ABSTRACT

Title of Thesis: ALTERNATIVE METHODS OF DESALINATION FOR SUB-SAHARAN AFRICA: A REVIEW OF PREFILTRATION AND MICROBIAL DESALINATION CELL TECHNOLOGY

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Our research project has addressed the global need for greater accessibility to potable drinking water, specifically within the regions of sub-Saharan Africa. Initially, we planned to design a unique desalination system that was composed of a pre-filtration unit, a microbial desalination cell (MDC) and a post-desalination treatment unit. When in-person lab work was no longer feasible due to COVID-19 guidelines, we refocused our project to review the construction, efficiency, and cost effectiveness of the different designs of potential prefiltration units and MDC configurations. Our review of potential prefiltration systems included both chemical and physical separation methods, and the review of the MDC included the air cathode, biocathode and stacked configurations. While researching the technical details of the prefiltration and MDC systems, we also considered the cultural and societal impacts of introducing a technology such as the MDC into our project region. Our project started as an analysis of an emerging technology, but as the team has grown, the project has transformed into a comprehensive review of the emerging microbial desalination technology and the societal impacts of implementing it into some of the water scarce regions of coastal sub-Saharan Africa.

ALTERNATIVE METHODS OF DESALINATION FOR SUB-SAHARAN AFRICA: A REVIEW OF PREFILTRATION AND MICROBIAL DESALINATION CELL TECHNOLOGY

by

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INTRODUCTION

Project Foundation

Ongoing urbanization worldwide, steady economic growth, and climate change, among many factors, contribute to an urgent demand for potable water across many regions of the world (Eberhard, 2019). This need for increased water accessibility is especially urgent in sub-Saharan Africa, where 42% of people do not have a basic water supply, and the population is urbanizing quickly; the urban population is expected to increase four-fold by 2050, up to 1.3 billion people (Eberhard, 2019). Insufficient water supply in some of sub-Saharan Africa's largest cities can be attributed to deteriorating water infrastructure due to rapid urban growth, contamination of drinking water sources, poor water quality, and rising water treatment costs (Pierce, 2017). Sufficient access to water means having a piped water connection nearby one's home, at a nearby public stand post or kiosk, or at a neighbor's home; however, more than one third of people living in sub-Saharan Africa still lack sufficient access to potable water (Eberhard, 2019; Pierce, 2017).

Our research project is focused on exploring an accessible, low-cost, energy-efficient seawater desalination system to address the issue of water accessibility within coastal regions of sub-Saharan Africa. Since surface water and groundwater sources are becoming scarcer in parts of Africa due to climate change and human activity (Takouleu, 2020), our team is focused on designing a desalination system suitable for seawater, which can be more readily available to coastal communities. Existing seawater desalination methods present a range of implementation issues, such as high energy costs, difficulty of connecting water distribution networks, and design and construction complexity (JICA, 2016). In our desalination system, we aim to keep both material and energy costs low, maximizing accessibility to allow for small-scale practical implementation in households and communities in sub-Saharan Africa. The system design we have extensively studied consists of a prefiltration process with multi-soil layering and ceramic pots, a microbial desalination cell system, and possibilities for post-treatment.

The goal of the system is to ultimately deliver clean drinking water to disadvantaged coastal communities in sub-Saharan Africa. In doing so, this project aims to address several of the Sustainable Development Goals published by the United Nations Department of Economic and Social Affairs. The goals that our project plans to address include: Good Health and Well-Being; Clean Water and Sanitation; Industry, Innovation, and Infrastructure; Decent Work and Economic Growth; and Reduced Inequalities. First, ensuring the well-being and continued health of all individuals is a goal that our project plans to achieve by researching energy efficient and cost-effective water desalination technology to water-stressed communities. The development of an effective filtration and desalination system will also ensure that coastal communities will have access to clean drinking water without taking the risk of consuming contaminated, untreated water. The organized production, manufacturing and maintenance of the system and its components has the potential to bring innovation and infrastructure to these regions, thereby promoting economic growth and development in the process. Finally, the lack of water accessibility by community members in sub-Saharan Africa will fall given the implementation of a cost-effective and highly capable water filtration and desalination system. In doing so, the inequities felt by water-stressed nations in regard to water accessibility will hopefully become less severe and finally address the disparities associated with access to clean drinking water in these communities.

System Composition

Seawater will serve as the input water source into the desalination system. There are many contaminants and particles within seawater which must be treated and/or removed from the water in order to meet drinking water standards outlined by the World Health Organization. Some of these contaminants are listed in Table 1, along with their particle sizes, requirements to meet drinking water standards, and human health effects. We further discuss the removal of these contaminants in later sections of the thesis.

Table 1. Sizes, Drinking Standards and Health Effects of Contaminants in Seawater. Adapted from World Health Organization (2017)

Component Type	Component	Particle Size (µm)	Drinking Water Standards	Health Effect
Bacteria	*Escherichia coli*	1 µm	None	Gastrointestinal illness
	Salmonella	1 µm	None	Gastrointestinal illness
Viruses	Hepatitis A virus	0.05 µm	None	Liver disease
	Poliovirus	0.05 µm	None	Spinal cord illness including paralysis
Protozoa	*Cryptosporidium parvum*	10 µm	None	Causes cryptosporidiosis disease, gastrointestinal illness

Metals	Lead	0.5 µm	0.01 mg/L	Kidney problems, Infantile illness or defects
	Copper	0.5 µm	2 mg/L	Gastrointestinal illness, liver or kidney damage
Inorganic chemicals	Nitrate	500 µm	50 mg/L	Infantile illness or death
	Sand	500 µm	< 600 mg/L	Taste/Quality
	NaCl	0.001 µm	< 600 mg/L	Taste
Organic chemicals	Glyphosate	500 µm	No guideline value (0-0.3 mg/kg body weight if consumed)	Kidney problems, reproductive difficulty

Testing for Water Quality

As this project seeks to decontaminate and purify seawater for drinking water quality, tests must be conducted to determine the efficacy and effectiveness of the water purification methods introduced in this work. The tests and instruments required to analyze the water quality of the finalized product after prefiltration, desalination, and potential post-filtration are described in Table 2.

Table 2. Summary of water quality tests used to analyze the final product. Adapted from Oram (2020), Voutchkov (2010) and World Health Organization (2017).

Measurement	Description	Importance	Instrument Used	Desired Reading
Salinity	Total amount of NaCl in the water	Water with high NaCl will be unpalatable	Salinity probe	< 600 mg NaCl/L water

		and dangerous to drink		
Biological Oxygen Demand (BOD)	Measures the amount of oxygen used by organisms while they decompose organic matter in the water	Higher BOD indicates more polluted water	BOD sensor	1-2 mg Oxygen/L water
Chemical Oxygen Demand (COD)	Measures the amount of oxygen used by chemical reactions in the water	Higher COD indicates more polluted water	COD sensor	1-2 mg Oxygen/L water
Total Nitrogen (TN)	Measures the amount of organic nitrogen in the water	Indicates domestic or agricultural contamination	TN Analyzer	1 mg Nitrogen/L water
Total Organic Carbon (TOC)	Measures total organic carbon in the water (Indicates organic materials [natural], disinfectants and disinfection byproducts)	High levels of TOC indicate that biofouling may have occurred	TOC Analyzer	< 0.5 mg Carbon/L
Total Dissolved Solids (TDS)	Measures the total of organic and inorganic substances in water	Unpleasantness to the taste would be objectionable to consumers	TDS meter	< 600 mg solids/L water
Turbidity	Measures the number and	Increased turbidity is	Turbidity sensor	< 0.5 nephelometric

	size of particles present	caused by poor source water and poor treatment		turbidity units (NTU)
pH	Measures the amount of hydrogen	Non-neutral water can cause health problems	pH probe	pH 6.5 - 8.5 (Typical pH of seawater is 7.6 to 8.3)
Temperature	Important quality of environmental parameters	Low temperature can cause increase in energy use in system, High temperature may cause accelerated mineral scaling and biofouling	Thermometer	> 12 ℃ and < 35 ℃

Team Decisions and the COVID-19 Pandemic

The first major team decision to be made was to choose a method of desalination to study. It was important to choose a technique that was relatively novel with reduced energy requirements compared to those of commercial desalination processes. The two methods of desalination that fit this criteria and were initially proposed was microbial desalination technology and cyanobacterial desalination. After spending some months researching the bacteria, we discovered that cyanobacteria can secrete toxic chemicals called cyanotoxins. As a result, the use of cyanobacteria as a means of desalination was deemed infeasible for this project. Therefore, the microbial desalination cell became the primary method of desalination that we explored for the remainder of the project.

