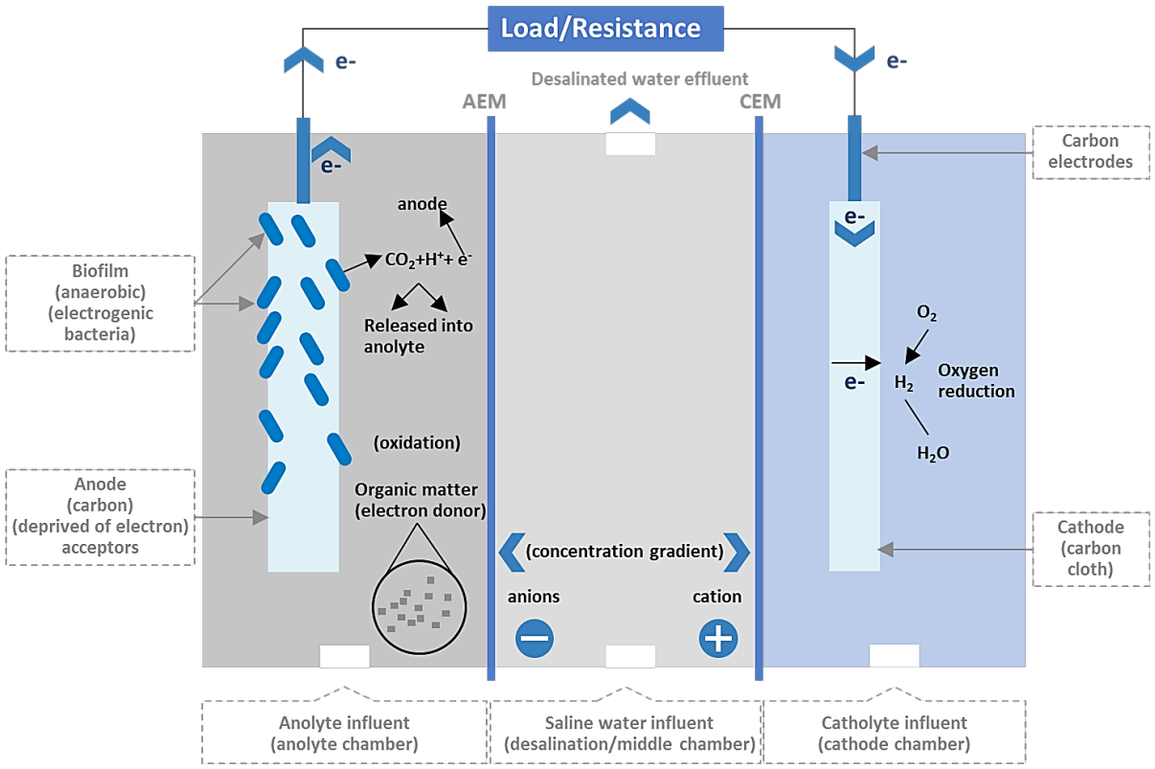


Fig. 1. Traditional MDC configuration (by author).

Table 1
MDC reactor performance terms

| Performance term | Details | Ref |
|---|---|---|
| Desalination efficiency or salt removal | The amount of salt removed from the desalination chamber or recovered from a concentrate chamber over a period of time expressed in percentage. | [8,85] |
| Specific desalination rate (SDR) | The salt removal based on salt solution volume, thus the volume of desalination chamber. | [20] |
| Total desalination rate (TDR) | The amount of salt removed from the desalination solution in an hour | [20,45] |
| Current production or power density (P) | Calculated as the product of measured current (I) and external resistance (E) all divided by the projected surface area (A) of the cathode. Thus $P = \frac{E \times I}{A}$ | [8,21] |
| COD removal, Nitrogen ($NH_4^+$-N, and TN) removal and removal of organic matter | Is the amount of COD and Nitrogen removed in the substrate over a period of time, mostly expressed in percentage. Measured by standard methods such as APHA method 5520 and HJ/T 399-2007. | [13,22,23] |
| Coulombic/current/Faradaic efficiency | This is the ratio of total Coulombs (unit of electric charge) that are transferred to the anode from the substrate to maximum possible Coulombs supposing all substrate removal produced current. | [12,13] |
| Effluent pH | The measure of the pH of the anolyte or catholyte over a period time depending on mode of operation | [21] |

results showed an enhanced salt removal profile compared that seen in a traditional MDC. Their results indicate that the electrical adsorption capacity of the activated carbon cloth (ACC) included totally increased TDS removal rate to about 61–82.2 mg TDS/g [24]. Desalination process basically depends on the salt solution and wastewater volume, HRTs of wastewater and salt solution concentration, the surface area of membrane, microbial oxidation and oxygen reduction reactions [8]. Numerous studies, as Table 3 summarizes, have placed much emphasis on the significant influence of the volumetric ratio of the chambers in the MDC reactor [7,25]. The trend in results shows that the lower the

Table 2
MDC configurations and design with details; adapted from [2,19]

| MDC configuration | Advantages | Challenges | Special features | Ref |
|---|---|---|---|---|
| Air cathode MDC | High reduction potential in cathode chamber | pH raise in anolyte with time decreasing | Cathode exposed to $O_2$ as terminal electron acceptor | [1,16,54] |
| Bio-cathode MDC | Self-generating and sustainable.<br>Enhance desalination with reduced start-up time. | A small reduction of cell potential during the batch mode of operation. | The reduction is enhanced by microbes. | [13,33] |
| Stack structure MDC | Improves charge transfer efficiency.<br>Increases energy recovery and desalination rate. | Increasing desalination chamber number resulted in declined current and SDR | Alternating IEMs | [16,18,20] |
| Recirculation MDC (rMDC) | Increases power and desalination efficiency.<br>Reduces the pH imbalance. | – | Recirculation of electrolyte, low concentration of buffer used. | [26,63] |
| Capacitive adsorption capability MDC (cMDC) | Reduces the pH imbalance.<br>Resolving ion migration problem. Increase desalination rate. | The effect of increased ion concentration on anode biofilm activity and community on the electrode was not studied as well as In-situ electrode regeneration methods | Incorporating capacitive deionization, double layer capacitor on the surface of the electrode, acid-producing chamber and bipolar membrane. | [24,56] |
| Upflow MDC | Increase desalination efficiency and power density. Efficient fluid mixing with the chamber.<br>Easier to scale up. | Decrease in pH at higher TDS removal rate | The tubular reactor containing two compartments and separated by IEMs.<br>Continuous operation with improved performance in desalination and current production. | [8] |
| Osmotic MDC | Improves desalination efficiency and performance.<br>Enhances organic matter removal. | Faced challenges such as system scale-up, FO membrane fouling, reduced energy consumption which needs further studies. | Forward Osmosis membrane used to replace AEM, Potassium ferricyanide as catalyst, increase water flux to dilute saltwater | [18,86,87] |
| Bipolar membrane MDC | High perm-selectivity.<br>Maintain pH in the anode chamber.<br>Enhance desalination efficiency.<br>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. | Bipolar membrane placed next to Anode Chamber; therefore four chambers, anion and cation selective layers laminated together to make a Bipolar membrane. | [1,18] |
| Decoupled MDC | Easy to scale up<br>Easy to control liquid volume ratios<br>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. | [72] |
| Separator coupled stacked circulation MDC (c-SMDC-S) | Checks pH imbalance<br>Improves Coulombic efficiency<br>Prevent biofouling<br>Smooth operation of system for longer period | – | Glass fibre attached to water-facing one side of the cathode and acts as a separator. | [88] |

