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Sustainable Materials and Systems for Water Desalination

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Microbial Desalination

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Abstract

Several investigations have established that due to population expansion and land use, fresh water scarcity has increased tremendously placing immense burden on desalination process as the major alternative remedy to freshwater supply. The increase in problems related to energy across the globe due to exhaustibility of fossil fuels. Hence, there is a need to search for other sources of energy to meet up with the growing demand. Globally, the existing methods of desalination are not cost effective; hence, scientists are searching for alternative ways to reduce the financial burden in the setup of water desalination techniques. One of the suggested areas is in the utilization of microorganisms. One of the suggested methods is in the area of energy conservation, when using water to produce energy via utilization or engaging the use microbial desalination. Therefore, this chapter intends to provide comprehensive information on the application of microorganisms for the water desalination. Several types of microorganisms that could be applied for water desalination were also highlighted. The modes of action through which they exhibited their action were also discussed. The principles involved in the process of desalination were also elucidated.

Keywords

Microbial desalination • Modes of action • Techniques • Water scarcity • Desalination techniques

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1 Introduction

Several people have witnessed acute shortage of portable water in many parts of the world mostly due to salt contents and contamination of oceans, lakes, and rivers (Shatat & Riffat, 2014). Thus to tackle this situation, water desalination techniques are deployed to satisfy human and animal water requirements. Studies have revealed that desalination is commonly utilized as an alternative means of providing drinking or portable water in areas that are experiencing scare supply of clean water. Water scarcity is estimated to affect one-fifth of the world's population, and this condition is predicted to be worsening due to many factors such as population explosion, climate change, industrial and household usage, and urbanization. The method of desalination can be deployed for wider range of primary source of water like seawater, groundwater and estuarine water containing inorganic ions, borate, bromide, sodium, potassium, and iodide of potential concern to humans (Cao et al., 2009).

Over the years, different technological advancements have been witnessed in the methods of water desalination such as the conventional methods like thermal, reverse osmosis, electrodialysis reversal systems, to the advanced method such as microbial-based desalination bioelectrochemical systems

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(BES) that uses bacteria to generate renewable energy as electricity, methane, and hydrogen. The conventional methods are more energy-dependent and expensive compared to the advanced method. Microbes in the anaerobic salty soil wetlands transform exudates in the roots of plants or dead plant material into CO_2, electrons plus protons. These products can be harvested via cathode and anode connections and converted to energy source. The energy can be harnessed as a potential desalination technique plus power generation utilizing bacteria and biodegradable organic matter. The microbial fuel cell is known to produce current by degrading microorganisms forming organic compounds and equally utilized in the treatment of waste waters (Xincao et al., 2009).

Studies have shown that due to population expansion and land use, fresh water scarcity has increased tremendously placing immense burden on desalination process as the major alternative remedy to freshwater supply. It has been shown that 18,000 desalination plants are been used globally producing average rate of 86.8 million m^3/day. The large development seen in desalination technology is mainly due to the rapid expansion and improvement in desalination technology with energy requirement and lower cost of production (Gede Wentena, 2016). Surya et al. (2015) have revealed that there is increasing rate of energy problem across the globe due to exhaustibility of fossil fuels; hence, researchers are beginning to harness other sources of energy to meet up with the growing demand. One of the suggested methods is in the area of energy conservation, when using water to produce energy via utilization or engaging the use microbial desalination. The authors have revealed that wastewater-based three-chambered microbial desalination cell could solve both energy and water crisis offering greater efficiency than the other such as thermal distillation, reverse osmosis, freezing, and electrodialysis.

Globally, the existing method of desalination is not cost effective; hence, scientists are searching for alternative ways to reduce the financial burden in the setup of water desalination techniques. One of the suggested areas is in the utilization of microorganisms such as *Saccharomyces cerevisiae* yeast to provide a sustainable energy supply, reduced toxic generation, and water desalination process with reduced cost. Though commercialization of this technology has suffered tremendous setbacks due to several factors like pH instability, low current output, and membrane biofouling plus polarization, scientists still believe that if all these challenges are resolved, microbial desalination holds a promising potential in the near future (Yahiaoui et al., 2020).

Therefore, this chapter intends to provide a broad fact on the use of microorganisms for the water desalination. Several types of microorganisms that could be applied for water desalination were also highlighted. The modes of action through which they exhibited their action were also discussed.

2 Principles Involved in the Process of Desalination

The principles of desalination centres on the doctrines establishing a technology for large-scale desalting of water. Some of the already established procedures include reverse osmosis, vapour reheat distillation plus hyperfiltration extremely important for water treatment during water shortage and contamination. Rozendal et al. (2008) revealed a new approach in water desalination using microbial-based techniques and also generated electrical current from the organic matter plus bacteria in another solution representing (anode). The authors showed that reduction in the salinity may require greater amount of anode solution; hence, the use of membranes will further increase ion exchange capacities. Thus, it was concluded that desalination of water is conceivable using equivalent amount of anode solution plus salt water.