With this new development in our project, we began researching the different configurations of the MDC and what materials are most commonly used in their designs. Our initial plan was to identify three major MDC configurations to build and test. The plan was to compare the differences in their energy production, rate of desalination, and ion transport when different materials/configurations were used. In doing so, we would be able to determine which designs and materials would allow for the most energy efficient and cost-effective MDC model.

Before we were able to begin testing, the COVID-19 pandemic caused the suspension of all nonessential research efforts at the University of Maryland during the spring of 2020 and restricted access to undergraduates during the following semesters. With the majority of the time we had allocated for experimentation and data analysis no longer available, we decided to change the direction of our project.

Instead of performing lab experiments with each of our MDC models and prefiltration system, we have authored a literature review that analyzes the different technologies within the spheres of prefiltration and microbial desalination. Based on the literature, we are now drawing conclusions on the suitability of these systems for providing access to potable water within regions of sub-Saharan Africa that suffer from inaccessibility to clean water.

PREFILTRATION

Prefiltration is an essential component in the seawater desalination process because it allows for removal of particles and microorganisms present in the seawater including various bacteria, viruses, protozoa, and metals as discussed in the introduction. Removal of larger particulate matter in the seawater, such as certain inorganic chemicals (e.g. nitrate and sand) and organic chemicals (e.g. glyphosate), may be accomplished through a prefiltration process. This ensures that the downstream microbial desalination cell system, introduced in this study, is able to function with higher efficiency due to significantly improved water quality, has reduced clogging in the downstream membranes, and has improved efficacy of pathogen post-treatments (Figure 1). This project attempts to construct a prefiltration and desalination system that is minimal in size, easily accessible to communities in sub-Saharan Africa, and cost effective. A number of prefiltration techniques are discussed in this section.

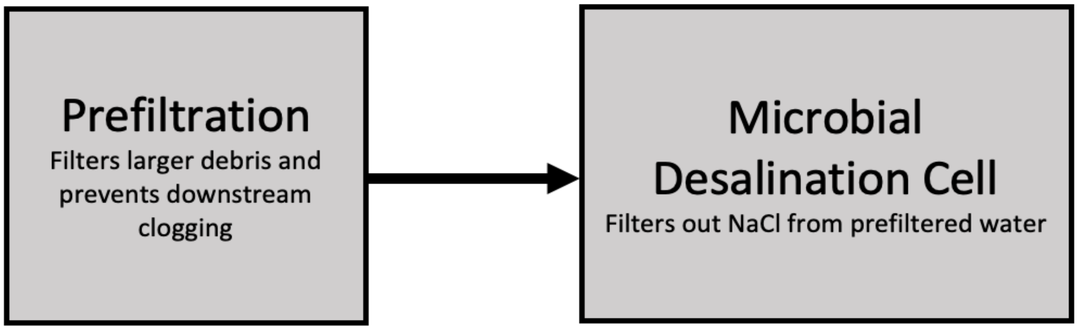


Figure 1. Water product from the prefiltration system will enter the microbial desalination cell.

Often, freshwater is not easily accessible in many regions of sub-Saharan Africa (Eberhard, 2019). Consequently, many communities use ground-, surface- or rain-water for drinking, which poses an increased risk of contamination and high salinity levels due to infiltration of seawater, especially in coastal communities (Pan Africa Chemistry Network, 2010). Seawater can contain particles and microorganisms, making it unsafe to drink and difficult to clean to drinking water regulations put in place by the U.S. Environmental Protection Agency. The US EPA specifies an extensive list of microorganisms, disinfectants, disinfectant byproducts, inorganic and organic chemical contaminants, and radionuclides that can present public health risks if found in drinking water sources (National Primary Drinking Water Regulations, 2021). Many of these particles may be removed from the seawater by prefiltration before the water enters the desalination system.

Another reason why prefiltration is critical prior to seawater desalination using membrane technology is that filtering seawater lowers the amount of fouling materials that can deteriorate membrane lifetime and efficacy in the microbial desalination cell system (Valavala et al., 2011). Suspended particulate matter, colloids, organic and inorganic compounds, and microorganisms all pose a threat to membrane efficiency by coagulating together and forming a layer on the membrane surface to cause fouling (Valavala et al., 2011). Growth of biofilms (biological fouling) also occurs as bacteria, fungus, and algae adhere to the membrane surface (Valavala et al., 2011). As a result of membrane fouling, membrane function and desalination efficiency decreases. Salt passage through the membrane, permeate flow, and pressure drop across the membrane all become lowered. Prefiltration aids in reducing these effects.

Types of Prefiltration Systems

A range of prefiltration technologies exist for the treatment of seawater prior to inflow through a desalination system. Techniques are used depending on the sizes, charges, and other chemical and biological characteristics of the materials to be removed from the water. Common pretreatment technologies include source water conditioning processes, such as coagulation, flocculation and pH adjustment, and granular media filtration such as anthracite and sand filtration (Voutchkov, 2010). Figure 2 shows an overview of prefiltration techniques that will be discussed in further detail below.

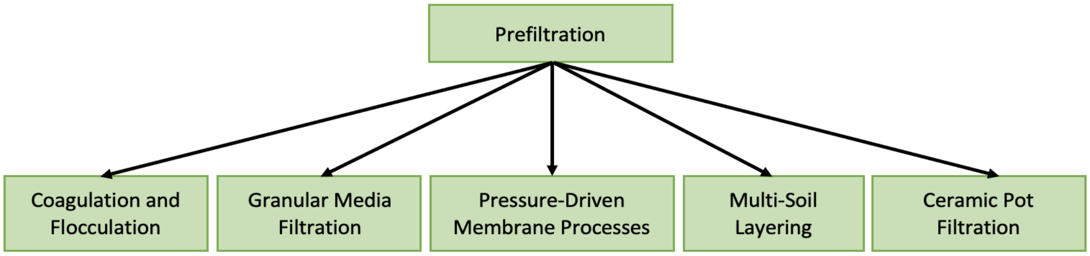


Figure 2. Graphical display of the prefiltration systems to be discussed in this section.

Coagulation and Flocculation

In the coagulation-flocculation process, fine particles, colloids, natural organic matter, and soluble organic and inorganic pollutants present in the seawater are able to agglomerate into larger particles which may be more easily filtered out (Teh et al., 2016). In the coagulation stage, dispersed coagulant is rapidly mixed into the water and treated with vigorous agitation. Water treatment coagulants are comprised of positive charged molecules, while most particles and microorganisms within seawater have a negative charge. Therefore, the coagulant is able to neutralize molecules from the seawater components thus making agglomeration more likely. In the flocculation stage, gentle agitation of the water mixture allows agglomeration of neutral particles into flocs, which settle within the solution and are removed as sludge (Teh et al., 2016).

Granular Media Filtration

Source water conditioning by coagulation and flocculation is an important step before granular media filtration since charged particles, colloids, and organic and inorganic matter in the seawater need to be neutralized prior to granular media filtration.

Granular media filters fall into two classifications: gravity filters and pressure filters. Gravity filters are reinforced steel structures that operate by the force of the water pressure drop and are used in both small and large desalination plants. Pressure filters are similar to gravity filters, but these filters are contained within steel pressure vessels which are used in small– to medium-sized desalination plants (Voutchkov, 2010). Since this project attempts to construct a prefiltration and desalination system that is minimal in size, easily accessible to communities in sub-Saharan Africa, and cost-effective, other prefiltration options are preferred to granular media filtration techniques.

Pressure-Driven Membrane Processes

While seawater pretreatment techniques such as coagulation, flocculation, and granular media filtration are conventional prefiltration techniques heavily incorporated into desalination plants in the past, microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are common membrane technologies that have become more widely used in industrial applications. These prefiltration technologies are pressure-driven separation processes and have the ability to remove a wider range of particles in comparison to conventional granular media filtration (Voutchkov, 2010; Ezugbe and Rathilal, 2020). Each of these processes varies in membrane pore size, material, and charge. Therefore, contaminants targeted for removal in each filtration system differ as well depending on the removal ability of each process.