(*Continued*)

Table 2 (*Continued*)

| | | | | |
|---|---|---|---|---|
| Ion-exchange resin coupled MDC | Stabilises ohmic resistance<br>Reduced energy consumption<br>Enhances charge transfer efficiency and desalination rate. | – | Desalination chamber packed with mixed anions and cations exchange resins. | [88] |
| Microbial electrolysis desalination and chemical production | Higher desalination rate<br>Low pH fluctuation | – | Involved an acid production chamber and a bipolar membrane | [20,46,89] |
| Submerged microbial desalination-denitrification cell | No bacterial leakage into ground water<br>No additional energy treatment for nitrate | The whole process ended up with the depletion of nitrate and ionic strength of groundwater.<br>The nitrogen species in the cathodic effluent required further treatment prior to discharge.<br>Adapted external nitrification of anodic effluent was beneficial to the current generation and nitrate removal rate but was not helpful for total nitrogen removal<br>Scaling-up in terms of volume and future application | Integrated with denitrification system into MDC<br>Removed nitrate ions from ground water are for electricity generation | [90] |
| Multi-stage Microbial Desalination Cell (M-MDC) | Simultaneous enhanced treatment and self-driven desalination of real domestic wastewater.<br>Enhanced nitrogen removal due to coefficient biological nitrification/denitrification and electrical migration.<br>Enhanced organics removal due to multi-stage anaerobic/oxic conditions of the anode and cathode. | Desalination was partial (43.4–75.7%).<br>Non-stacked resulting in relatively low current and desalination efficiency.<br>Aeration of biocathode increases cost and energy.<br>Further treatment of concentrate | Two alternating anode and biocathode chambers, with AEM and CEM at opposite position as in the conventional MDC.<br>A concentrate chamber with deionized water with mixed ion exchange resins | [13] |
| Photosynthetic Microbial Desalination Cells (PMDCs) | Beneficial use of algae as a passive biocathode by in situ oxygen generation and COD removal. | – | Microbial solar desalination cells supported by a photosynthetic microorganism, i.e., microalgae<br>(*Chlorella Vulgaris* sp.), as a biocatalyst in the biocathode. | [25,39] |

compartment volume of the anolyte and catholyte, the lower the efficiency of the reactor [3]. Zuo et al. made their cathode chamber thinner to minimize the ohmic resistance created by the spacing between anode and cathode [23].

The properties and dimensions of materials included in operation have a substantial role in the efficiency of the reactors. Qu et al. used thin tubes for recirculation which prevented equalization of the electrolytes' potentials that could have been caused by a large conduit for charge [26]. Ion-exchange resin coupled MDC adopted the use of ion resin which operated as ionic conductors, stabilized internal resistance and decreased the energy consumption of the system [27]. Ion exchange resins and IEMs have been used by some researchers as a medium for ion exchange and results have shown increasing desalination rate attributable to decreased internal resistance [13,20,28].

Intermembrane distance is the distance between the IEMs used in MDC. It has been proven that it has an

Table 3
Start-up and steady state conditions of different researchers; adapted from [7,25]

| $V_{anode}$: $V_{cathode}$: $V_{middle}$ | Start-up protocol | Steady state period | Output parameters | | | | | Ref |
|---|---|---|---|---|---|---|---|---|
| | | | Salt Conc./ g/L | DE/% | COD/g $COD/m^3$ | E.P./ $kWh/m^3$ | C.E./% | |
| 100:33:1 | Transfer of preadapted MFC anode | 1.6 g $L^{-1}$ sodium acetate in nutrient solution as anolyte, Ferricyanide in Cathode in a Fed-batch mode | 5 NaCl | 90 | – | 2 $W/m^{-2}$ 31 $W/m^{-3}$ based on the total reactor volume | – | [11] |
| 36:11:1 | Transfer of preadapted MFC anode | Same anolyte and catholyte (sodium acetate (1.64 g/L) in a nutrient buffer solution) continuously circulated from a 500 mL and a 150 mL bottles, respectively, at a rate of 5 mL/min | 20 NaCl | 80 | – | – | – | [20] |
| 4:4:1 | 1-week anode in-sit stabilization | Electrolytes were replaced every 24 h the salt solution was circulated separately in the desalination and concentrated chambers with two reservoirs of 2.4 L with dilute and concentrate were replaced every 12 h | 0.5 NaCl | 95.8 | – | 33.1 $W/m^{-3}$ in a month | – | [85] |
| 4:2:1 | Inoculation with a mixture sludge for a long period | Medium containing acetate in a 50 mM phosphate buffer solution amended with 12.5 mL/L mineral and 5 mL/L vitamin solutions. 0.3 g/L sodium acetate (~260 mg/L COD) and 1 g/L sodium acetate (~840 mg/L COD) | 35 NaCl | 42 | 74–77 | – | 22.7 ± 2.9 to 2.2 ± 0.2 | [71] |
| 3:3:1 | Transfer of preadapted MFC anode | Fresh dewatered sludge prepared ad anodic substrate; biocathode inoculation from topsoil with solution as substrate aerated at 300 mL/min, reference electrode | 5 NaCl | 46.37 | 25 | 3.178 $W/m^{-3}$ (130 d) | – | [65] |
| 1.5:1.8:1 | Transfer of preadapted MFC anode | – | 20 NaCl | < 84 | 72–94 | 65 $W/m^{-3}$ in max power conditions 31 $W/m^{-3}$ in oxygen reduction reaction | 60 Reduced to 20 (due to recirculation) | [18] |

(*Continued*)

