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Microbial Desalination Cells for Low Energy Drinking Water

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ABSTRACT

We have all encountered the question at least once in our lives: "If Earth has 71% of its surface covered by water, why is only 1% of it drinkable?" This scarcity of drinkable water is due to the fact that the remaining 99% consists of ocean water with a high salt content, making it unsuitable for consumption. Desalination is a process designed to extract mineral components from saline water. In broader terms, desalination involves eliminating salts and minerals from a given substance. The development of a portable desalination system is crucial to address water challenges in rural areas and during emergency situations.

We present a field-deployable desalination system employing multistage electro-membrane processes. This system is comprised of a two-stage ion concentration polarization process and a one-stage electro-dialysis process, effectively converting brackish water and seawater into potable water. Additionally, sodium hydroxide, also known as caustic soda, can be used as a pretreatment agent for seawater entering the desalination plant. This pretreatment alters the water's acidity, helping to prevent membrane fouling—a major cause of disruptions and failures in conventional reverse osmosis desalination plants.

Keywords: desalination, ion concentration polarization, salt remova

I. INTRODUCTION

Desalination plants in India serve as an additional water source for human consumption. The desalination of seawater plays a crucial role in meeting the freshwater demands of both people and the environment. Many major urban cities in India grapple with chronic water scarcity issues. These cities rely on groundwater and surface water sources, which are insufficient to meet the existing water demands. Moreover, the increased use of groundwater is depleting underground aquifers at an alarming rate, and the future demand for water is expected to continue rising.

One promising technology in this context is Ion-Concentration Polarization (ICP), which occurs at the junction of microfluidic and ion-selective nanofluidic channels when an electric field is applied. This phenomenon creates a depletion zone that repels charged particles. ICP has been widely utilized for concentrating analytes and has even been applied in the reverse process—concentrating ions from saltwater while producing pure water as the output. For instance, Kim et al. demonstrated the application of ICP in a planar microfluidic device equipped with a Nafion® nanoporous membrane. Despite being a micro-scale device, their system exhibited energy efficiency comparable to large-scale reverse osmosis plants. Subsequent research has explored various configurations, including planar nanoscale pathways, PDMS slices filled with nanoporous membranes, and triangular nanochannels along the edges of planar nanoporous membranes.

Reverse osmosis is another important method in desalination. It involves reversing the direction of osmosis by applying pressure to the solution side. This causes the pure solvent to flow out of the solution through a semipermeable membrane, effectively removing impurities such as salts and minerals from seawater. Reverse osmosis is a widely used technique to obtain fresh water for human consumption and various domestic and industrial purposes.

Advantages of Desalination:

1.ProvenTechnology:Desalination is a well-established and reliable technology with a track record of providing clean, drinkable water.

2. Food Supply Chain Improvement:Increased availability of freshwater through desalination can help address water-related issues in the food supply chain, ensuring stable food production.
3. Drought Resilience:Desalination offers a crucial source of water during droughts, reducing the impact of water scarcity on communities and agriculture.
4. Reduced Water Disputes:Desalination can mitigate political disputes related to water diversion, as it provides an independent source of water supply.
5. Energy Generation:The energy generated during the desalination process can be harnessed for other purposes, contributing to sustainable energy production.
6. Economic Stability:Desalination helps stabilize economies by ensuring a consistent water supply for industries, agriculture, and households.
7. Future Water Reserves:Desalination allows for the creation of strategic water reserves, ensuring a reliable water source for future generations.
8. Community Water Independence: Communities with desalination facilities gain greater independence and resilience in managing their water resources.
9. Industrial Benefits:Various industries benefit from the presence of desalination facilities, including agriculture, manufacturing, and technology sectors.
10. Versatile Location: Desalination facilities can be established in a wide range of locations, making them adaptable to different geographical and environmental conditions.
11. Marine Life Preservation:Advanced desalination technologies can minimize the environmental impact on marine life, promoting sustainability.
12. Diverse Fuel Options: Desalination technologies can be powered by various energy sources, including renewable and conventional fuels, offering flexibility in energy choices.