Reverse osmosis is known for its efficiency in separating small particles (10^{-4} to 10^{-3} micrometers), including bacteria and ions, such as sodium and chloride ions, up to 99.5% (Ezugbe and Rathilal, 2020). However, the energy requirement of RO, in terms of pressure as the driving force, is much higher than the other three processes (Ezugbe and Rathilal, 2020). The size of filtered particles also differs for each process (Ezugbe and Rathilal, 2020). These differences are visible in Table 3. These pressure-driven membrane processes have been used in different combinations for applications in wastewater treatment settings (Ezugbe and Rathilal, 2020). This project will explore an alternative prefiltration process to pressure-driven membrane technologies in an effort to develop a more cost-effective and accessible seawater desalination system.

Table 3. Summary of Pressure-Driven Membrane Processes.

Name	Energy Requirement	Filtration Size Ability
Reverse Osmosis (RO)	15-75 bar	10^{-1} to 10 micrometers
Microfiltration (MF)	1-3 bar	10^{-1} to 1 micrometers
Ultrafiltration (UF)	2-5 bar	10^{-3} to 1 micrometers
Nanofiltration (NF)	5-15 bar	10^{-3} to 10^{-2} micrometers

Multi-Soil Layering

Another type of prefiltration system, the multi-soil layering (MSL) system, consists of multiple soil mixture layers and permeable layers stacked on top of one another and composed of anything from zeolite to clay aggregates to activated-carbon (Ho & Wang, 2015). The concept of this system is to allow the seawater to flow downward, by the force of gravity, through each of the soil mixture and permeable layer components using the soil's inherent abilities to filter contaminants from water. Soil is naturally able to cleanse rainwater and meltwater as it infiltrates the beginning layers of soil and moves through to the groundwater table through physical, chemical, and biological processes. Physically, large contaminants can get caught in soil pores, thereby physically being removed from the sample of water (Sindelar, 2015). Chemically, clay particles in soil naturally have a negative charge thereby attracting positively charged pollutants from entering the groundwater system (Sindelar, 2015). Finally, biologically, soil microorganisms can break down organic contaminants before the water makes its way into the groundwater (Sindelar, 2015). The layers pull out contaminants of the water based on physical and chemical properties, thereby preparing the water for drinking or agricultural purposes in the process. MSL systems have been shown to reduce biological oxygen demand, chemical oxygen demand, total suspended solids, and color in contaminated waters (Ningsih, et al., 2020). These systems are widely used in industrial, domestic, commercial, and personal wastewater treatment settings (Ningsih, et al., 2020).

Material Layers for Multi-Soil Layering System

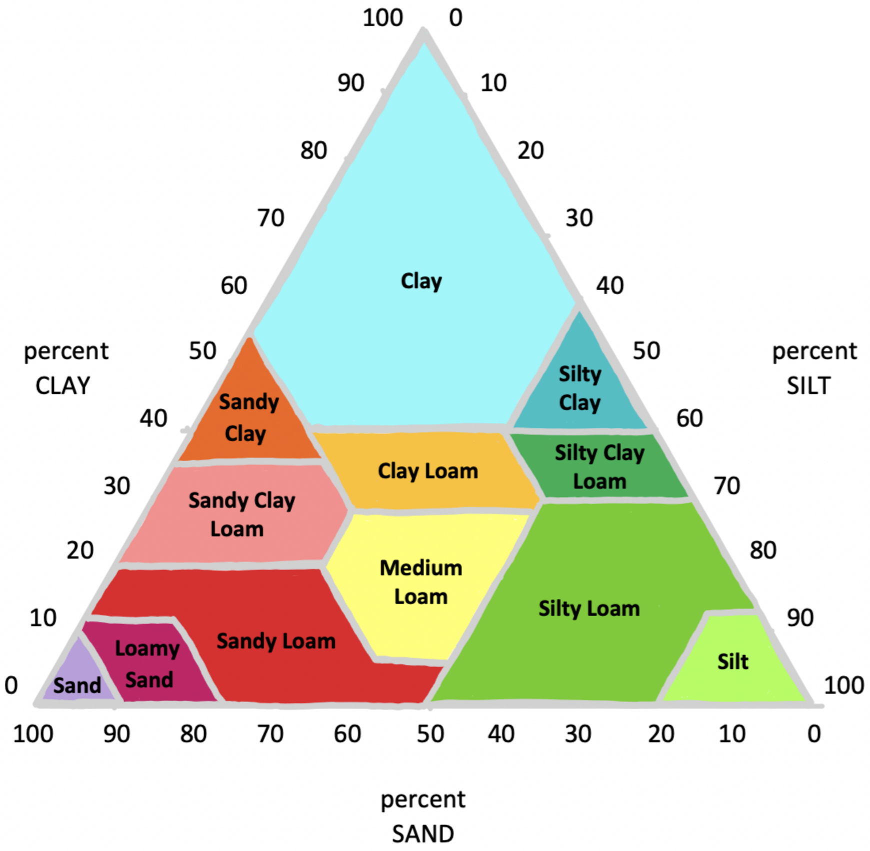
The components of the layers are also an important aspect of the MSL system. There are two different types of MSL layers: the Soil Mixture Layers and the Permeable Layers. They differ in conditions and components, which enable the processes that can occur (Table 4). Porosity of each layer defines the retention time of the water passing through, so that the processes occurring in each layer have ample ability to remove respective contaminants (Table 1) (Sbahi et al., 2020; Latrach et al, 2018).

Table 4. Comparison of Soil Mixture Layers and Permeable Layers in MSL Systems.

Name of Layer	Soil Mixture Layers	Permeable Layers
Processes that occur	Denitrification Absorption Filtration	Nitrification Absorption Filtration
Conditions	Anaerobic Low Porosity	Aerobic High Porosity
Typical Material Composition	Powdered Activated Charcoal Sawdust Iron Scraps	Zeolite Gravel

Soil makes up the largest component of the Soil Mixture Layers with over 70% of the composition. The soil in the MSL system serves as organic matter for microorganisms and the carbon absorbs high amounts of organic matter in water, which increases the decomposition of this organic matter (Ho & Wang, 2015). Soil also provides the habitat for microorganisms to remove phosphorus and provides the pore space for the water to flow through (An et al., 2017).

Looking at the African soil study conducted by Hartemink & Hunting (2008), the specific soil located in sub-Saharan Africa is sandy loam soil. The composition of sandy loam soil can be found from the Soil Triangle (Figure 3). With the goals of designing a cost-effective and accessible technology for stakeholders in sub-Saharan Africa, sandy loam soil is used in this study's MSL system to most represent this environment.



Sandy Loam Soil	
Component	**Percentage**
Sand	45-85%
Clay	15-55%
Silt	0-50%

Figure 3. Soil Triangle used to define component percentages of soil types. Sandy loam clay is defined.

The other materials needed for MSL system layers are as follows: powdered activated charcoal, zeolite, pebbles, and jute. Sawdust and iron have been used in other research studies as supplements for the aforementioned materials (Ho & Wang, 2015). Powdered activated charcoal provides increased absorption capacity of organic materials (An et al., 2017). It is the most effective material for organic material absorption, and although it is not as available as the other materials, it is a necessary part of the system. Zeolite has a suitable cation exchange capacity and pore size, thereby allowing for the removal of ammonia nitrogen, and dissolved metals from the MSL system (Hong et al., 2019). Sawdust also has organic matter absorption capabilities and is being researched to remove dyes, oils, toxic salts, and heavy metals. This material could potentially enhance zeolite as under optimal conditions, sawdust can remove more than 90% of heavy metals (Shukla et al., 2002). Pebbles are used to mitigate the effects of bottom submersion of the upper layers and provide the cleanest output of water (Song et al., 2018). Finally, jute allows for nitrate and phosphorus removal through the denitrification processes housed there (An et al., 2017). Sawdust is used in some studies as a replacement for jute as well, and iron can be used to increase phosphate-adsorption capabilities if necessary (An et al., 2017). The Soil Mixture Layers are shaped into blocks and wrapped in jute which alternate throughout the system (Figure 4).