Table 3 (*Continued*)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1:2:1 | Inoculation of a pre-a adapted biofilm | After each cycle, chambers were sparged with ultra-high purity nitrogen gas for 15 min and refilled with substrate solution (50 mM PBS, sodium acetate, minerals and vitamin solutions as anolyte and 50 mM PBS as catholyte). Ag/AgCl reference electrodes. Resistance of 10 Ω | 5 & 20 NaCl | 43% 5 g $l^{-1}$ NaCl & 37% 20 g $l^{-1}$ NaCl | 77±3% | 480 mW/$m^2$ | 68±11 | [1] |
| 1:1:1 | Pre-treatment of MDC and material prior to inoculation, 2 L of FWM with 20 mM of acetate (anolyte) 2 L of 0.025 Na2SO4 (catholyte) 2 L of 30 mM of $NaHCO_3$ circulated for 2 hours, then inoculated with 300 ml of culture (left overnight without circulation) then recirculated at 75 ml/l for 100 h | Electrolytes refreshed, closed circuit using 2.5 Ω of resistance recirculated for 65 hours. Ag/AgCl reference electrodes to maintain stable potential | 5 NaCl | 87 | 53 | Electric current (0.72 –0.32 mA/$cm^2$) | WP-0.308 L/$m^2$/$h^1$ | [44] |
| 11.3:9.2: 1 | Transfer of preadapted MFC anode, Anaerobic microorganisms were obtained from an acetate-fed anaerobic reactor. | 1.6 $gL^{-1}$ sodium acetate in nutrient solution (1248 mg $L^{-1}$ COD) as electrolytes and replaced every 48 h, Saline water replaced when the conductivity of the saline water was <10 $mscm^{-1}$ Bio-cathode, Resistance at 200 Ω | 35 NaCl | 92 | 56.2 | 14.49 $Wm^{-3}$ | 96.2 ± 3.8 | [33] |
| 13: 10: 1 | Transfer of preadapted MFC anode | Cathode fed with a solution containing 4.4 g $KH_2PO_4$ and 3.4 g $K_2$-$HPO_4$-$3H_2O$. Air cathode, Resistance at 200 Ω | 35 NaCl | 77 | 62.6 | 8.74 $Wm^{-3}$ | – | [33] |
| 0.9 : 0.5: 1 | The microbial consortium was grown in air and algal cathode MFCs prior to its transfer into the air and algal MDCs | 500 mg $L^{-1}$ COD glucose *Chlorella vulgaris* bio-cathode | 10 NaCl | 40 | 65.6 | 0.151 $Wm^{-3}$ 0.21 kW h/$m^3$ | – | [25] |
| 2.3:2.7:1 | Transfer of preadapted MFC anode | Activated Carbon Cloth (ACC) used as electrode material for pH control. Ferricyanide as a catalyst in Cathode, electrolyte operated in fed-mode. Ag/AgCl reference electrodes to maintain stable potential | 10 NaCl | 69.4 | – | Current (max)-2.5 mA | | [24] |

(*Continued*)

Table 3 (*Continued*)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7:9:1 | Bacteria they were taken from anode and biocathode of a mature MFC that was initially inoculated with sludge from anaerobic (anode) and oxic (biocathode) tank of a wastewater treatment plant | ACAC (1) and AACC (2) mode concentrate batch circulation at 12 mL/min. Operation at varying HRT; 4, 8, 12, and 16 h. | Simultaneous desalination and treatment of real domestic WW | 56.4 (43.4–75.7) | In 1; 51.5 In 2; 60.6 | – | 1<br>1.8 - 6.0<br>2<br>8.4 | [13] |
| 13:8:1 | The anode was inoculated with effluent from an existing MFC and enriched by operation in a conventional one-chamber MFC | Synthetic seawater as catholyte, fresh medium was provided in the anode chamber with 1 g/L sodium acetate in a phosphate buffer with minerals and vitamins A continuous flow operation in three stages to increase desalination of the synthetic seawater. | 35 NaCl | 98 | 77–99 | 800–1140 mW/m$^2$ | 80 | [34] |
| 1:1:1 | Anode was inoculated with a microbial consortium collected from an UASB of a dairy wastewater treatment plant Microalgae Chlorella vulgaris (as biocathode) was grown in the cathode chamber using the medium Cathode chamber. | The microbial inoculum and the wastewater (COD-1000 mg/L) were introduced to the anode in 1:1 ratio under ambient temperature of 25 ± 3$^C$ | 15 NaCl<br>35 NaCl | - | - | 20.25 mW/m$^2$ | - | [91] |

D.E – Desalination Efficiency;
COD – Chemical Oxygen Demand removal (Waste water treatment capacity);
E.P – Energy production;
C.E. – Coulombic Efficiency;
WP – Water Production.

essential impact on performance since desalination process decreases with increasing intermembrane distance. It remains one of the key factors that need to be investigated for more understanding of MDC's operation [29]. Ping and He concluded in their study that at a smaller intermembrane distance, specific desalination rate, as well as desalination efficiency, is higher [30]. In general, reducing the intermembrane distance can effectively reduce the internal resistance. Other studies also proved that, at a minimum intermembrane distance, resistive loss in the electrodialysis stack was negligible [31–34].

Electrodes play a very vital role in the operation of MDC since power output depends greatly on the potential difference between the anode and the cathode [12]. Materials used as electrodes basically ought to have; high electrical conductivity, a large surface area with accessible pores, enhanced mass transfer characteristics, chemical stability, mechanical strength, biocompatibility, low cost, and scalability [16]. Anode surface is known to be the single largest contributor to "activation losses" aside the amount of energy gained by biofilm during metabolism process [10,12,35]. The introduction of brush anodes provided a surface area of about 300 to 1,500 times more than the previous carbon fibre papers (electrodes) which were not practical in commercial scale-up or bacterial growth. Consequently making anodes no longer a limiting factor in power production. To boost the current generation of the reactor, some studies proposed that electrode should be made from materials with the larger surface area where the larger mass of biofilm can adhere to, in order to enhance current generation [2,10]. Aidan et al. confirmed that the large surface area of activated carbon enabled bacteria growth which led to larger microbial cultures resulting in increased electron transfer in the anodic chamber [36]. Again it provided more room for the combination of protons, electrons and oxygen that closes the circuit for enhanced performance. Cathodic reactions (oxygen reduction) in MDC require a source of oxygen which could be abiotic (air cathode or air pump) or biotic (biocathode). Air cathode has shown high desalination rates due to their high reduction potential and cost-effectiveness [1]. Biocathodes, on the other hand, provide a surface for microorganisms for aerobic processes (as well as anaerobic) which catalyzes oxygen reduction (sometimes other processes) allowing more electrons to flow for high desalination and reactor performance [37]. Recent configurations aim at making the reactor operate in a more sustainable and cost-effective way, thereby choosing biocathodes over the air-cathodes [25,38–40]. Air-cathodes require expensive catalyst materials, have slower redox kinetics under ambient conditions and require high energy requirements to maintain optimal dissolved oxygen [25]. Meanwhile, biocathodes (biological cathodes) utilize microorganisms as biocatalysts to accept electrons providing a different path for oxygen reduction which has economic viability and environmental sustainability of bioelectrochemical systems. They have therefore demonstrated to be a promising advancement in the pursuit to implement MFCs and MDCs for practical applications because of potential cost savings, waste removal, and operational sustainability in as much as it improves desalination rates extends power production and COD removal [25,41]. Kim et al. in their research recommended that, to construct a more efficient reactor: (i) reduce electrode spacing by eliminating the narrow membrane joint between the chambers to enable direct contact of the anode and cathode with the membrane, (ii) reduce reactor volume by constructing the cathode chamber half the size of the anode, (iii) provide a large anode electrode surface area in order to eliminate "dead volume" in the head space, (iii) enhance consistent voltage production by continuous flow of anode substrate-containing medium across the biofilm, (iv) use air-cathode instead of aqueous-cathode to eradicate a buffer solution to improve performance especially in terms of power generation [42]. Researchers should look more into affordable materials as well as different forms of materials such as carbon and graphene which are more efficient in properties and structures