The basic principle of desalination involves the removal saline water source plus devotes energy to two distinct streams, one with salt-free fresh water and salty brine. A reliable and proper desalination technology utilizes lower quantity of energy to generate a huge volume of fresh water plus small amount extremely concentrated brine. In a study, the performance of single- and double-membrane microbial desalination cell was used to investigate the operation mode flow in water desalination. The authors revealed that there was increased generation of energy after the cycle; hence, the technology is eco-friendly, safe, and cost effective for desalination (Cheng et al., 2006). Another study by Zhang et al. (2010) revealed that analyte solution in the microbial desalination cell acts as buffer, catalyst, and substrate for the microbes. Studies have revealed that two kinds of microbes are utilized in this process, those using synthetic facilitated electron transfer and those that do not (exoelectrogens).

APHA (1998) have revealed that traditional wastewater purification methods are energy consuming and lot of resources wasted in the cleaning process. Scientists hence have developed microbial nutrient recovery cell technology as a desalination technique and also regenerate lost nutrients in waste water management. This technique has proven to be efficient, self-stimulated approach and sustainable wastewater purification strategy using bioelectrochemical system. Zhang and He (2012) described the microbial fuel cell-based technologies as emerging innovations for the applications in bioremediation, seawater desalination, biosensors plus hydrogen production.

2.1 Air Cathode Microbial Desalination Cell

In air cathode microbial desalination cell, the most usually used oxidizing agent in cathode chambers is oxygen provided by bubbling air via water in the cathode chamber. The process involved in the different microbial techniques for desalination and principles involved were elaborated in Table 1

2.2 Biocathode Microbial Desalination Cell

Cheng et al. (2006) demonstrated the utilization of biocathode in cathode chamber, by engaging microbes as oxidizing agents.

2.3 Stack-Structure Microbial Desalination Cell

In this arrangement similar to stacked electrodialysis cells, series connections are made in the cathode and anode sections. In the operation, ions move out from desalination chamber to freshwater chambers, forming one dilution section plus two concentrated sections (Chen et al., 2011).

2.4 Microbial Electrodialysis Cell

In this classification, microbial desalination cells are reorganized to generate H^+ from the cathode compartment while desalination process is going on (Mehanna et al., 2010).

2.5 Microbial Electrolysis Desalination and Chemical-Production Cell

In this setup, acids and alkaline solution are generated during desalination. Application of large quantity of current will induce a potential difference and create water splitting into hydrogen and hydroxyl ions.

2.6 Microbial Capacitive Desalination Cell

In microbial capacitive desalination cell, stimulated carbon membrane associations are used to absorb deionized ions and stored in electrical double layer capacitors. Electrical neutrality is the hallmark of this setup via the free movement of cations during desalination.

2.7 Upflow Microbial Desalination Cell

This arrangement is made up of fitted cylindrical sectors containing analyte solution and anode electrode. Oxygen is been utilized as electron acceptor due to exposure to air (Zhang et al., 2010).

2.8 Osmotic Microbial Desalination Cell

In osmotic microbial desalination cells, desalination plus dilution concept is into practice utilizing osmosis combined with electric potential gradients which assist in lowering salinity in the desalination chamber.

Table 1 Different microbial techniques for desalination and principles involved

Microbial technique	Principle	Authors
Bioelectrochemical system		APHA (1998)
Microbial fuel cell	Activity of microbe	Zhang and He (2012)
Biocathode microbial cell	Engaging microbes as oxidizing agents	Cheng et al. (2006), Croese et al. (2011), Al-Mamun et al. (2018), Wen et al. (2012)
Stack-structure microbial cell	Electrodialysis	Chen et al. (2011)
Microbial electrodialysis cell	Electrodialysis	Mehanna et al. (2010)
Upflow desalination cell	Utilization of oxygen as electron acceptor	Zhang et al. (2010)
Microalgal biocathode	Utilization of high carbon by Chlorella vulgaris	Zamanpour et al. (2017), Powell et al. (2009), Wang et al. (2020)
Bacterial biocathode	Transformation of CO_2 into carbon derivatives using acetogenic bacteria	Saeed et al. (2015), Zaybak et al. (2013)

2.9 Submerged Microbial Desalination–Denitrification Cell

In this arrangement, combined direct nitrate elimination and desalination exist in groundwater desalination using two chambers of cathode and anode. Nitrate ions move as a result of electrical potential generation into the anode chamber and later reduced by denitrifying bacteria.

2.10 Principles Entailed in the Process of Desalination

The principle behind the procedure involved in desalination entails the organic migration of waste water to the anode compartment where there is increased microbial population and creation of biofilm, and in the course of the degradation of biological matters, there is production of electricity (Elimelech & Phillip, 2011; Lovley, 2012; Yuan et al., 2017). Electrons that migrated to the cathode produced electrostatic energy when present in water that is salty propel the anions near the positively charged and negatively charged electrode (Kim & Logan, 2013). This process provides double advantage of treatment of waste and production of bioelectricity (Fritzmann et al., 2007; Sophia et al., 2016).

There are two primary processes that are mostly used in desalination, that are;

i Thermal desalination process
ii Membrane desalination process.

Thermal desalination process: This desalination process is also known as distillation. It is a primitive way of converting sea water into drinkable water. This method is widely used because it is usually cost effective. This application mode is centred on the boiling of salty water and allowing it to evaporate then the condensed water would be collected to obtain pure and drinkable water (World Health Organization, 1993). These entail the following:

Multi-stage Flash Distillation: This entail boiling of water speedily when force of vapour exists quickly lowers beyond the vapour pressure of the fluid at a specific temperature. Subjecting the water to heat remains foremost to it being introduced into the flash compartment, the steam produced is compressed to the surfaces that are in interaction with the fresh water. Multi-stage flash is usually simple to build and easy in functioning; the plant is also referred to as the energy intensive process, owing to the fact that it entails both heat and mechanical energy.