Disadvantages of Desalination:
1. Chemical Waste Disposal: Desalination processes produce significant chemical waste, which requires careful disposal and management to prevent environmental harm.
2. Brine Disposal: The generation of brine, a byproduct of desalination, poses challenges in terms of responsible disposal. It can have adverse effects on aquatic ecosystems, particularly smaller organisms.
3. Health Concerns: There are health concerns associated with desalination, primarily related to the chemical additives and byproducts involved in the process. Proper monitoring and treatment are essential to ensure water safety.
4.High Energy Consumption: Desalination plants consume a substantial amount of energy, making them energy-intensive operations. This high energy demand contributes to operational costs and environmental impacts.
5. Capital Costs: The initial capital investment required for establishing desalination technologies is often substantial, posing financial challenges for many regions or organizations.
6. Elevated Energy Costs: The ongoing energy costs for running desalination plants can be quite high, further straining budgets and contributing to environmental concerns if non-renewable energy sources are used.
7. Electrolyte Removal: Certain desalination methods may inadvertently remove essential electrolytes from the water supply, potentially affecting the water's taste and nutritional value.
Not Always Environmentally Friendly: While desalination produces freshwater, it does not necessarily create water that is beneficial for the environment. The brine discharge and environmental impacts can harm local ecosystems.
It's important to note that advancements in desalination technology and better management practices are continually being developed to address some of these disadvantages and minimize their impact on the environment and public health.

Microbial Desalination Cells for Low Energy Drinking Water

In 2020, approximately 8% of the total capacity, which amounted to 101.6 million cubic meters per day (Mm3/d), was derived from wastewater sources. Around 20% of the capacity came from brackish water sources, primarily brackish groundwater, while the majority, about 60%, was sourced from seawater (as depicted in Figure 1.2). Seawater is the dominant source for desalination globally, contributing to a worldwide water production of roughly 60 Mm3/d. Irrespective of the source water type, reverse osmosis (RO) is the preferred desalination technology, accounting for approximately 70% (67 Mm3/d) of the global capacity. Distillation plants, including multi-stage flash (MSF) and multi-effect distillation (MED) facilities, constitute 24% or 23.2 Mm3/d of the global capacity, with market shares of 17% (16.6 Mm3/d) and 7% (6.6 Mm3/d), respectively.

The Electrodialysis (ED) process holds a market share of around 2% (1.97 Mm3/d). Other processes in use include electro-di-ionization (EDI), accounting for 0.3% (0.3 Mm3/d), and Nano-filtration (NF), accounting for another approximately 2% (1.8 Mm3/d) of the world's desalination capacity. The distribution of these processes changes when considering different source water types (see Figure 1.3). For seawater desalination, seawater reverse osmosis (SWRO) and thermal processes dominate global production (34.4 and 25.7 Mm3/d, respectively). MSF is the primary thermal process, accounting for 31% of global seawater desalination production. In contrast, RO is the dominant process for brackish water (90%, 17.8 Mm3/d) and wastewater (91%, 6.9 Mm3/d) desalination, with distillation playing a minor role for these source waters.

The desalination market is predominantly influenced by reverse osmosis (RO), with relatively less competition between multi-stage flash (MSF) and multi-effect distillation (MED). Nonetheless, the high energy costs associated with desalination remain a significant concern. Energy consumption constitutes 75% of the operating cost of desalination when excluding capital costs or 40% when including capital costs. This energy cost is approximately ten times higher than that of conventional water sources, leading to elevated water prices that can exceed 0.5 €/m3.

Recently, a novel technology called the microbial desalination cell (MDC) has emerged, demonstrating the ability to desalinate water without the need for external electrical power. This technology relies on the electrical energy produced through the degradation of organic matter in water by bacteria. Derived from microbial fuel cells (MFCs), MDCs utilize the electric potential generated by the microbial metabolism of organic compounds to drive desalination, akin to Electrodialysis (ED). The advantages of MDCs include reduced reliance on external energy for desalination and simultaneous wastewater treatment (WWT). Additionally, MDCs operate under neutral pH, pressure, and temperature conditions. A typical MDC comprises three chambers: an anode, a middle (salt) chamber, and a cathode (as illustrated in Figure 1.7). These chambers are separated by an anion exchange membrane (AEM, situated between the anode and the middle chambers) and a cation exchange membrane (CEM, located between the cathode and the middle chambers). Bacteria growing on the carbon-based anode electrode break down organic matter while releasing electrons and protons in the anode chamber. Terminal electron acceptors (e.g., ferricyanide or oxygen) in the cathode chamber are reduced by accepting these electrons through an external circuit.