### *3.2. Operational conditions*

Various researchers have shown several conditions under which MDC can be operated. Modes of operation, batch or continuous, significantly affect the performance and stability of MDC [2]. In the batch mode of operation, electrolyte conductivity reduces with time leading to a gradual increase in internal resistance thereby reducing general performance. Gude et al. had results that demonstrated the effectiveness of treating domestic wastewater and simultaneously generate electricity in a continuous mode proving the impact of this mode of operation on performance [16]. One of the promising future recommendation of MDC is for it to be operated in a continuous flow mode, though so far little has been done about the challenges that come with such mode of operation. In continuous flow mode, the chambers of the reactor are fed with solutions circulating (pumped) continuously (in cycles) at a hydraulic retention time (HRT). The configuration of SMDC has been operated effectively producing encouraging results in a continuous mode with the help of its stacked desalination and concentrate chambers [20]. A novel of multi-stage microbial desalination cell (M-MDC) also operated successfully in a continuous mode, introducing an ACAC mode (anode(1)-cathode(1)-anode(2)-cathode(2)) and AACC mode (anode(1)-anode(2)-cathode(1)-cathode(2)) showing an anaerobic/oxic processes in the anode and cathode respectively. The AACC mode proved to enhance energy recovery as the ACAC enhanced wastewater treatment proving the fact that operational conditions significantly affect MDC performance [13]. Continuous flow mode has been found feasible to control pH imbalance, substrate concentration at a low cost in practical application and to boost useable electrical output of MDC [2,21,39,42,43] electricity generation, and wastewater management. MDC emerged from the microbial fuel cell (MFC). More studies should be carried out to boost its potential in MDC performance.

Conditions made available at different stages of operations play a very vital role in the physiological growth of microorganisms. A report by Borjas et al. enlightened the concept of start-up and steady state periods in operation which described the period when microorganisms colonize to grow on the electrode surface and when they mature to produce electric current respectively as sensitive periods during operation [44]. Availability of

substrate to microorganisms is a controlling factor during the physiological steady state period of operation and conditions during this period is vital in the performance of the reactor. A summary of such is shown in Table 3, as different conditions have impact on results (performance) in terms of desalination, COD removal, power density, water production and Coulombic efficiency. Microorganisms function efficiently in specific temperature ranges; MDC has been demonstrated to operate well in an ambient temperature of 25°C [13], again other studies have also proved to this effect [14,45–49]. Microbial adaptations and their environmental perturbations contribute significantly to the challenges and performance of MDC technology [2]. Anodic conditions should enable microorganisms to be able to hydrolyze cellulose and become electrochemically active in an anaerobic environment. Accordingly, utilizing an anode as an alternative electron acceptor during metabolism (oxidizing) in an ambient temperature of 23 ± 3°C [39,50]. Aerobic conditions are mostly provided in the cathode chamber to enhance the oxygen reduction reaction process, Gil et al. in their experiment with MFC confirmed that an aeration rate around 100 mL/min is sufficient to enhance performance. Their results actually attested that dissolved oxygen (DO) is a major limiting factor for MFC as well as MDCs [21,47]. Furthermore, numerous studies have attested to the fact that conductivity and concentration of anode substrate, pH of environment, surface area and potential of electrode as well as materials used influence the activities of microorganisms in the anode and cathode chamber of the reactor as summarized in Tables 3 and 4 [1,2,24,51,52]. The varying trend in performance reveals that, different operation (environmental) conditions influence microbial activities which is a driving force of the whole process. Just like other biological technologies, more studies should be carried out on operation conditions especially suitable conditions for the diverse species of microbes used in MDCs to enhance its efficiency.

### 3.3. Substrate (anolyte and catholyte)

Electrolytes (anolyte and catholyte) significantly influence performance since they are the source of organic matter and nutrient (for bacteria metabolism), reservoir for ion species (for desalination, contamination and electrodialysis) and medium for pH variation [25,32,37]. Many researchers have used different substrate in varying concentrations and operations modes such as acetate [1,11,53], xylose [21] with phosphate buffer solution (PBS) [26], enriched cellulose degrading rumen microbial consortium [39], synthetic wastewater containing acetate [8], wastewater [36,51,54], untreated domestic wastewater [13,26,55], as anolyte to boost the activities and by-products of exoelectrogenic bacteria in the anode chamber. Meanwhile, ferricyanide [11], PBS with NaCl [47], and many others (as shown in Table 3) have also been used as catholyte. These studies have verified that substrate properties; significantly concentration, have relevant influence on MDC performance and efficiency. Concentration losses occur often as a nutrient gradient in the substrate reduces gradually with time as the bacteria consumes it. A study on an M-MDC attested to this, when its maximum performance was attained by an increase of 0.6 mA in current generated, 40.2% COD removed and 47.3% desalination efficiency when concentration of anolyte was increased by adding 1.4 g/L glucose [13]. Volume ratio of electrolytes and saline water has also been proven to have relevant impact of general performance especially desalination efficiency. Kim and Logan raised in their report that, high salinity removals require a large volume of electrolyte especially anolyte to enhance performance otherwise results in partial removal. Such that an MDC achieved 40–60% salt removal owning to the electrolyte volume being only two to three times the desalinated water [18]. They interpreted the results such that, for practical applications, MDCs are more likely to be used for partial salt removal from seawater which demands further studies for more understanding.

### 3.4. Conductivity

Conductivity is expressed as basically the concentration of ion present in an electrolyte that has the capability to transfer electric charge. In another context, it refers to the measure of a material's (electrodes) ability to transfer electric charge (in this case) from one point to another. Generally, the higher the concentration of the saline water, the higher its conductivity (thus higher concentration gradient between the desalination chamber and the electrode chambers) thereby increasing desalination performance. When the concentration of salt water is higher than that of the electrolytes, the desalination performance will be enhanced by dialysis [56]. The total ion concentration is of more relevance to the performance of solutions (esp electrolytes) as it may contain some ionic species that may be involved in other processes inhibiting performance. These species can consequently decrease conductivity and thereby increasing internal resistance [7,11,22]. Desalination process in a fed-batch mode of operation, under a constant applied potential, is likely to have a reduction in conductivity which will be corresponding to its desalination process over a period of operation [7]. Conductivity of saline water in the middle chamber decreases with time as the ions migrate in the anode and cathode chamber [55]. Full-scale demonstrations of MDCs using real wastewater has been a challenge due to low conductivity, different studies have shown that enhanced performance where conductivity increased with decreased internal resistance [57,58]. High electrical conductivity as reported by Gude et al. is one of the basic requirements of an electrode material to enhance performance as it may enhance bioelectrochemical kinetics of the surface reactions. Various materials, such as carbon cloth, graphite felt, carbon brush, granular graphite, stainless steel mesh and graphene, have been introduced on the subject of electric conductivity of about ~10 S/cm [16,59]. In terms of energy generation output of MDC, the electrode's ability to conduct electricity is very significant.

#### 3.4.1. Presence of ions species (Ionic composition)

There is a limited understanding of the ionic transport mechanisms of different species present in saline or electrolyte and its implications on MDC performance (especially membrane fouling and scaling) [23]. The presence of multiple ions in water will definitely affect MDC performance in terms of desalination and power generation.