The materials of this MSL are accessible to most regions of the world. With respect to rural sub-Saharan Africa, sand can be collected from a beach or bought easily from a store. Soil can be collected from the outdoors, in places like a local garden or park. As this study optimized the soil for the region of sub-Saharan Africa, this particular soil, sandy loam soil, should be readily available, even with the similar compositions of other soils in the region. Rocks and pebbles of all sizes can be collected from various sites. Sawdust is also readily available and could be acquired from the logging industry or a wood-working shop. Natural zeolite deposits have historically been discovered in Ethiopia and other regions of the Rift Valley, thereby making this material locally accessible and cost effective (Gómez-Hortigüela et al., 2013). It costs from $0.50 USD to $4.50 USD per kilogram to purchase this material in the region (Virta, 2002). Using local Sub-Saharan African activated carbon suppliers, like Aquamat and RotoCarb, would prevent the need for this material to be shipped across countries. The cost in total for this material is < 2.5 USD/kg (Siwila & Brink, 2020). Jute is used as packaging in an abundance of shipped food products. As only a small piece is needed, this material can be repurposed from the packaging. Overall, this system could cost less than $3 USD total for all materials.

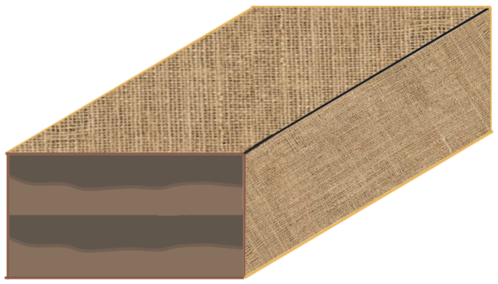


Figure 4. Soil Mixture Layer wrapped in jute.

Construction of Layers

Multiple studies have shown unique layer orientations to optimize MSL systems. The first orientation is to have multiple Soil Mixture Layers and multiple Permeable

Layers. Some studies shift Soil Mixture Layers within Permeable Layers (Approach 1) (Latrach et al., 2016), whereas others stack these layers in a rigid, alternating pattern (Approach 2) (Pattnaik et al., 2008) (Figure 5).

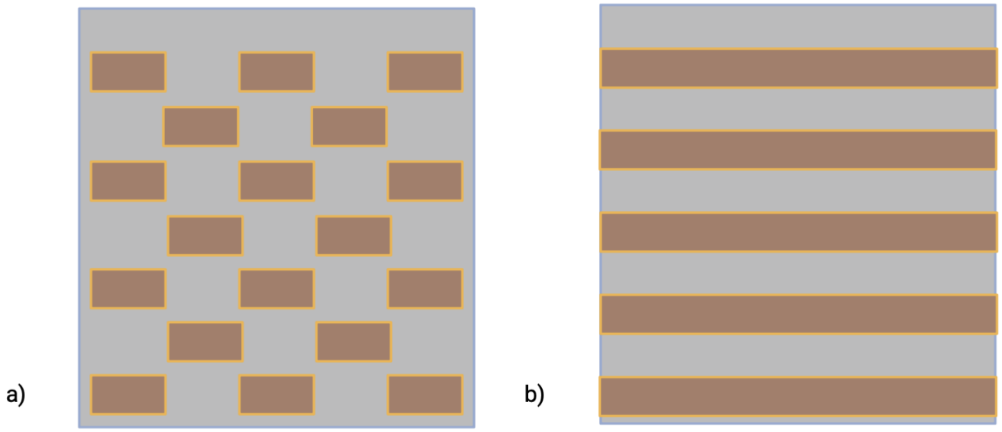


Figure 5. a) Approach 1 allows each layer type multiple passes to remove each category of contaminants. b) Approach 2 encourages contaminated water to flow through each of the layers a set number of times for more robust decontamination.

Other studies have tested hybrid Multi-Soil Layering System by using two MSL Systems and pumping the water from the first system to the next system to the collection pipe (Approach 3). In this approach, the composition of the Soil Mixture Layer and the Permeable Layers are different between the systems, thereby adding the chemical and biological processes of additional materials. In one study, the first MSL system had Soil Mixture Blocks composed of ceramic, charcoal, limestone, and iron, with the second MSL system having Soil Mixture Blocks composed of clay, ceramsite, steel, charcoal, vesuvianite, and limestone (Wei & Wu, 2018). The first set of materials have outstanding ammonia removal, phosphorus removal, and nitrification capabilities, whereas the second set of materials accomplish the same processes but with three times less efficiency (Wei & Wu, 2018). With this set up, most of the contaminants would be removed in the first stage, and the second stage would refine and enhance the water quality at the end. Another two-stage approach like the previous, involves using the same materials to provide added retention time within the system. The drawback to this approach is that it would take significantly more time to decontaminate the water, but it is capable of reducing key contaminant parameters by over 90% (Latrach et al, 2018).

Novel Multi-Soil Laying System Design Approach

The innovative design introduced in this review combines a novel organization of materials with current approaches, like the Soil Mixture Layer block system and the two-stage approach. The novel organization mimics the innate filtering abilities of soil as water makes its way to the groundwater level (Figure 6). It aims to deconstruct the Soil Mixture Layers and the Permeable Layers so that each of these components has their own full layer, instead of being mixed, like Approach 1 and Approach 2.

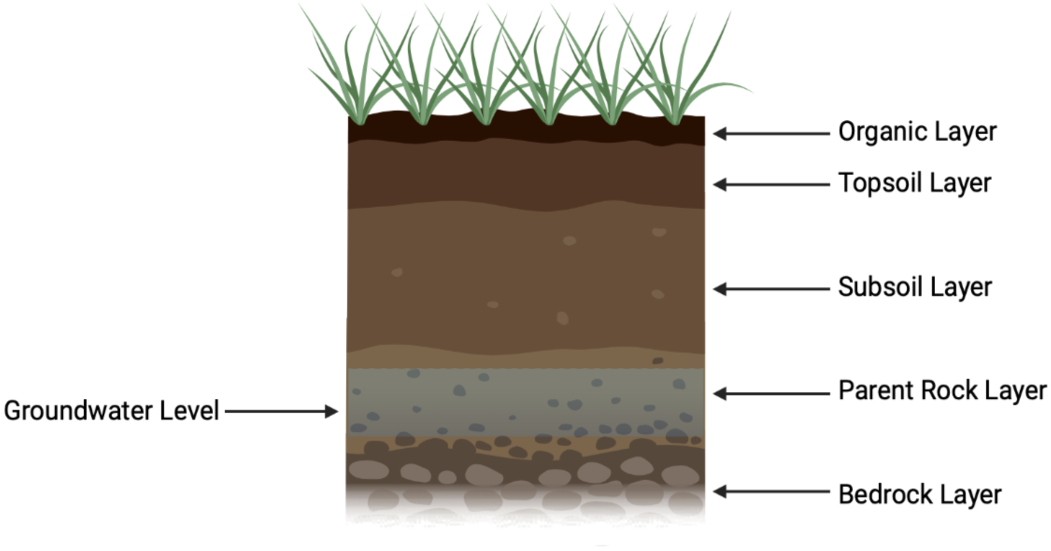


Figure 6. Model of the soil as it cleanses rainwater and meltwater through several layers until it reaches groundwater.

The layers, from top to bottom, are biofilm layer, zeolite layer, activated carbon layer, sandy loam soil layer, pebble layer, and jute layer (Figure 7). These layers could remove the contaminant at once, rather than requiring repetitive flows. The order of these layers is designed to remove larger contaminants first and refine these contaminants as they flow through the system.