Multi-effect distillation: This process occurs in succession of vessels and utilizers. It operates on the principles of evaporating and condensation at lowered standard pressure. This process operates at reduced temperature of 70 °C, leading to reduced corrosion of cylinder and the establishment of scale on the cylinder surface.

Vapour compression evaporation: This process does not use steam heat. The heat used in evaporating the feedwater is gotten from the density of the vapour and not through uninterrupted heat exchange from stream released during a boiling process.

Cogeneration system: This is a process in which energy source can function differently doing various things, for example, production of electrical power and removal of salt from water sample. This process entails the production of high-pressure steam to function in the turbines and the steam is formed when boiled at 5408 °C. There is reduction in the temperature and energy level when the vapour expands the turbines.

Renewable energy distillation/solar water desalination: This process is used for small-scale setups. Energy gotten from the sun is utilized in evaporating renewed water from salty water. Steam gotten during this process condenses on a transparent glass or covering and is latter obtained as fresh water from the condensate. This process is usually adopted in parched areas where there is lack of fresh drinkable water (Bodzek, 2000; Worldwide Desalination Research and Technology Survey, 1994).

Membrane process: Membrane process utilizes penetrable film to mobilize either water or salt to form two zones of varying concentration to form fresh water. This is usually employed in community waste water treatment. This could be categorized into the following.

Reversed osmosis: This method utilizes pressure as propelling force that pushes the water via a temporarily penetrable sheath into a concentrated saltwater. Practically, the feedwater is being pumped into a confined vessel, in contradiction to the membrane, to pressure it (Logan et al., 2006). As the water product passes via this membrane, the feedwater and brine solution become extra and extra concentrated. A reverse osmosis consists of four major process which are;

(i) Pretreatment system.
(ii) Pressurization.
(iii) Membrane separation.
(iv) Post-treatment stabilization.

Pretreatment: Feedwater entering was being pretreated to be well matched by the members by eliminating suspended solids, regulating pH, and addition of a threshold eradicators to regulate scaling initiated by some elements like calcium sulphate.

Pressurization: The pump elevates the force of the pretreated feedwater to a functional pressure that is suitable for the film and the saline nature of the feedwater.

Membrane separation: The penetrable membrane hinders the path of liquefied salts while allowing the removal of salt from produced water to go through.

Post-treatment stabilization: The product water gotten from the film assembly normally needs pH adjustment and the removal of gas previously and then transferred to the circulation system as drinking water. The product goes through a ventilation column where the pH is raised from a value of about 5 to a value near 7, which make the water drinkable and useable (Logan et al., 2006; Kutty, 1995).

Electrodialysis

This electrodialysis process contains film with positively charged ions and anions exchange groups. In the pressure of straight current electric field, positively charged ions and anions move to their corresponding electrodes so that there will be formation of ion-rich and ion-exhausted streams in other places within the membranes (Logan et al., 2006; Furukawa, 1999).

Membrane Distillation

The principle here is the use of thermal and membrane technologies. Here, the variation in the temperature is formed amongst the supplied solution that is to contact the surface on the side of the micropermeable sheath and there remains left over space on the other side. Variation in the temperature leads to the variation on the vapour pressure and causing migration of vapour formed via the membrane on the concentration surface (Alabdula'aly & Khan, 1997).

Secondary/Alternative process

This method can be tackled in two different ways which are freezing and ion exchange. In the course of freezing, liquefied inherent salt in the feedwater are divided in the period of production into crystals below measured conditions. Before the entire water is freezed, the mixture is washed and rinsed, eliminated the salt in the remaining water while, for ion exchange, organic and inorganic solids are found to interchange one-type cation or anion restrained on the surface of another kind of cation found in the solution (Logan et al., 2006).

(A) Types of microbial desalination

Osmosis MDC: Osmosis microbial desalination cell was developed during research by replacing anode exchange membrane with osmotic membrane. In this system, water is pressured out of salty water due to the increased osmotic pressure of the fundamental compartment and ions are circulated round the membrane. In respective of the diluted salt water in the middle compartment, lack of membrane selective paths brought about the ability of unwanted ions to deter the effectiveness of the microbial desalination cells (Zamanpour et al., 2017; Zhang et al., 2012).

Zhang and He (2015) stated that this system is a distinct type of membrane because it exploits the osmotic liquid movement from the positively charged electrode to the salty water, thereby allowing dilution process to take place and desalination of the water sample (Zhang & He, 2015; Zhang et al., 2011; Zhao et al., 2006). This kind of microbial desalination, where there is separation of the positively charged electrode compartment and middle compartment by AEM through a forward osmosis membrane (FOM). The forward membrane permits the passage of liquid and decreases transmission of ions from the central compartment of anode then the cathode compartment (Kim & Logan, 2013; Zhao et al., 2006). They found out that the salt was really not eliminated but became concentrated. They also discovered from their study that high-energy method of osmotic MDC had an outcome of greater water desalination effective in the generation of power via salty water and reduced conductivity (Saeed et al., 2015).