Table 4
Influence of materials on performances of MDC adapted from [16,34]

| AEM | CEM | Anode | Anolyte (g/L) acetate/xylose | Cathode | Catholyte | Saline water conc. (g/L) | Desalination % | COD removal % | Voltage (Open circuit) | Power density | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AnAEM, DF120, Tianwei Membrane | CM-I7000, MII | Carbon felt | 1.6 | Carbon felt | Ferricyanide | 5–35 | 94–88 | – | 700 mV | 2 $W/m^2$ | [11] |
| AMI 7001,MII, R-5500, Solvay Advanced Polymers | CMI-7000, MII | Ammonia treated Carbon cloth BASF, NJ | 1 or 2 | Platinum (0.5 mg $cm^{-2}$ Pt) and four PTFE diffusion layers on a 30% wet-proofed carbon cloth | 50 mM PBS | 5–20 (Water) | 43–67 | 77 | | 480 $mW/m^2$ | [1] |
| AMI-7001, MII | CMI-7000, MII | Graphite granule | 4 | Carbon cloth (platinum) | | 30 | 99 | – | – | 30.8 | [8] |
| AMI-7001, MII | CMI-7000, MII | Carbon brush | 3 | Carbon cloth (platinum) | | 35 (artificial sea water) | 94.3 ; 73.8 | 92 | – | 28.9, 11.1 $W/m^3$ | [92] |
| AR204-SZRA-412 | CR67-HMR-412 | Heat treated Graphite brush | 2 | Carbon cloth (PTFE) | 100 mM PBS | Mixture of anions and cations ($Mg^{2+}$& $Ca^{2+}$, $Cl^-$, $Br^-$ $SO_4^{2-}$) with $Na^+$ | 13–29 | 25 | – | 660 $mA/m^2$ | [23] |
| AMI 7001 | CMI 7000 | heated graphite | Wastewater | Carbon cloth | Ferricyanide | 5.85 (Water) | 66 | – | CCV = 700 mV, $R$ = 1000 Ω | 8.01 $W/m^3$ | [51] |
| DF120, Tianwei | CMI-7000, MII | Carbon graphite fibre brushes | Solution of xylose (1 g/L) in an either a 25/50 mM phosphate buffer solution | Air cathode | 25 mM or 50 mM PBS | 20 (Water) | 39–25 | – | CCV = 500 mV, $R$ = 1000 Ω | 931 $mW/m^2$ | [26] |
| AMV, Asahi glass | CMV, Asahi glass | Graphite fibre granules | 1 | Platinum nanoparticle catalysts | Synthetic seawater | 35 (Water) | 98 | – | – | 800–1140 $mW/m^2$ | [34] |
| DF120, Tianwei Membrane | CMI-7000, MII | Carbon felt | 1.64 | Carbon cloth (platinum) | PBS | 20 (Water) | 99% | – | 7.43 mA | – | [20] |

(*Continued*)

Table 4 (*Continued*)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AMI-7001S, MII | CMI-7000S, MII | Graphite rod pushed to carbon felt | 1.6 | Graphite rod pushed to carbon felt | Aerobic biocathode | 35 (water) | 56.2, 92.0% | | 609 mV | 0.94 W/m$^2$ | [93] |
| AEM, DF120, Tianwei | CEM, Ultrex CMI7000 MII | Carbon graphite Fibre brushes | Xylose (1 g/L) | Carbon cloth (platinum) | 50 mM PBS | 20 NaCl | 12%, Salt removal: 97 ± 1% at an HRT = 2 d 76 ± 1% at an HRT = 1d | – | – | 860 ± 11 mW m$^2$ | [33] |
| AMI-7001, M.I.I | CMI-7000, MII | Carbon fibre felt | – | Carbon fibre felt | With potassium ferricyanide, | 700, 100 mg/L | – | – | – | 360 mW/m$^2$ | [69] |
| AMI-7001, MII | CMI-7000, MII | Carbon brush | Treated Wastewater from OsMFC with 1 g/L Sodium acetate | Carbon cloth (platinum) | Acidified water, salt water, anode effluent | 10–35–50 g/l (catholyte of OsMFC) | 95–85 | 85% | – | 12.45 W/m$^3$ | [28] |
| AEMs (1.8 mol/kg, Shanghai, China | CEMs (2.0 mol/kg, Shanghai, China | Conductive activated carbon granules | Domestic wastewater | conductive activated carbon granules (biocathode) | Domestic wastewater | Domestic wastewater | 52.4–56.4 | 92.5 | 17.2 | – | [13] |
| AEM, Selemion AMV, Asahi Glass, Japan | CEM, Selemion AMV, Asahi Glass, Japan | Granular activated carbon | sodium acetate, PBS buffer | Air cathode | 100 mM PBS solution | 20 g/L of NaCl | 72 | – | 28.6 mA to 19.2 mA with increase in desalination cells | – | [45] |

Cations, such as $Ca^{2+}$ and $Mg^{2+}$, present in saline water during long-term operation can cause a decrease in electric conductivity as well as scaling of membrane surface [28]. One major challenge faced in MDC's operation is that ions present in solutions turn to react with the natural organic matter in water forming fouling layers on membrane surface. This phenomenon causes membrane fouling which inhibits performance of the membrane; described section 3.10. Then again, anions such as $NO_3^-$ and $SO_4^{2-}$ under anaerobic conditions (in the anode chamber) are reduced into $N_2$ and $H_2S$, which end up decreasing Coulombic efficiency as they compete with the anode as electron acceptors for electron produced by microorganisms. These anions are in a competitive migration which is basically affected by the high molar conductivity of the anions involved in that way impeding desalination efficiency [18,23,28]. More studies have to be carried out on the mechanisms ionic species are involved in as well as how to reduce the impact of other reactions and processes that inhibit general output.

### 3.5. Charge transfer efficiency

Knowing the driving force of MDC processes, a number of electrons is required to remove an equivalent amount of salt during desalination. Due to some factors a percentage of electrons may be lost to drive other processes rather than salt removal (cathode reactions) which may affect the efficiency of desalination. Such factors include Coulombic efficiency, back diffusion, influence of membrane and electrodialysis process. Other processes such as the influence of other electron acceptors such as sulphate, nitrate and $O_2$ diffusing into the chamber on membrane in the anode may contribute to such effect [47]. This phenomenon causes the need for more organic oxidation reactions to drive desalination than actually needed [8], if not, output is affected. The improvement in the desalination mechanism of stacked reactors is the effect of a large pair of ions split as a result of each electron transport through the system enhancing the charge transfer efficiency [45,60]. Trend in MDC studies shows that much has not been done in this area in spite its significance. More investigations should be focused on understanding charge transfer efficiency and how to increase it, significantly the factors listed in this section.