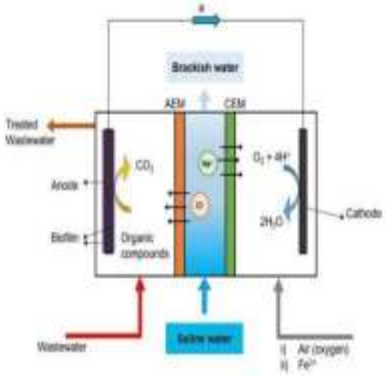

Fig -1 Schematic Diagram of Electrode Assembly

In an MDC (Microbial Desalination Cell), anions and cations are driven to migrate through the Anion Exchange Membrane (AEM) and Cation Exchange Membrane (CEM) to balance the electric charge in the anode and cathode chambers. As a result, the water in the central chamber is desalinated through the migration of ions from the central compartment to the adjacent ones.

In the early stages, lab-scale MDC devices from 2009 could only produce a few milliliters of drinking water. The largest scaled-up MDC before the start of the MDC project produced 0.077 liters per square meter per hour (L/m2/h) for partial desalination from 52.4 to 20 millisiemens per centimeter (MS/cm).

While complete desalination in MDCs can be achieved without an external electrical source, the specific production of such a 'microbial-passive' system is significantly lower, approximately 200 times lower compared to conventional desalination systems like RO, which can produce 15-20 L/m2/h.

To increase desalinated water production while keeping energy requirements low, one option explored in MDC is integrating it as a pre-desalination step with conventional RO desalination units. By pretreating the feed water with an MDC, the salinity is reduced, leading to lower energy demands for downstream RO. It is estimated that about 1.8 kWh of bioelectricity can be produced by an MDC from treating 1 cubic meter of wastewater (WW).

The MDC overall process scheme involves initial treatment of municipal wastewater in a conventional anaerobic reactor. The effluent from this reactor is used as fuel for the MDC, resulting in treated wastewater with a 90% reduction in initial chemical oxygen demand (COD). In conventional RO desalination, seawater undergoes several pretreatment steps, such as chemical coagulation, settling, and filtration, to protect membranes from particles and organic matter. In MDC, these pretreatment steps are replaced by Nano-coated ceramic membranes, reducing chemical usage, footprint, and energy demand by 80%. After pretreatment, seawater enters the MDC unit, where it's partially desalinated (70-90%), before undergoing full processing in the RO unit.

Microbial electrochemical technologies (METs) involve interactions between electroactive bacteria and electrodes. A variant of this technology, the microbial fuel cell (MFC), directly converts soluble organic matter into electric current. This power can enhance organic matter degradation and drive electrochemical processes, making it a self-sufficient and decentralized system. The MDC combines aspects of an MFC and an Electrodialysis(ED) cell to treat wastewater and desalinate seawater using energy generated from the oxidation of organic matter.

MDC technology offers the potential to desalinate saline water without consuming electric or thermal energy, making it an energy-saving and environmentally friendly alternative to conventional processes. Its versatile applications make it a feasible option for both desalination and wastewater treatment, offering energy savings and reduced greenhouse gas emissions compared to traditional methods.

The MDC unit typically consists of at least three chambers: an anaerobic anodic chamber for organic matter oxidation, a central desalination compartment separated by AEM and CEM membranes, and a cathodic chamber where the reduction counter-reaction takes place. CEM and AEM are alternately placed between the cathodic and anodic compartments in an MDC reactor.

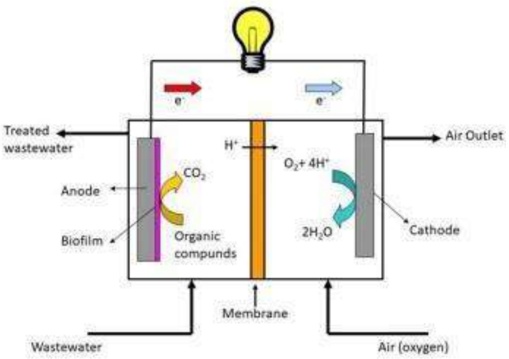

Fig – 2 Schematic Diagram of a Microbial Desalination Cell (MDC)

MDC Operation:

An MDC utilizes the potential difference created between the anode and cathode chambers by feeding the anode compartment with organic matter (e.g., wastewater) and the cathode compartment with a catholyte (e.g., a Fe3+ complex or oxygen in an acidic solution). This potential difference drives the migration of ions through anion exchange and cation exchange membranes, leading to desalination of the saline compartment (central compartment). MDCs are sustainable because they do not require external energy input; instead, they harness energy from microbes breaking down waste.