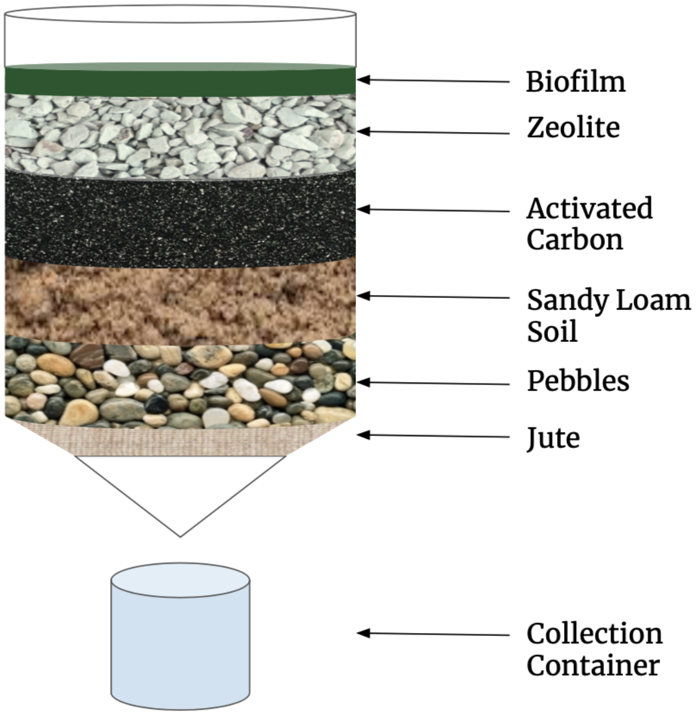


Figure 7. The MSL system design of this study includes six layers that aid in decontamination of the water.

Another novel addition to the MSL is a top layer of a bacterial biofilm capable of removing pathogens from the saltwater. A halotolerant bacterium is required as the salt concentration could disrupt a bacteria’s cell membrane causing it to implode. Halotolerant bacteria such as Proteobacteria and Actinobacteria could be useful in such prefiltration necessities as these types are regularly found in municipal wastewater systems and in anode chambers of Microbial Fuel Cells (Guang et al., 2020). Biological or parasitic contaminants are removed at the top of the system so that these biological materials do not live deeper within the system or manage to pass through the aerobic layers.

The system would require more intensive pumping systems as the materials associated with previous studies' Soil Mixture Layers might have difficulty flowing through the layers with gravity alone. By comparing this approach to previous approaches, it could be determined whether the system models soil decontaminating mechanics efficiently and whether this novel system is as effective at removing BOD, COD, TN, TSS, and turbidity, as described in Table 2.

Other Notable Multi-Soil Layering System Construction Elements

MSL systems are contained within a nonporous and nonreactive material to encase all of the layers. The material of choice for industrial MSL systems is plastic as it is durable and has different compositions. Typically, these units are arranged in a rectangular format, with dimensions of 1-2 meters wide and 2-3 meters high (Ho & Wang, 2015). For the MSL system in this study, plastic was chosen as plastic water bottles and other plastic wastes, can be found in local waste sites or even in plastic litter in sub-Saharan Africa. These plastic wastes could be constructed to fit the desired measurements using locally sourced binding materials.

The industrial MSL systems also include an inflow and outflow of water pipes as well as a switchable, perforated ventilation device. This allows for the adjustment of productivity of the system by allowing for control of aeration (Ho & Wang, 2015).

Areas for Growth in Multi-Soil Layering Systems

Recent studies have delved deeper into innovative approaches to enhance Multi-Soil Layering Systems. One such approach is to add sand filters at the outflow pipe so that there is improved removal of organic matter, overly abundant nutrients, bacteria, and parasites (Latrach et al, 2016). In this study, the added Sand Filter was able to reduce 100% of parasitic worm eggs, thereby reducing the risk of parasitic infection for those using this water effluent (Latrach et al, 2016). Fine sand ($d_{10} = 0.25$) would be the preferred type, as it filters 99.99% of fecal pathogens (Bomo et al, 2003). However, coarse sand ($d_{10} = 0.86$) does remove 99.96% of fecal pathogens (Bomo et al, 2003). For the system in the present study, fine sand filters can enable more efficient filtration of fecal coliforms, which may evade MSL filtration measures and present in the effluent.

One additional add-on is the use of additional systems, like ceramic pot filtration, which will be discussed further in the next section. Overall, these improved MSL systems can then enhance the function of the Microbial Desalination Cell system, this review discusses.

Benefits of Multi-Soil Layering

MSL systems are capable of being decentralized systems for use in villages or rural areas where domestic wastewater treatment plants are not feasible or there is no infrastructure to do so (Deshpande & Thorvat, 2018). The MSL system is also less susceptible to clogging than other prefiltration systems, uses readily available materials to produce reusable water, operates at low costs, and can be used in urban developing countries since it only requires a small area of land (Ho & Wang, 2015). Expensive infrastructure is not needed to construct an MSL system. This approach is also able to be paired with a microbial desalination cell to mitigate the interference of contaminants like algae, sediments, microbes, and colloidal particles, while the water is being desalinated (Sy et al. 2019; Alagha & Abuhajar, 2020).

Ceramic Pots

Another prefiltration method is ceramic pot filtration. Ceramic pot filtration is a point-of-use method of water filtration involving the use of porous ceramic materials (Figure 8). They are made of various compositions of clay soils, sawdust, and other natural components mixed together and molded at a high temperature. When fired, the organic components disintegrate, leaving a porous structure behind (Yang et al, 2020). These ceramic structures, often shaped into pots, are then used to filter water. They are shown to be effective at removing microorganisms like *Escherichia coli*, reducing turbidity, and removing metals like iron, and even removing water hardness (Table 1) (Zereffa and Bekalo, 2017, Yang et al, 2020, Bulta and Michael, 2019).

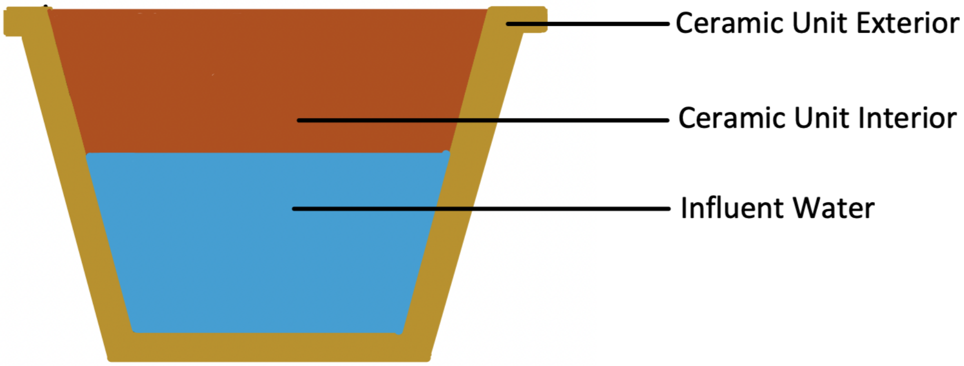


Figure 8. Diagram of Ceramic Pot.

In a ceramic filter, there is a tradeoff between composition of organic matter in the ceramic and filtration of bacteria (Bulta and Michael, 2019). When the organic matter burns, it leaves pores approximately 1 micron wide (Bulta and Michael, 2019). Bulta and Michael (2019) found that reducing porosity from 64% to 52% resulted in an increased removal of *E. Coli* and other coliforms from 77% to 96%. This reduction in porosity comes from a reduction in composition of sawdust in the original ceramic material mixture (Bulta and Michael, 2019).

Silver colloids can also be added to the materials of the ceramic pots, where they act as an antibacterial agent (Jackson and Smith, 2018) (Figure 9). One method of adding silver is to paint a solution of silver nanoparticles onto a ceramic pot to add silver colloids to filtration. A newer, more effective method of incorporating silver into filtration is mixing silver nitrate into the clay and sawdust mixture prior to firing (Jackson and Smith, 2018). Silver nitrate can kill some bacteria and render other species unable to reproduce. It also prevents mold from growing on the ceramic, leading to less clogging and prolonged filtration capability (Bulta and Michael, 2019). In addition to bacteria, silver impregnation also helps to kill *Cryptosporidium parvum*, the protozoa responsible for the water-borne gastrointestinal disease Cryptosporidiosis (Abebe et al., 2015). Finally, silver was also found to reduce virus-sized microspheres in water, a promising result for virus testing (Bielefeldt et al., 2010).