### 3.6. Electrode materials

The electrochemical gradient resulting from the voltage potential between the electrodes and the high concentration of $H^+$ ions in the anode chamber drives processes in the MDC reactor [24,39]. An important feature of a polarized electrode is for it to enhance biofilm growth and uniform distribution of cell activity. This establishes a low-resistance pathway between biofilm cell and electrode to lessen electron acceptor limitations [7,61]. Electrode polarization is therefore substantial in MDC since it influences the interaction between the microbes and electrode surface thereby causing charge accumulation in the cytochromes networks. Different bacteria adapt different mechanisms, direct contact, nanowires (wired), and mediators (wireless), in order to transfer electrons to an electrode [62]. When the electrode potentials are maintained constant throughout desalination process, as a study did with the help of a reference electrode potential, the performance of the reactor is boosted when the overall potential of the cell is maintained steadily. Electrode potential (of the anode) is likely to increase with substrate removal when pH in the anode chamber decreases ending up in a poor performance of the reactor (thus a decline in current) [26,63,64]. The closer the potential of the anode is to zero volts, the more energy the reactor can produce in the view of the fact that bacteria can then gain more energy by using the electrode as an electrode acceptor instead of other chemical ionic species present in the chamber [10]. Actually, an increased and stable anode potential provides sufficient anode polarization where current passage is stable enough for biofilm colonized at the surface to have enough electroactive capacity to drive the process [7,24,49,65] moving charged ions from a middle chamber between two membranes in a type of microbial fuel cell called a microbial desalination cell. Desalination efficiency using this approach is limited by the voltage produced by the bacteria. Here we examine an alternative strategy based on boosting the voltage produced by the bacteria to achieve hydrogen gas evolution from the cathode using a three-chambered system we refer to as a microbial electrodialysis cell (MEDC). The cathode's potential and its reactions (water reduction) is directly proportional to that of anode in that it increases as the anode's increases and the vice versa.

### 3.7. Resistance

#### 3.7.1. Internal resistance

One of the critical challenges with MDC than MFC is the increase in internal resistance owing to the additional chamber and installation of IEMs [53] but adding a desalination compartment and an ion-exchange membrane may increase the internal resistance (Ri). MDCs have anode and cathode resistance (also known as ohmic losses) which extensively affects energy recovery, in that the lower the resistance the higher the current [28,39,47]. Generally, internal resistance is influenced by bacteria-electrode connection, resistance of electrode charge collector interfaces, rate of ion transport across the membrane and the conductivity of electrolytes, salt solution concentration and membrane (IEMs) [7,10,20,36,53] but adding a desalination compartment and an ion-exchange membrane may increase the internal resistance (Ri). The simultaneous substrate consumption by biofilm and ion loss in the desalination chamber results in an increase in internal resistance, which ends up decreasing the current along with one batch cycle of operation [24]. The electric potential created by the salt gradient on account of the additional concentrate and desalination chamber introduced in the SMDC significantly impeded the ion transfer between chambers resulting in a decrease in SDR [20]. Many studies have proposed new configurations (shown in Table 2) for MDC especially with regards to materials that can restrain internal resistance to amplify power output and to reduce the cost of desalination. This proves the influence internal resistance has on conductivity and general performance of MDC [2].

Junction potential, concentration difference between two ionic solutions in the chambers coming into contact, has been proved in some reports as an impelling cause

in increasing reactor efficiency as it reduces internal resistance. Reports further show that junction potential increases with increasing initial saline water concentration in so doing overcoming potential losses associated with the desalination chamber [34,53,66] but adding a desalination compartment and an ion-exchange membrane may increase the internal resistance (Ri). Electrode resistance can as well be reduced by increasing the surface are of the electrode or enriching their respective chambers with biofilm [67]. Other studies have recommended smart engineering designs to reduce the distance between electrodes so that resistance is reduced sufficiently [64]. These factors should be considered in reactor construction and operation to reduce internal resistance in order to boost performance.

#### *3.7.2. External resistance*

MDC's electric circuit is normally closed over a varying load using an external resistance. Also with variable external resistance, a polarization curve can be obtained to determine an approximate total internal resistance of the cell [10], the quantity of losses (activation, ohmic, concentration) [39] and power density. A number of studies show that maximum current increases by decreasing the ohmic external resistance [68]. The Zhang and Angelidakiin their report on a novel MDC application in ammonia recovery proved that performance of MDC is affected by varying external resistance [22]. In that, all parameters except power density increased with decreasing external resistance (thus increasing current density). Their report was in concurrence with previous studies which demonstrated that lowering the external resistance within a certain range (>10 Ω) can promote the output of the MDC cell. Chen et al. demonstrated that, even though exoelectrogenic bacteria could behave unstable and thereby producing fewer electrons when external resistance is too low (<10 Ω), SDR and current generated can be enhanced by reducing external resistance (as well as charge transfer efficiency) [20]. External resistance more than 500 Ω can be a rate-limiting factor (as it can limit electron flow between electrodes) when electron consumption rate is lower at the cathode than the transfer rate [42,47]. With such results, we can conclude that the impact and significance of other factors on SDR, DR and current generation, become very prominent during processing when external resistance is less than 10 Ω otherwise is an improvement in performance.

### *3.8. Hydraulic retention time (HRT)*

HRT mainly controls the duration (retention time) at which all the reactions occur in the chambers of the MDC cell. The performance of M-MDC was evaluated by varying HRT of the wastewater to 4 h, 8 h, 12 h, and 16 h [13] and the results proved the substantial impact HRT has on pollutant removal (COD, $NH_4^+$-N, and TN), current production, Coulombic efficiency and desalination efficiency in both fed-batch and continuous modes of operation. Their results also showed a maximum boost in their reactor's performance by approximately 31% as they increased the HRT to 64 h. Qu et al. in their investigation of MDC under continuous flow conditions demonstrated an improvement in desalination (salt removal) and power by increasing HRT from 1 day to 2 days; at a flow rate of 0.02 mL/min though they had a decrease in the overall Coulombic efficiency [69] and then on to the anode of the next reactor, which avoided pH imbalances that inhibit bacterial metabolism. The salt solution also moved through each desalination chamber in series. Increasing the hydraulic retention times (HRTs. There is a high influence of HRT on total dissolved solutes (TDS) removal, given that TDS removal increases with increasing retention time resulting in higher current generation, of which a study by Jacobson et al. confirmed. They also expressed relation between retention time and saline water volume, in that longer HRT would decrease TDS removal rate significantly when there is a large difference between the anode volume and the salt solution volume [8]. Increasing the HRT for saline water in the middle chamber is scientifically right to enhance desalination, but larger middle chambers increase ohmic resistance thereby affecting overall performance. Ping et al. worked on the consequence of intermembrane distance (*see section 3.1.1*) on performance of MDC and its relationship with HRT and flow rates within the middle chamber. Their results explained that, at the same HRT, small intermembrane distance improves desalination efficiency as well as specific desalination rate significantly whiles a larger distance with equivalent influent flow rate does not negatively affect performance [34].