Osmotic MDC is widely known in performing these key objectives, which are; anode exchange membrane is replaced with forward osmotic membrane thereby improving the dilution of salty water (desalination), dilute salt water by increasing water flux thereby enhancing the remover of biological matter from waste water, potassium ferricyanide is utilized to speed up reaction allowing this forward osmotic membrane to be cost effective compared to the anode electrode membrane (Zhang et al., 2012). Although forward osmotic membrane was found to be more susceptible to fouling that ion exchange membrane, with a consequence of escalation in the internal osmotic resistance thereby reducing water flux (Kim & Logan, 2013).

Biocathode MDC

Biocthode MDC is an advanced system of electrodes which encourages the reduction in electrochemical reactions and prime catalysis is done by microorganisms (bacteria and algae). Microorganisms perform reduction presses in the cathode or present on electrode (Croese et al., 2011). This type of MDC does not need high catalyst of its lower maintenance, self-regenerating properties and production cost (Al-Mamun et al., 2018; Zhang et al., 2012). The bacteria performed as catalyst in the compartment because they were active to electrode and causing oxidation reduction reaction resulting in the increase in the removal of salt from water (Wen et al., 2012).

There was advancement in biocathode microbial desalination cell which comprises of the use of cathode, middle, and anode compartment. This reaction was related to microbial fuel cell only that middle compartment remains filed with salty sea water which initiates the desalination reaction by potential gradient amid the anode and cathode, and then fresh water is produced from the sea water owing to migration of ions to the negatively charged and positively charged electrode (Brastad & He, 2013). The biocathode is subjected to optimal conditions; start-up time of the microbial desalination cell could be remarkably reduced, consequently increasing the general performance of the cell (Luo et al., 2017; Tchobanoglous et al., 2003).

Nitrifying and denitrifying bacteria and algae could be used as biocatalyst in biocathodes because they can produce electron acceptors at negatively charged electrode which is needed in reducing reaction (Clauwaert et al., 2007). Some microalgae biocathodes could remain used in appropriating nutrients that were missing and melted biological substance in order to produce bioenergy by the microalgae biomass (Arana & Gude, 2018; Gude, 2016). Literature has shown that specialized microorganisms which are known as electrotrophs possess the capacity in gaining electrons directly of via the negatively charged electrode, thereby exploiting various routes for electron acceptors for example iron, carbon dioxide, O_2, or nitrate (Saeed et al., 2015; Zaybak et al., 2013).

Microalgal biocathode MDC: *Chlorella vulgaris* is high and accessible (microalgae) was found to utilize high carbon content such as bicarbonate and carbon dioxide to produce oxygen under favourable condition leading to the production of solar power (Powell et al., 2009; Zamanpour et al., 2017).

Bacterial biocathode MDC: The use of bacterial biocathode microbial desalination as electron in biocathode is a complicated and strenuous method. However, anaerobic facultative autotrophic biocathodes have proven to be more effective and virtually achievable method established via pre-improvement of heterotrophs (Zaybak et al., 2013). This deviceallows CO_2 to be transformed into carbon-based derivatives via replacing hydrogen by negatively charged electrode that serves as source of energy and source of electron source with the aid of acetogenic bacteria (Saeed et al., 2015).

Staked MDC

Staked microbial desalination is exceedingly convenient owing to their level of productivity in recovering more energy when equated to other microbial desalination system and is inexpensive. In these setup, bacteria oxidizes the biological matter in the anode compartment thus leading to extraordinary retrieval of energy (Shehab et al., 2013).

Researchers sated that this system could be upgraded by multiple sets of ion exchange membrane inserted amongst the cathode and anode compartment, so as to improve the effectiveness of charge transmission and then permit the highly saline water to run across sequence of microbial desalination cells that supports the removal of more salt (Al-Mamun et al., 2018; Gude et al., 2013).

Subsequently, stacked arrangement operates based on bioelectrochemical response, whereby fluctuating of systems plus functioning strictures like assembly of electrodes, whichever sequence or parallel and hydraulic movement methodologies may disturb the procedure of salt removal (desalination). Disruption of pH amongst the cathode and anode compartments could affect the desalination process when more than one compartment is used. When there is great decrease in the pH level at the anode level, this could lead to reduced performance of the microbial population in the compartment of the positively charged electrode, but an increase pH level in the compartment of the negatively charged electrode compartment may result in great loss of potency and reducing the general course productivity (Cheng et al., 2010).

Upflow MDC

Upflow cell is exceptional kinds of cell where mixtures of solution inside the compartment can be accomplished deprived of shaking and recover 100% water (He, 2011; Qu et al., 2012). This technique enables microbes present in the positively charged compartment to stay in the supernatant method and effectively perform extreme oxidation of biological material (He et al., 2006; Saeed et al., 2015). Promoter (catalyst) utilized in the upflow microbial desalination cell is combination of carbon and platinum; this mixture deposits on the exterior layer (Jacobson et al., 2011). The upflow system is made up of cylindrical unit which is comprised of twofold sections where internal section full of pellets from graphite then delivered an advanced superficial part for oxidation reaction to be done. Two bars of graphite were absorbed as current collectors in the graphite granules which are known to tolerate conduction of electrons. The external unit which contains salty water symbolizes desalination compartment which was extra secured by cation exchange sheath cylinder, thereby allowing superficial part of the amplified to take part in the desalination process from stage to stage (Jacobson et al., 2011). The benefits of upflow are that there is usually effective fluid mixing within the compartment, very easy to scale up, and this system improves desalination.