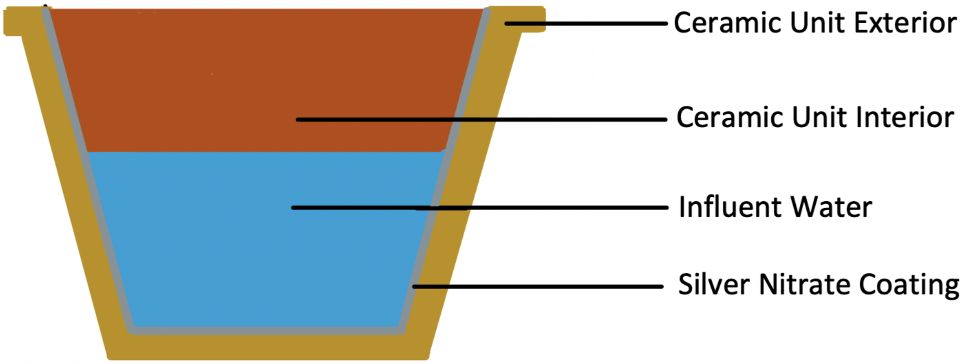


Figure 9. Diagram of Ceramic Pot with Silver Nitrate Coating.

Ceramic filtration is often used in developing countries due to its effectiveness as well as its accessibility (CDC). The ceramic pot filters require a low, one-time cost of $7.50-$30 before distribution and maintenance costs. This means that a family that uses 20 liters of water per day for 3 years pays up to 0.14 US cents per liter filtered (CDC). The low cost is due to the cheap and widely available production materials needed like clay and sawdust. Kilns are also made of clay but reinforced with metal rods (Potters for Peace). When ranked in comparison to other point-of-use water filtration methods like flocculation combined with chlorination, ceramic filtration provided the best water output quality (Yang et al., 2020).

Ceramic filtration was shown to be effective at removing up to 97% of microbes (Zereffa and Bekalo, 2017; Bulta and Michael, 2019). It reduces turbidity by up to 82% in one study (Bulta and Michael, 2019) and up to 89% in another (Zereffa and Bekalo, 2017), thus making it a good candidate for seawater prefiltration prior to desalination. As mentioned earlier, it is important for the desalination step to have water that is free of microbes and other pollutants. This will allow for the highest rate of desalination possible.

Longevity studies on ceramic pot filters have shown no decrease in performance for up to five years. Therefore, barring structural damage the ceramic pots should be effective for that span (Campbell, 2005). However, Campbell's study did not indicate how much volume had been filtered through the tested pots throughout their 5-year lifespan. In addition, the study recommends replacing these filters every two years in case of cracks or breakage (Campbell, 2005). Even despite this biannual need for replacement, the low cost per-filter still makes this a sustainable prefiltration method for developing communities.

Future Prefiltration Goals

The MSL system and ceramic pot filtration are both more feasible pre-filtration systems in comparison to such as reverse osmosis or the other membrane filtration techniques. Overall, they are less-intensive and less high technology systems than other options on the market. This means that communities in sub-Saharan Africa can create these systems on their own without heavy machinery, tools, or other rare materials.

There is little available research comparing the filtration abilities of the multi-soil layering system to ceramic filtration. One potential avenue for future study is to conduct experiments between the two to ascertain their effectiveness at removing target microorganisms as well as concentrations of metals and other pollutants (Table 1). Since the layers of an MSL system must be housed in a container, a ceramic pot could be used for additional filtration (Figure 10a). Another configuration could be to leave the systems separate but experiment with using them sequentially - feeding the outflow of one into the other (Figure 10b). These configurations need to be tested to determine whether one is more effective than another. If the difference is negligible the configuration in Figure 10 could reduce material cost and lead to a more accessible product.

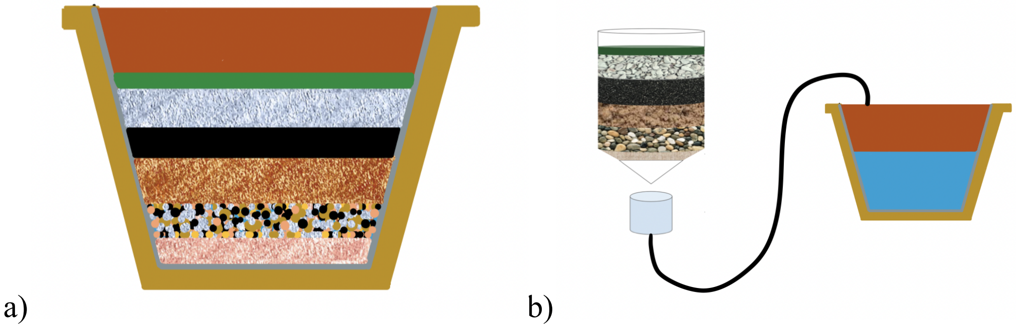


Figure 10. a) Diagram of MSL layers housed in ceramic pot. b) Diagram of MSL connected to ceramic pot in series.

A new study by Rivera-Sánchez et al (2020) created a similar filtration system to the one theorized above by using silver-impregnated ceramic pots in combination with silver-impregnated activated carbon and zeolite. This study evaluated the removal of bacteria *E. Coli* and *Salmonella* and found a removal rate of 98%-99.98% (Rivera-Sánchez et al., 2020). These results are promising and indicate that a combination system as described above would yield effective results in bacteria removal. In addition, in order to create prefiltration systems for desalination tailored to specific communities, the local seawater must be analyzed to determine exactly which contaminants need to be removed and at what quantities. Then, the exact configurations for the seawater input can be created.

MICROBIAL DESALINATION CELL

Introduction

This chapter aims to evaluate current desalination technologies, presently applied microbial desalination cell (MDC) materials and designs, and trends in ion-exchange efficiency and energy production. The discussion continues by addressing various materials, including electrodes, membranes, and electroactive bacteria, and three major configurations of an MDC: the air cathode, the biocathode, and the stacked membrane designs. The various benefits and drawbacks of each component and design are addressed as the practicality of implementing these technologies in water-inaccessible areas of sub-Saharan Africa is explored. Ultimately, this comparative analysis will determine which design of an MDC is most capable of achieving high rates of desalination and energy production while minimizing costs. Current desalination technology is addressed briefly to bring awareness to the dominating forms of seawater desalination and the current standards for salinity removal and energy production in the industry of desalination.

Conventional Desalination

Desalination is commonly performed on the industrial scale through thermal processes or physical separation techniques that utilize membrane technology. Thermal processes operate on the principle of evaporation while membrane processes use filtration as the primary means of desalination (Ebensperger & Isley, 2005). Processes such as multi-stage flash (MSF) distillation, multi-effect distillation (MED), and vapor compression variants – thermal and mechanical (TVC, MVC) – are all examples of thermal desalination technology. Membrane desalination is predominantly performed using reverse osmosis (RO). As of 2015, approximately 65% of all global desalination was performed through reverse osmosis (Kokabian et al., 2019). By mid-2016, approximately 73% of all global desalination efforts utilized membrane technology in some capacity (Kokabian et al., 2019). In total, the International Desalination Association reports that over 75% of the world's desalination capacity is performed through MSF distillation or RO, while MED technology is steadily rising in popularity (Kokabian et al., 2019). Although these technologies have evolved and improved, the amount of energy and funding needed to maintain and operate a desalination plant using thermal or membrane technology strengthens the need for alternative means of desalination. It is estimated that the minimum amount of energy needed to desalinate seawater to produce fresh water is 1.07 kWh/m^3 (Kokabian et al., 2019). However, it has been shown in practice that more than 650 kWh/m^3 is required to achieve a successful conversion from saltwater to freshwater via single-stage evaporation of seawater, 68 kWh/m^3 for MSF distillation, and 2.5 kWh/m^3 for RO, respectively (Kokabian et al., 2019; Kim et al., 2019). These energy requirements are often fulfilled through the burning of fossil fuels. Roughly, one ton of oil is required to produce 20 tons of fresh water, assuming that all of the oil's internal energy is converted to heat with 100% efficiency (Kokabian et al., 2019).

Unfortunately, areas that are experiencing the most intense forms of economic water scarcity are also the areas that do not have the financial or material resources to maintain a large desalination plant. As a result, microbial desalination technology is being explored as a potential option that can guarantee low financial and energetic costs for seawater desalination. One of these technologies involves microbial desalination cells

(MDC). A key benefit of MDC technology is that the electrical current that is produced during the desalination process can be collected from the system and reintegrated to reduce electrical utility costs for the desalination plant.