MDC Designs:

Various MDC designs have been explored, including cubic and tubular reactors, stacked cells, batch recirculation systems, bio cathode MDCs, and innovations like the use of Nano-coated ceramic membranes, ion exchange resins, and microfiltration processes. While most prototypes are at lab scale (milliliters), a pilot-scale MDC unit capable of partial seawater desalination has been reported.

MDC as Pre-treatment for RO:

MDC technology can serve as a pre-treatment for reverse osmosis (RO) to reduce energy costs for desalination. By lowering the salinity of the feed water, MDCs can decrease the energy demands of downstream RO. An MDC can produce around 1.8 kWh of bioelectricity from handling 1 m3 of wastewater.

Electrodes in MDCs:

Electrodes are vital components in MDCs, as they determine the potential gradient driving the desalination process. Low-cost, scalable, carbon-based collector and electrode materials are developed to facilitate electrical wiring, organic matter metabolism, and biofilm growth.

Life Cycle Assessment (LCA):

LCA is a standardized technique used to assess the environmental impacts associated with the life cycle of products or technologies. The LCA for MDCs considers various factors, including construction, operation, and emissions associated with the catholyte. MDCs contribute to impact categories such as climate change, human toxicity, and fossil depletion, with emissions from the catholyte being a major contributor.

Environmental and Social Impacts and Benefits of MDC:

MDCs share environmental impacts with other desalination methods, including potential water pollution from chemical use in membrane cleaning. However, MDCs offer unique benefits, such as reduced air pollution and contributions to climate change when compared to traditional desalination methods. The use of renewable energy sources can further reduce environmental impacts.

Release of Treated Wastewater:

An area of concern is the use and disposal of wastewater (anolyte) from MDCs. To address potential contamination concerns, it is essential to test MDCs with real wastewater and monitor the presence of substances, including nanoparticles, in the discharged water.

Reducing Operating Costs:

MDC technology has the potential to reduce the operating costs of desalination plants, which can be significant. By using renewable energy sources and improving the efficiency of MDCs, the costs associated with desalination can be lowered.

Increasing Access to Drinking Water and Sanitation:

Affordable desalination technology can enhance access to drinking water, particularly in regions with access to seawater or brackish water. This can lead to improvements in water and sanitation, fulfilling human rights and sustainable development goals.

Overall, MDC technology offers a sustainable and energy-efficient approach to desalination with potential environmental and social benefits, but challenges such as improving efficiency and addressing environmental impacts need to be carefully considered and mitigated.

II. CONCLUSION

In conclusion, microbial desalination cells (MDCs) offer a promising technology with the potential to address multiple challenges in the water sector:

MDCs, when used as pre-treatment for reverse osmosis (RO), offer a dual solution to two pressing water-related problems: the scarcity of drinking water and the contamination of water bodies due to the discharge of wastewater.

MDCs leverage the chemical energy present in wastewater to reduce the salinity of seawater and brackish water. This innovative approach not only provides a source of freshwater but also minimizes the environmental impacts associated with conventional desalination methods, which rely heavily on energy-intensive processes.

While MDCs share common environmental impacts with traditional desalination plants, such as potential water pollution from chemical usage, they offer unique environmental benefits. These benefits primarily stem from the reduction in energy consumption achieved by harnessing energy from wastewater, thereby reducing greenhouse gas emissions and other environmental burdens.

significant impact exclusive to MDCs is related to the production and use of the catholyte. Strategies to reduce the negative impact of catholyte production, such as regeneration and reuse, can further enhance the environmental sustainability of MDC technology.

Overall, the adoption of microbial desalination cells as a pre-treatment for reverse osmosis represents a promising and sustainable approach to water resource management. By simultaneously addressing water scarcity and wastewater contamination while reducing energy consumption and associated environmental impacts, MDCs offer a potential solution to some of the most pressing challenges in the water sector. Continued research, development, and implementation of MDC technology hold great promise for the future of sustainable water resource management.

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