Photo-MDC

This system improves energy yield of microbial desalination cell by employing sunlight potential as an initiator without increasing the cost of functioning. Heamatite nanowire photo-anodes are some of the examples of this type of microbial desalination cell and are known to be useful in proficient setup (Qian et al., 2014) nanowire-bacteria hybrids for unassisted fixing of solar energy CO_2 (Liu et al., 2015; Zang et al., 2014). Researchers have presented high-performance photo-microbial desalination cell where the anode is improved with nanostructure. Then, they perceived that there was maximum density of the current of the photo-MDC in the course of this method remained at 8.8 Am^2 double the unmodified microbial desalination cell by means of 20 g/L original concentration of briny. Despite the concentration of salt discovered in the central compartment remained beneath 1.4 mg/L of waste, remover of salt was 96%. There could be greater attraction in the combination of MDC with biophoto-electrochemical cell.

Capacitive MDC

This type of microbial desalination cell is engrossed on the usage of carbon materials with greater exterior area at two electrodes. There is usually likelihood of variation between the permeable anode and cathode. Capacitive deionization as technologically advanced into two subsequent techniques which are desorption and adsorption. Here, the ions were primarily separated from saline and desalination of water concurrently takes place. Moreover, the adsorption techniques show two electrical layers made together on charged cathode and anode owing to migration of ions separated from water sample. Then, there is substitution between the electrodes present in the solution, and there is total discharge of zero voltage by the electrode, there is supply of energy, and ions were released into solution producing unwanted water steam (Wen et al., 2012).

Researchers stated that there was formation of doubled layer capacity on the high surface area of electrodes, and there was adsorption of ions when salt solution was placed amongst the anode and cathode. The ions found in the saline were adsorbed on exterior areas of the electrodes by dual-coating capacitors, as soon as the potential gradient was disconnected, ions were allowed to return into the solution. There was immediate deionization of the salty water irrespective of the pollution of the cathode and anode compactly through the salt (Saeed et al., 2015; Santoro et al., 2017; Zhang & He, 2012); this type of membrane was developed by the introduction of membrane capacitive deionization which is cationic selective membrane incorporated on the negatively charged electrodes and anions exchange membrane was incorporated on the positively charged electrons (Zaybak et al., 2013).

One main stated flaw in the performance of this system is increased concentration of salt anolyte and catholyte. The result in this buildup of ions alters pH of the catholyte and the anolyte resulting in reduced metabolism of the microorganisms. Therefore, there would be need for replacement of catholyte and anolyte and reapplication of water (Al-Mamun et al., 2018; Forrestal et al., 2012; Saeed et al., 2015).

Bipolar membrane MDC

In bipolar membrane system, desalinate water also generate hydrochloric acid as well as sodium hydroxide concurrently. This system consists of a cathode exchange membrane and an anode exchange membrane layered together to produce a single membrane. When subjected to appropriately high electricity potential variation, water splits to protons and hydroxyl ions by the border of the layered ion exchange membranes, thereby resulting in the discharge of hydroxl ions in the direction of the anode compartment and the protons close to the side where there is combination through chloride ions entering from the middle section to form the HCl (Forrestal et al., 2012; Buck, 2014).

This reaction is crucial in evading reduction of pH in the anode compartment, thereby undertaking a cogent role in the microbial desalination cells (Forrestal et al., 2012). The limitation posed on the MDC could be dealt with by the use of exterior voltage to manoeuvre the bipolar membrane. Studies have shown that the least voltage needed to separate water is 0.83 V but, practically, the essential voltage surpasses 1.2 V; then, it could be concluded that the possible variation produced by MDC only is insufficient to measure up to the condition of bipolar membrane functioning and exterior voltage of approximately 1 V is required to function properly. Bipolar membrane is more prone to biological pollution due to their contact to saline in the anode compartment (Kim & Logan, 2013; Mehanna et al., 2010). Splitting of water at the bipolar membrane is intricate in removing salt from water. The degree of saltwater is also great due to the cost of preservation of anolyte pH (Chen et al., 2012). This system has high ion selectivity, long-lifespan membrane of biofilm, increased level of salt remover, and maintenance of preferred pH in the anode compartment.

Recirculation MDC

Recirculation microbial desalination cell is a system where solution of anolyte and catholyte is usually uninterruptedly recirculated via the MDC in order to counterbalance pH value (Luo et al., 2011). Numerous investigations have been performed with the objective of eliminating the inequity of pH in the microbial desalination cell compartments. These include adding of buffers and the initiation of increased volume of anolyte (Al-Mamun et al., 2018). Researchers have shown that the recirculation of catholyte and anolyte has encouraging energy production and salt water removal. Recirculation system functions having 50 mM of phosphate buffer generated 335 extra power; hence, at ambient temperature and favourable situations, cell worked with at 25 mM produced 53% additional power (Luo et al., 2011). Therefore, increased buffer concentration is not very important for the improvement of the density power, so then, an optimum concentration should be acknowledged.