Microbial Desalination

The MDC is a type of microbial fuel cell (MFC) that utilizes organic matter in wastewater as the driving force for performing the desalination process. The fundamental design of an MDC is a three-chambered device that includes an anode, a desalination chamber, and a cathode (Figure 11). The organic matter is delivered to the anode chamber through a feed of wastewater and the electroactive bacteria present begin to form aggregates and a biofilm on the anode as they oxidize the organic substrates (Figure 12). The released electrons run through an external circuit to reach the cathode and react with an electron acceptor, typically oxygen, to form water. Between the anode and cathode chambers is a separate desalination chamber that contains the saltwater to be desalinated. The desalination chamber is separated by an anion exchange membrane (AEM) and a cation exchange membrane (CEM), respectively. The oxidation and reduction reactions at the electrodes create an electrical gradient between the two chambers and attract the cations and anions in the desalination chamber to the cathode and anode chambers, respectively, effectively desalinating the saltwater.

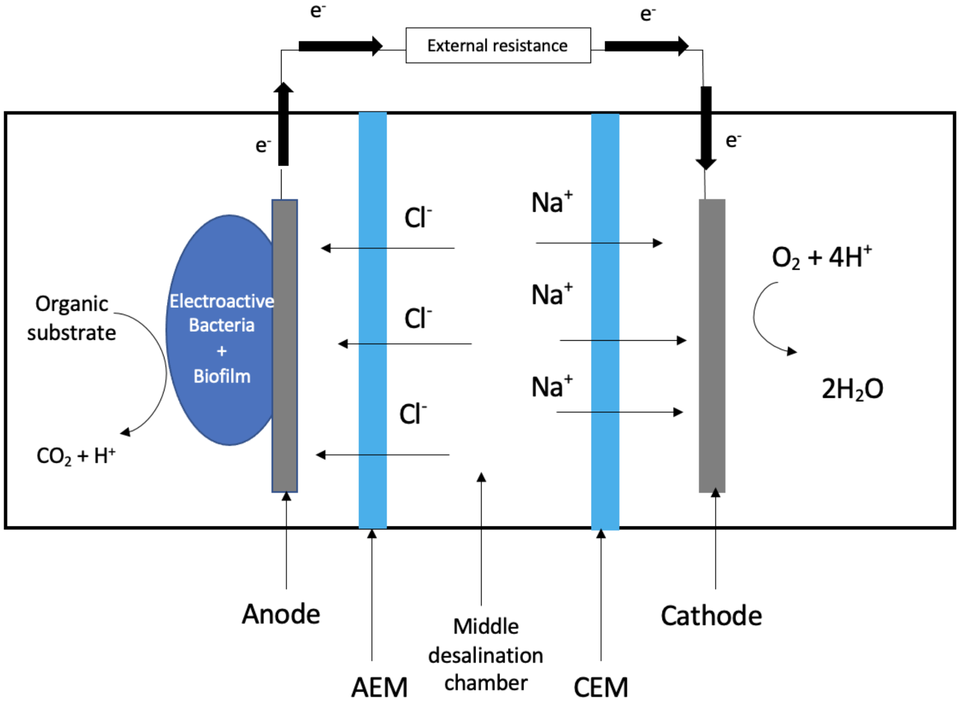


Figure 11. Schematic of a conventional MDC.

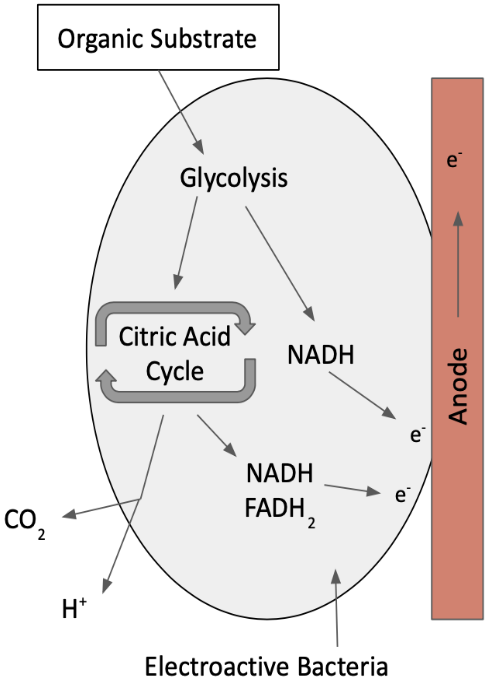


Figure 12. A representation of the biochemical pathways that are exploited within electroactive bacteria to drive desalination within the MDC.

The MDC has several different components, the properties of which will affect the cells desalination capacity and desalination efficiency. Table 5 lists the different MDC components and the effects that they can have on the electrochemistry, the mass transfer of ions, and the energy generated within the cell.

Table 5. Components of the MDC and how they contribute to the function of the cell.

Component	Effect
Electrode/Catalyst Material	Efficiency of oxidation or reduction
Ion Exchange Membranes	Mass transport of ions across cell
Catholyte	Mechanism of reduction
Respiring Bacteria	Mechanism of organic oxidation
Organic Substrate	Mechanism of oxidation

It is important to choose materials for the MDC that maximize its efficiency by increasing the rate of oxidation and reduction reactions at the anode and cathode respectfully, as well as maximizing the rate of mass transfer of the ions out of the middle chamber. However, the cost of these materials can restrict the ability of water-distressed regions to properly fund the construction and implementation of this MDC technology. Therefore, careful consideration and project planning is needed to effectively incorporate new, cost-effective desalination technology into these regions affected by economic water scarcity. In comparing different desalination cell designs, it is important to consider the economic viability and practicality of these technologies. Sustainable desalination systems can only be implemented into target regions if they remain cost effective and hold long-term benefits for global populations. Therefore, this review further intends to explain the electrochemical principles that drive the electricity generation and desalination capacity of the MDC and to explore the pros and cons of three major MDC configurations: a biocathode, an air cathode, and a stacked membrane design.

Chemical Processes within the MDC - Electroactive Bacteria

Desalination and the production of energy within an MDC originates from the reactions of electroactive bacteria in the anode chamber with organic matter. The carbon source for the microorganisms at the anode is present in wastewater, allowing the MDC to simultaneously assist in wastewater treatment efforts in addition to desalination and energy production (Luo et al., 2012). The oxidation of the organic matter powers the MDC, so the growth and activity of the anode-respiring bacteria are important. The conditions of the anode chamber, such as salinity, pH, temperature, and nutrient concentration, must be carefully controlled to maintain an environment that is favorable for bacterial growth (Guang et al., 2020). Commonly used electroactive bacteria in desalination systems include nitrate-reducing bacteria (i.e., *Pseudomonas, Ochrobactrum*), metal-reducing bacteria (i.e., *Geobacter, Shewanella, Geopsychrobacter, and Geothrix*), and sulfate-reducing bacteria (i.e., *Desulfuromonas, Desulfobulbus*). Fermentative bacteria, such as *Clostridium* and *Escherichia coli*, are also capable of generating electricity anaerobically when used in conjunction with desalination cells (Guang et al., 2020). Studies have shown that bacterial activity and biochemical pathways can be altered, when bacteria are exposed to altering the electric potential between the two electrodes, enhancing the energy production of the cell as a result (Guang et al., 2020; Kumar, Singh, & Zularisam, 2016). Overall, there are several parameters within an MDC that can affect the growth, metabolism, and electron transfer capabilities of its electroactive bacteria. Furthermore, MDC systems with mixed cultures of electroactive bacteria have shown much greater rates of desalination and energy production than other systems with pure cultures of bacteria (Guang et al., 2020). Table 6 summarizes some of the performances of electroactive bacterial species used in a variety of MDC configurations.

Table 6. The metabolic performance of electroactive bacteria in MDCs. Adapted from Guang et al., 2020.