### *3.9. pH imbalance/fluctuation*

In MDC operation, the bio-film release protons and electrons as a by-product of oxidizing the bio-pollutants in the substrate supplied. These protons react with anions migrating from the desalination chamber (and other ionic species probably within the anodic chamber) to produce internal biofilm acidification as a result of metabolism in the chamber [7,63]. As the desalination process occurs over time, protons accumulate as a result of microbial respiration causes the pH in the anode chamber to decrease (acidic). Meanwhile, hydroxide accumulates in the cathode chamber due to oxygen reduction thereby increasing pH within the cathode chamber. With time, this imbalance in pH adversely affect microbial growth and activities in the anode chamber and the reduction efficiency of electron acceptors in the cathode chamber [8,11,17,26,51]. Many researchers have experienced low voltage production and potential losses of about 0.095 V during operation which is commonly attributed to inhibition of exoelectrogenic activity (disrupts lifecycle) due to the pH fluctuations in the anolyte and catholyte [26,36,63,70]. According to a study by Qua et al. the anode pH affected the anode potentials of many MFC and was the major reason for low desalination efficiency of MDC [26]. Controlling pH in an economical design has become an essential key for optimizing MDC performance in terms of power generation and water desalination [2], Table 2 shows a summary of different configurations and their approach to controlling pH imbalances. In all the approaches to control pH imbalance, recirculation seems to be a promising solution but has challenges in a continuous mode of operation. In this system of operation the anolyte and catholyte solutions are recirculated with the help of a pump, mixing the solutions at a steady speed. The process steadily prevent the pH differences in the electrolytes

[2,18,26]. Electrolytes may be recirculated individually from a bigger tank (tank to chamber cycle) [44,63,71] a large-scale MDC system (total liquid volume of 105 L or between the chambers (anode to cathode chamber cycle) [18,25,26,72]. Capacitive deionization (CDI) is a technique that has been used in removing dissolved charged (ions) in aqueous solution. They mostly include materials with capacitive adsorption capable such as adsorptive activated carbon cloth (as used by Forrestal et al. in Capacitive MDC (cMDC)) [24,73]. Other carbon-based and carbide-derived materials have the ability to absorb excess ions in aqueous such as an anolyte in the case of MDC [74]. We propose that materials with capacitive adsorption capability should be included in reactor design (within chamber walls or attached to membranes) to reduce the presence of migrated ions even as recirculation is still adapted. Future studies may focus on how to form better carbon-based materials as part of reactor configuration to control pH imbalance as well as regeneration methods as Forrestal et al. also suggested.

### *3.10. Membrane*

MDC is a membrane-dependent technology since it function basically depends on IEMs separating the desalination (middle) chamber from the anode and the cathode chamber. Membranes used in the MDC reactor create a bipolar process since they can separate ionic species in solution driven by electric current. They may cause water dissociation in the reactor during processing which contributes significantly to lower current density. Given the fact that, electrons released into the chamber are used in dissociation instead generating current through the electrodes [8]. It has been reported that desalination efficiency of MDC can be increased by 50–63% when membranes with higher ion exchange capacity are used [1] but any reduction of salinity will benefit the energy efficiency of a downstream reverse osmosis (RO) as they are responsible for the transport of targeting ions [31,60]. The use of a cellulose acetate membrane in an experiment by Aidan et al. yielded 62% desalination showing that some percentage of desalination is affected by the type of membrane [36]. A study of the trend in results of various researches proved that large surface area of IEMs enhances ion transport (salt removal) [8,11]. Obviously this makes the properties of membranes vital and influential in the performance of MDC. However, stabilities and integrity of the membranes after long-term operation in MDCs are still unclear and require further research [58]. In long-term operation, two major concerns of applying membranes to a bioelectrochemical treatment system are biofouling and chemical scaling/inorganic scaling.

#### *3.10.1. Biofouling of membrane*

One of the major challenges in electrodialysis, fouling of ionic exchange membranes, occurs when there is an accumulation of undesired solid materials at the phase interfaces [63,75,76]. Just as previous membrane technologies face, pre-treatment techniques and methods as well as more resistance materials have been proposed to reduce this effect [15,77] many countries are unable to afford these technologies as a fresh water resource. However, the steady increasing usage of seawater desalination has demonstrated that seawater desalination is a feasible water resource free from the variations in rainfall. A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. The process requires some form of energy to desalinate, and utilizes several different technologies for separation. Two of the most commercially important technologies are based on the multi-stage flash (MSF. Biofouling in IEMs occurs mainly when organic compounds with a complex composition (including organics and humic acids) are present of in the substrate (anolyte) especially when actual wastewater is used [23,31,78]. This phenomenon increases internal resistance resulting in a reduction in both desalination efficiency and current production. The impact of biofouling on performance (rate of conductivity) is noticeable in a long-term of operation. Also, the evidence of its mechanism is different at each sides of the membrane as each side comes into contact with different solutions [31,60].

#### *3.10.2. Chemical scaling/inorganic scaling*

Precipitation of inorganic compounds (commonly magnesium, calcium, barium, hydroxyl, bicarbonate and sulphate) is the main cause of scaling of ion exchange membranes. Scaling is very sensitive to pH changes, in that alkaline pH enhances scaling formation due to the reactions of ions with hydroxides at the interfaces of the membranes [79]. It was observed in a study that CEM needs more maintenance during operation since its resistance increases more significantly than that of AEM [23,60,79]. Luo et al. observed a remarkable difference in the current density which was attributed to membrane scaling and the transport behavior differences between the divalent cations and anions. Though they proposed approaches such as modification of membrane surface, reducing the pH of the catholyte, and periodic cleaning to lessen membrane scaling, it is still an area that needs further research to enhance long-term application [23,31].

## 4. Outlook

MDC, though a promising sustainable technology, faces challenges in maximizing its performance (desalination, energy generation and wastewater treatment) to suit large-scale applications. Just like any other technology that employs biological processes and the use of membranes, its output is influenced by operating conditions and factors. Though the influence some factors (as discussed) have on performance is more significant than that of others, it is essential to focus on the fact that the presence or absence of one factor can influence the impact another factor has on the reactor's performance and efficiency. We propose that more studies should be done on the relationship between the factors as summarized in Table 5. With a thorough understanding of these factors and their optimal ranges that boost performance, advancement in the development of MDC technology can be achieved.

Table 5
MDC performance controlling factors relationship

| Factors | | Significant influence | |
|---|---|---|---|
| | | Factor influences | Factor is influenced by |
| MDC configuration | | | |
| pH imbalance/fluctuation | | • Microbial activity (growth)<br>• Performance (power generation, desalination) | • HRT<br>• Mode of Operation<br>• Materials<br>• MDC configuration<br>• Substrate configuration |
| Operation conditions | Temperature | • Microbial activity (growth)<br>• Performance (power generation, desalination) | |
| | Modes of operation | • Conductivity<br>• pH<br>• Substrate<br>• Internal Resistance<br>• Performance (power generation, desalination) | |
| | Stages of operation | • HRT<br>• Microbial activities (growth)<br>• Performance (power generation, desalination) | • HRT |
| | Dissolved Oxygen | • Microbial activities (growth)<br>• Oxidation and reduction reactions<br>• Performance (power generation, desalination) | |
| HRT | | • Performance (power generation, desalination) | • Salinity (volume and concentration) |
| Membrane | Membrane | • Internal Resistance<br>• Performance (power generation, desalination) | • Ion exchange capacities<br>• HRT<br>• Substrate<br>• Surface area |
| | Biofouling | • Internal Resistance<br>• Performance (power generation, desalination) | • Substrate<br>• HRT |
| | Scaling | • Internal Resistance<br>• Performance (power generation, desalination) | • Substrate<br>• HRT<br>• Membrane surface area<br>• pH |
| Electrode potential | | • Conductivity<br>• Microbial activity (growth)<br>• Oxidation and reduction reactions<br>• Performance (power generation, desalination) | • pH<br>• Material property<br>• Surface area<br>• Polarization<br>• Substrate |
| Resistance | Internal | • Performance (power generation, desalination) | • Anode/cathode resistance<br>• Ion transport rate across membrane<br>• Conductivity of electrolytes<br>• Substrate concentration<br>• Oxidation and reduction reactions |
| | External | • Performance (power generation, desalination) | • Range applied during operation 3 |
| Substrate and saline water (concentration) | | • Internal resistance<br>• Microbial activity (growth)<br>• Microbial oxidation and reduction reactions<br>• Columbic efficiency<br>• Conductivity<br>• Voltage and Power generated<br>• Ion transport from middle chamber to anode and cathode chambers | • Mode of operation |