One main difficulty in this system is the hindrance of the membrane in cooperation with hydroxyl and proteins manufactured during redox reaction, in cathode and anode compartments (Kim & Logan, 2013). Oxidation of the biological matter discharges protons that are not capable to migrate to the cathode compartment, while hydroxyl ions are formed by means of the reduction reaction (Luo et al., 2011; Qu et al., 2012). This may result in frequent pH imbalance within the cell, where there is increase in pH in the cathode and reduction in the anode.

Modes of action of microbial desalination

The mechanism of action of desalination is established on the relationship amongst living microscopic entities and electrodes via the reduction of biological matter (Logan et al., 2017; Schröder et al., 2015). Microbial desalination cell exploits the possibility variance generation from oxidation made by anode producing bacteria to initiate the movement and removal of salt ions. Overtime the bacteria utilize the biological matters in the waste water thus, making the clean. Electricity is produced and water desalination is done concurrently (Xiaoxin et al., 2009; Schröder et al., 2015; Sevda et al., 2015).

The rate at which desalinated cells work is being quantified by its efficiency in salt removing ability Jacobson et al. (2011), overall salt removing rate (Chen et al., 2012) specific desalination rate (SDR) current density (Jacobson et al., 2011; Qu et al., 2012); removal nitrogen (Zhang & He, 2015; Zuo et al., 2017), removal of biological materials (Luo et al., 2017) Faradaic potential, pH discharge and the anode in the microbial environment (Qu et al., 2012).

Forrestal et al. also explained the mode of action of microbial desalination by stating that the setup is comparable to that of a MFC which comprises of dual compartments with cathode, two electrodes, and anode. Then with the third compartment which is divided by an anion exchange membrane, cation exchange membrane, a marginal, peripheral circuit, that is accountable for the anaerobic and aerobic and procedures at both corresponding electrodes. There is increase on the carbon-based matter in the anode compartment thereby leading into the creation of biofilm that produces an electric current. The pollutants in the slush are then oxidized by the aid of the biofilm via stringent adherence to anode, releasing together the electrons and the protons from the bio-slush and the production of current of atoms by circuit conveyance that are composed of electrodes. Electrical current is then created by the probable variance produced amongst the anode and cathode owing to the presence of O_2 in the cathode compartment (Forrestal et al., 2012).

Sevda et al. (2015) also explained the mode of action of microbial desalination by stating that the anode cavity and the cathode cavity are usually parted by ion exchange membrane. Desalination cavity is made when the ion exchange membrane makes a border on the salt solution. Organic materials in the waste water go into the anode part where formation of biofilm takes place owing to the increased microbial load that oxidizes organic material, causing in the fabrication of electrons at the electrode and liberating protons into the solution (Chen et al., 2011). The electrons formed migrates via an exterior resistance to the electron acceptor at the cathode, water is produced.

Microbial desalination is a unique technology that utilizes energy gotten from the metabolism of electroactive microorganisms usually bacteria and algae at the process of degraded biological material in order to provide ecological safe water (drinkable). This process allows various techniques to take place concurrently. This process includes desalination of water, waste water treatment, and also the creation of electricity. Microbial desalination Cells (MDCs) comprise of an electrochemical material that has three compartments (Cao et al., 2009).

The anode part consists of an electrode which is usually enclosed with a biofilm which oxidizes the biological materials present in the waste water, thereby transmitting electrons from the biological material (substrate) to the electrode. Thereafter, the electrons utilize an exterior circuit locate the area where the cathode resides; this is where reduction reaction is done. There is usually movement of ions imposed by electric potential. Consequently, desalination initiated when positive ions migrate via the cation exchange membrane (CEM) from salty area to the cathode and the negatively charged ions then migrate within the anion exchange membrane from the salty area to the anodic area (Wen et al., 2012). Cao et al. in their study used 9 cm^2 cross section of a cell with the aid of salty volume compartment of 11 mL; there was 90% elimination of salt (Cao et al., 2009).

Several researches have shown that cubic along with tubular devices, amassed cells in the course of using batch recirculation, and biologically produced cathodes increases the release of water due to the application of exterior voltage (Chen et al., 2011; Mehanna et al., 2010a, Kim & Logan, 2013a; Jacobson et al., 2011a). This could also be achieved by forward osmosis, interchange of ion resin in the partitions, or through microfiltration procedures (Lovley, 2012; Zhang & He, 2012; Zhang et al., 2010, 2012; Zuo et al., 2017).

The reaction that happens in the cathode is one of the most crucial reaction phases in this setup. Studies have shown that applying oxygen reduction method in the cathode section has been of greater benefit by utilizing the oxygen as electron acceptor (Lu & Li, 2012). Zhao et al. (2006) in their studies stated that there are three primary things that disrupt the proper activity of cathode which are pH, concentration of the catholyte, and the lead (Pb) of the catalyst. The reduction of oxygen in diverse pH environment is usually made possible by the present Pt, gold, and silver metals which is often as promoter in electrochemical devices (Ge et al., 2015). Liu et al. (2015) revealed decreased in the operational oxygen in the system having used MnOx as a substitute catalyst instead of using the former costly metals (Lu & Li, 2012; Zhao et al., 2006). Additional transitional metals were also worked on by researchers (Wang et al., 2015; Zhang et al., 2016) amongst other metals (Vij et al., 2017), added that iron was used also as the other properties where altered (Vij et al., 2017; Yuan et al., 2015b).

Cao et al. (2009) used ferricyanide catholyte as electron acceptor in the growth of microbial desalination cells. There were about ninety-four 94% elimination of salty water and 2 $W \cdot m^{-2}$ production of energy was attained, thereby meaningfully increasing the activity of the system when compared to when osmosis reverse is used in the cathode reaction. However, owing to how expensive the reagents are, the application of ferro-ferriccyanide catholyte would be possible in the technical approach if the redox mediator is less expensive and easy approach was implemented for the rejuvenation of the catholyte solution as soon as it is exhausted. There could be the implementation of two different approaches to establishment of microbial desalination cell (MDC) innovation in producing drinkable and eco-friendly water using only low energy. These methods are:

Operation of MDC by the use of reduced oxygen in cathode reaction: Operating the microbial desalination by the use of reduced oxygen in cathode reaction is usually set up as air dispersion cathode prepared of carbon nanofibres and Fe nanoparticles as catalyst is usually appropriate and less expensive electricity for eco-friendly uses.

Operating the MDC by the use of Ferro-ferricyanide redox pair in cathode reaction: This method employs one ferro-ferricyanide redox catholte as a substitute to oxygen reduction. This was done in order to improve the obtainable potential in the microbial desalination cell thereby allowing enhanced functioning.

Specific examples of authors that have utilized microbial desalination for the management of water

Alhimali et al. (2019) highlighted the importance of microbial desalination cell which is a microbial electrochemical system as a proficient means of utilization in desalination with lower energy consumption. Recently, more attention has been focused on microbial desalination cell; hence, the authors investigated bioelectricity generation plus behaviour of ions transportation in microbial desalination cell. From the results obtained, they suggested that optimization of the salt transfer with ion diffusion coefficients is needed to boost microbial desalination cell performance.

Carmalin and Bhalambaal (2016) revealed that microbial desalination cells are a modified version of microbial fuel cells that utilize organic compounds from exoelectrogenic bacteria in wastewater to generate energy. The authors showed that enhancement in water desalination plus energy generation can be stimulated by activated carbon.

Chojnacka et al. (2012) suggested that algal biomass could be a very good source of renewable and valuable active substances with diverse range of industrial applications to meet up with the growing demand on energy and water. The authors revealed that the commercial and productivity value of microalgal biomass and seaweeds is huge; thus, microalgae can be harnessed foe proficient supply of energy and water desalination. It should be noted that not all techniques are capable of removing natural ionic contaminants, though most techniques remove significant amount, but some remnant of pathogenic waste may still be found or transfer.

Wang et al. (2020) showed that algae biocathodes have received tremendous attention as an alternative substitute to abiotic cathodes known to cause release of toxic chemicals and very costly to use. The authors deployed the use of *Chlorella vulgaris* microalgae to treat landfill leachate under different conditions. From the results obtained, they suggested that algae biocathodes boosted the sustainable efficiency microbial desalination cells and equally generated bioenergy. Ummy et al. (2016) revealed that yeasts such as *Saccharomyces cerevisiae* are potential biocatalysts due to their physiochemical properties as non-pathogenic organisms in microbial fuel cells utilization. The authors suggested that further development is needed to make yeast a robust material for energy production and desalination agent.

Also, modifications of microbial fuel cells (MFCs) to microbial desalination cells (MDCs), research has helped in the extensive study and design of these MDC devices leading to a considerable upgrade over the years (Kim & Logan, 2013; Sevda et al., 2015). Brastad and He (Brastad & He, 2013) investigated the efficacy of the use of MDCs in purification of water. MDCs were reported to remove a significant of arsenic, copper, mercury, and nickel, and it was concluded that MDCs can be used to reduce water hardness. Xincao et al. (2009) studied the use of a microbial fuel cell having acetate as its substrates in desalination of water having various original salt concentrations which varies from 5 to 35 g/L. The bacteria cells were recorded to have eliminated salt present in water to about 90%, by utmost production of 2 W/m^2 of the microbial desalination cells. During the desalination process, there was a decrease in voltage as the cycle proceeded while after the desalination, the microbial cells had an improved resistance of 970 Ω from the initial 25 Ω. A new, energy producing and cost-effective desalination procedure was recorded by the authors. The use of stacked microbial desalination cells (SMDCs) in attaining potable water by evaluating the desalination rate was also investigated by Chen et al. (2011). At to 0.0252 g/h, it was reported that the frequency of desalination was increased when a two-desalination chamber of stacked microbial desalination cell was used. The SMDCs were recorded to have a greater external resistance which was 1.4 times greater than a single desalination chamber. Jacobson et al. (2011) performed a four-month study set to investigate an uninterruptedly active upflow MDC to eliminate salt and create electricity. They observed that in four days, there was a > 99% salt elimination achieved and the production of 62 mA of energy and a total dissolved solid (TDS) removal rate of 7.50 and 5.25 g for TDS salt solution volume and wastewater volume, respectively. It was also observed that a 30.8 W/m3 power density at its highest was also produced in this process. They concluded that the UMDC technique produced a significant increase in energy and further reduced the TDS.