(*Continued*)

Table 5 (*Continued*)

| | | | |
|---|---|---|---|
| Conductivity | Conductivity | • Internal resistance<br>• Performance (power generation, desalination) | • Electrolyte concentration<br>• Salt water concentration<br>• Mode of operation |
| | Charge transfer efficiency | • Oxygen reduction<br>• Performance (power generation, desalination) | • Presence of ion (electron acceptors)<br>• Membrane consumption |
| | Presence of ions species (ionic composition) | • Membrane fouling and scaling<br>• Charge transfer efficiency<br>• Coulombic efficiency | • pH |
| | Columbic efficiency | • Resistance of membrane<br>• High ion generation in anodic chamber<br>• Oxygen cross over through membrane or membrane is highly porous. | |
| Material and dimension | Material properties | • Electrical conductivity<br>• Electrical absorption capacity<br>• Resistance<br>• Mass transfer characteristics | |
| | • Surface area | | |
| | • Volumetric ratio | • Relation between chambers | |
| | • Electrode materials | • Electrical conductivity<br>• Surface area<br>• Mass transfer characteristics<br>• Chemical stability<br>• Low cost<br>• Scalability | |

Considering the huge percentage of electricity generated in the municipal for water and wastewater treatment, the concept of generating electricity stored in wastewater is very sustainable. MDC technology simultaneously desalinates saline water, treats wastewater and generates electricity as well. This promising technology requires no or less aeration and little or no external energy supply. Various researchers have proposed that this technology can be used as pre-treatment for desalination processes such as Reverse Osmosis (RO) and in wastewater treatment (industrial and domestic) [71,80–83] especially within developing countries. In the past 15 years, remarkable progress has been achieved on the commercial applications of membrane technology in China. The membranes demand in China exceeded 30 billion yuan (US$ 4.8 billion. Zuo et al. recently introduced a multi-stage microbial desalination cell for simultaneous desalination and organics/nitrogen removal of domestic wastewater, providing a promising potential in municipal or industrial reclamation [13].

On the other hand, biological treatments, which is one of the most common technologies adapted in wastewater treatment, are mostly not efficient due to the impact of high salt content on microorganisms. High salt concentrations in industrial wastewater (commonly $Ca_3(PO_4)^2$ and NaCl) causes plasmolysis which has inhibitory effects on conventional biological treatment methods and as a result restrains its efficiency [84]. For efficiency, it will be very significant to reduce these high concentrations before channeling industrial wastewater for biological treatment. Therefore significant research is needed to enhance MDC capacity to be used as a pre-treatment method to reduced salt and COD concentrations in different industrial wastewater to improve the efficiency of other treatment processes especially biological treatment as described in Fig. 2. We, therefore, proposed importantly;

1. Thorough performance study to analyze the relationship between operation controlling factors.
2. Develop configurations of the MDC reactor to suit operating conditions and performance.
3. Modification of ion exchange membrane to withstand biofouling and scaling.
4. Advancement in the use of bio-cathodes especially algae.
5. Improving MDC capacity to simultaneously treat and desalinate the same wastewater (industrial wastewater) as it generates energy for its processes and others.

**Abbreviations**

ACC — Activated carbon cloth
AEM — anion exchange membrane
CEM — Cation exchange membrane
FWM — Fresh water medium
HRT — Hydraulic retention time
IEMs — Ionic exchange membranes
MDCs — Microbial desalination cells
METs — Microbial electrochemical technologies
MFC — Microbial fuel cells

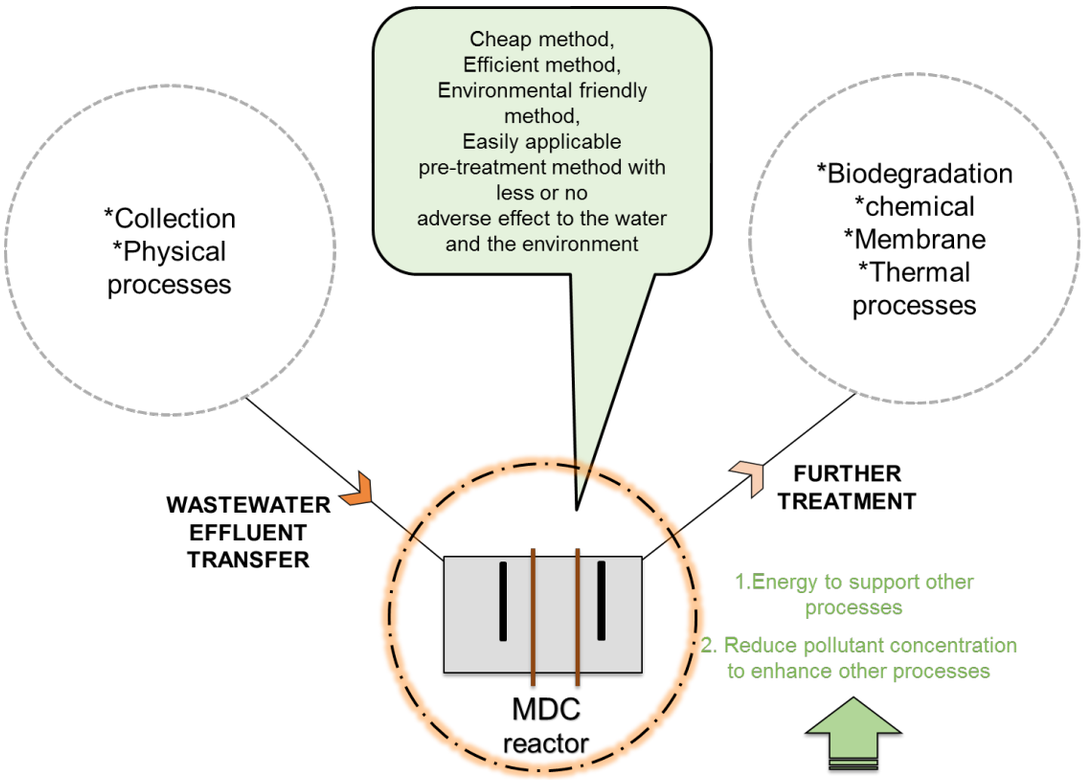


Fig. 2. Using the MDC capacity as a pre-treatment method to reduced salt and COD concentrations in different industrial wastewater.

MII — Membrane International Inc.
M-MDC — Multi-stage microbial desalination cell
PMDCs — Photosynthetic microbial desalination cells
SDR — Specific desalination rate

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