Over a period of eight months, Luo et al. (2012) reported the several changes entailed in the properties of membrane and the different microbes found at the anode of an MDC. They recorded a decline by 27% of the desalination proficiency, and a reduction of MDC function was also recorded after a while evident by 47% deterioration in density of the current produced. It was also observed that scaling and fouling occurred at the cathode and anode of the membrane, respectively, with the phylum Proteobacteria being dominant at the AEM which improved system resistance thereby lowering ion transfer, and thus, the translation to energy efficiency is reduced. In order to reduce the problems of the migraton of ions which is caused by the MDC systems, Forrestal et al. (2012) investigated a novel microbial desalination cells; capacitive adsorption capability (C-MDC) having the ability to transfer ions to an adsorptive activated carbon cloth which are in turn used as electrodes, and they are further used for electrochemical ion adsorption purposes. It was discovered that in a single batch desalination cycle, 69.4% salt was eliminated without addition of salt to the anodes and cathode, and the total dissolved solids (TDS) (61–82.2 mg) were reduced by the adsorption of 1 g activated carbon cloth, which served as the electrode.

Mehanna et al. (2010) demonstrated the effectiveness and salt elimination capability of MDC. It was recorded that MDC reduces the conductivity of salt water prior to reverse osmosis treatment procedure in achieving potable water. They studied a three-sized chamber air cathode MDC and discovered that with the reduction of the conductivity of the salt water, there was a production of a $480 mW^{-2}$power density when 1 gL acetate solution was used.

Morel et al. (2012) compared the desalination abilities of the classic MDC (C-MDC), and the MDC compacted with ion exchange resin (R-MDC). The R-MDC showed a 1.5–8 times better desalination potential rate with a low concentration of NaCl (10–2 g/L) than the classic MDC(C-MDC). It was recorded that due to the ion exchange resin which served as a conductor, there was an upsurge in ohmic resistance of R-MDC which was 55–272% lowered than that of the C-MDC; therefore, R-MDC stopped the increase in the resistance of the solution. It was concluded that R-MDC is best appropriate for water/waste water with decreased salinity.

Stoll et al. (2015) investigated that after one hour on the carbon electrode, there was a removal of 36 mg per gram of salt removal from the water produced. In an improved development by Wen et al. (2012), aerobic bacterial cells were used as a catalyst on the cathode of MDC and were compared with an air cathode MDC to ascertain its efficiency in waste water treatment and desalination. Under the same conditions, the voltage (136 mV greater than air cathode MDC) and the columbic efficiency at $96.2 \pm 3.8\%$ were reported to be significantly increased in the bacterial catalyzed cathode MDC than when compared to the air cathode MDC. With anode solution of 0.441 L, the salinity of 39 ml of salty solution was decreased by 92% in the biocathode catalyzed MCD, and this method was concluded to be more efficient method in water desalination. In a further enhancement of MDC technology, Yuan et al. (2015b) in a synergistic approach to eliminate chemical oxygen demand (COD) for water treatment and efficiency in energy, MDCs, and forward osmosis (FO) were employed in desalination of waste water. This was carried out by a pretreatment at the MDC anode, and furthermore, the effluent was sent to the forward osmosis for conclusive retrieval. The authors discovered that in the saline water, the conductivity reduction was improved to 99.4% by the MDC-FO technology, and it also reduced COD, and the waste water volume was also reduced by 93% and 65%, respectively, when compared to a single MDC. It was also recorded that the reduction in NaCl had an effect on the reduction of the COD. This is a hopeful method used for predesalination and waste water treatment of saline water. The synergistic utilization of forward osmosis and MDC (FO-MDC) in pretreatment of wastewater was studied by the use of mathematical predictive models. This was done by incorporating FO with MDC to the model. They reported that key parameters were detected, and this was further attained by amending definite waste water of domestic origin with 500 mg glucose and a buffer of 50 mM $NaHCO_3$. They concluded that with appropriate proficiency, desalination could be effective and achieved (Yuan et al., 2015b).

In an in situ removal of nitrate from wastewater, it established a submerged microbial desalination cell serving in the removal of nitrate, water treatment, and energy production (Zhang, 2012). A total of 90.5% nitrate was removed and a current density of 3.4 A/m^2. It was reported that the external resistance was 10 Ω at a 12 h retention time. It was concluded that SMDC is promising for the elimination of nitrate in ground water.

3 Conclusion and Future Recommendation to Knowledge

This chapter has provide a comprehensive information on the application of microorganism for the water desalination. Several types of microorganisms that could be applied for water desalination were also highlighted. The modes of action through which they exhibited their action were also highlighted. The principles involved in the process of desalination were also elucidated. During this study, it was discovered that commercialization of this technology has suffered tremendous setbacks due to several factors like pH instability, low current output, membrane biofouling plus polarization, scientist still believe that if all these challenges are resolved, microbial desalination holds a promising potential in the near future. Also, during this study, detailed information on principles involved in the process of microbial desalination such as air cathode microbial desalination cell, biocathode microbial desalination cell, stack-structure microbial desalination cell, microbial electrodialysis cell, microbial electrolysis desalination and chemical-production cell, microbial capacitive desalination cell, upflow microbial desalination cell, osmotic microbial desalination cell, submerged microbial desalination–denitrification cell was also highlighted. This study also established that microorganisms are sustainable tools that could be applied for maintenance of a cleaner environment (Ukhurebor, et al., 2021a, 2021b; Osemwegie, et al., 2021; Adetunji, et al., 2018a, 2018b, 2017, 2014, 2019).

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