Electroactive Bacterial Species	Configuration	Oxidative Substrate	COD Removal	Desalination %	Power Output
Debaryomyces hansenii	Conventional MDC	Glucose	-	55%	488 mW/m^3
Proteobacteria	Conventional MDC	Domestic Wastewater	55%	<66%	3.6 W/m^3
Actinobacteria	Conventional MDC	Municipal Waste Water	52%	66%	8.01 W/m^3
Pseudomonas putida	Multi-Chambered MDC	Steel Plant Waste Water	70%	-	10.2 mW/m^3
Bacillus subtilis moh3	Conventional MDC	0.1% yeast extract	Total decolorization	62%	0.15 W/m^3
Bacillus subtilis moh3	Conventional MDC	0.1% yeast extract	Total decolorization	57%	0.14 W/m^3

The materials needed to construct an MDC also include cathodes and anodes, multiple ion exchange membranes, the catholyte and anolyte solutions, and, as previously mentioned, electroactive bacteria. The selection of these materials in combination with MDC designs are primary factors that determine the cell's overall performance. Variables such as the desalination rate, total salt removal, energy production, and coulombic efficiency of the MDC change based on the overall construction and design of the device (Ramírez-Moreno et al., 2019).

Electrodes connected through wire form a circuit between the anode and cathode chamber, allowing electrons to pass from the anode to the cathode. As a result of this process, the anode chamber assumes a positive charge and the cathode chamber assumes a negative charge. As a result, any positively or negatively charged ions in the desalination chamber will migrate to the chamber opposing their charge. Each chamber is separated by an ion-exchange membrane, which facilitates the migration of salt ions in the desalination chamber to the adjacent chambers that oppose their charge. Equilibrium is eventually established when the electrochemical potential of the ions in the electrolyte solution is equivalent to the potential of the ions in the membrane (Strathmann et al., 2013). This equilibration slows the desalination process and prevents the system from achieving maximum efficiency. By providing a fresh inflow of organic matter into the anode chamber and regularly changing the catholyte mixture to provide an adequate amount of chemical electron acceptors, the MDC can function at its maximum potential.

Materials and Design Selection for MDC

Electrodes

For the purpose of seawater desalination and effective electrochemical interactions, the material and properties of the electrodes hold great significance. One of the major challenges in advancing this technology is providing a solution that improves the bioelectric performance of the cells while not increasing the costs. The selection of electrodes in microbial fuel and desalination cells has previously been based on the biocompatibility, conductivity, scalability, and cost effectiveness of the electrodes themselves (Kalathil, Patil, & Pant, 2017; Schwenke & Schweiss, 2018). Electrodes should possess large surface areas, corrosion resistance, and high mechanical strength to operate with maximum efficiency and for extended periods of time. Popular electrodes in recent studies have been either carbon-based, metal-based, or synthetic electrodes (Kalathil, Patil, & Pant, 2017). Carbon is one of the most commonly used materials for electrodes due to its low cost, high flexibility, ease of use, and low weight; these properties, in particular, simplify the manipulation of carbon into several electrode designs, such as the following: carbon brush electrodes with a three-chambered air-cathode MFC (Logan et al., 2007), graphite plate electrodes with a dual-chambered air-cathode MFC (Dewan et al., 2016), and carbon mesh with a single chamber cube air-cathode (Wang et al., 2009). Carbon-based electrodes, such as carbon fibers or graphite rods/plates, are particularly attractive due to their good electrical conductivity, low cost at large scales, long-term corrosion resistance, high durability, and nontoxic/biocompatible nature (Schwenke & Schweiss, 2018). Other forms of carbon electrodes also include carbon paper, carbon felt, carbon fibers, and even carbon nanotube-based composites (Mustakeem, 2015). The active surface area of carbon electrodes is also enhanced since they are porous materials which increases the contact between the electrode and the biofilm at the anode, thereby increasing the effective electron transport across the cell by the anode (Schwenke & Schweiss, 2018).

Metal-based electrodes, such as platinum or stainless steel, boast high electrical conductivities and corrosion resistance, but their high cost compared to carbon-based electrodes has made the selection of alternate materials more popular in demand.

Specifically, transition metal oxides have been studied as alternate electrode materials to cut costs without sacrificing bioelectric efficiency; in fact, metal oxides such as manganese oxide can also serve as biocatalysts during the redox reactions of the cell, thereby enhancing the catalytic activity, stability, and overall rate of reaction within the cell (Dessie, Tadesse, & Eswaramoorthy, 2020). Currently, enhancing the desalination rate and energy production of a cell while maintaining low production costs is a major obstacle in improving electrode performance and overall MDC function (Mustakeem, 2015).

Membranes

The selection of the anion and cation exchange membranes is yet another important factor is designing a functional MDC. Synthetic and commercially available membranes have been the subjects of several comparative studies addressing desalination enhancement and power production (Lopez Moruno, 2018; Ping et al., 2013). Some of the popular types of ion-exchange membranes are Nafion®, Flemion®, and Aciplex® because of their high chemical resistance, mechanical strength, and high proton conductivity (Yaroslavtsev and Nikonenko, 2009; Yee et al., 2012). Membranes like Nafion® produce a higher level of salinity reduction, but these materials are more susceptible to membrane fouling (Ping et al., 2013). Membrane fouling is the result of the accumulation of organic matter and or microorganisms on the membrane, thereby inhibiting ion transport and resulting in the deterioration of membrane performance (Ping et al., 2013). Nafion® membranes enable greater rates of desalination, but the energy generated after prolonged membrane fouling decreases sharply thus requiring the consistent replacement of the anolyte and AEM to maintain effective desalination and energy production rates (Ping et al., 2013). Despite their popularity in commercial and industrial applications, the use of membranes such as Nafion®, Flemion®, and Aciplex® is limited by their significant costs which can range from $700 to $1,400 per square meter and reduced performances under conditions such as high temperature and low humidity (Peighambardoust et al., 2010; Yee et al., 2012).

A popular alternative to commercially available membranes is the original design of synthetic membranes created for an experiment's specific needs. Generally, incorporating membranes that are thinner and more conductive than their commercial counterparts ultimately enhances the desalination rate and power output of an MDC (Lopez Moruno, 2018). These designs often originate from utilizing commercially available polymers with ionic groups, rather than using the much thicker and less conductive commercially available membranes directly. One study in particular produced data consistent with other MDCs using similar membrane technology and reported a maximum power generation of 235 ± 7 mW/m^2 and a decrease in solution conductivity up to 80% after three days running the MDC. Furthermore, membranes with smooth, flat surfaces outperformed membranes with unique topologies and fluctuating lateral feature sizes (Lopez Moruno, 2018). Due to the high ionic conductivity of the flat membranes, these membranes were able to outperform those with different topological patterns and, therefore, yield higher desalination rates and power output.

In conclusion, non-fluorinated membranes serve as an alternative to high-cost ion exchange membranes, which are typically manufactured with perfluorinated or partially fluorinated materials, dramatically decreasing the cost of the membrane (Yee et al., 2012). Synthetic polymers such as polyimides have been shown in research to be capable of assuming a wide range of chemical structures, making their synthesis in a laboratory setting more practical (Ivanov et al., 2018). Polyimides, including partially fluorinated and non-fluorinated polymers, also boast high mechanical strength as well as chemical and thermal stability: qualities of importance when utilizing membrane technology (Ivanov et al., 2018). Therefore, a possible solution for minimizing the cost and maximizing the efficiency of membranes would be for an MDC to include membranes developed from commercially available non-fluorinated or partially fluorinated polyimides. The process of fully fluorinating membranes is an expensive step in their development, often the result of inflated costs (~\$700/m^2), so limiting this step in their manufacturing should offer reduced costs for an MDC with partially/non-fluorinated membranes (Pasupathi & Maiyalagan, 2021). The results from these membranes are similar to those of Nafion, specifically, but their costs can be dramatically reduced nonetheless (Ivanov et al., 2018). Due to the fact that the ion exchange membranes are inherently the most expensive part of the MDC, minimizing their cost contributes greatly to the overall financial expense of building the MDC system.

MDC Configurations

Traditional Three-Chambered Cell

The MDC configurations discussed in this chapter are all derivatives of the three-chambered, chemical catholyte MDC designed by Cao et al., (2009). This MDC is a three-chambered polycarbonate shell that uses an anolyte of sodium acetate and a nutrient buffer, and a catholyte of ferricyanide and a potassium buffer solution (Figure 13).

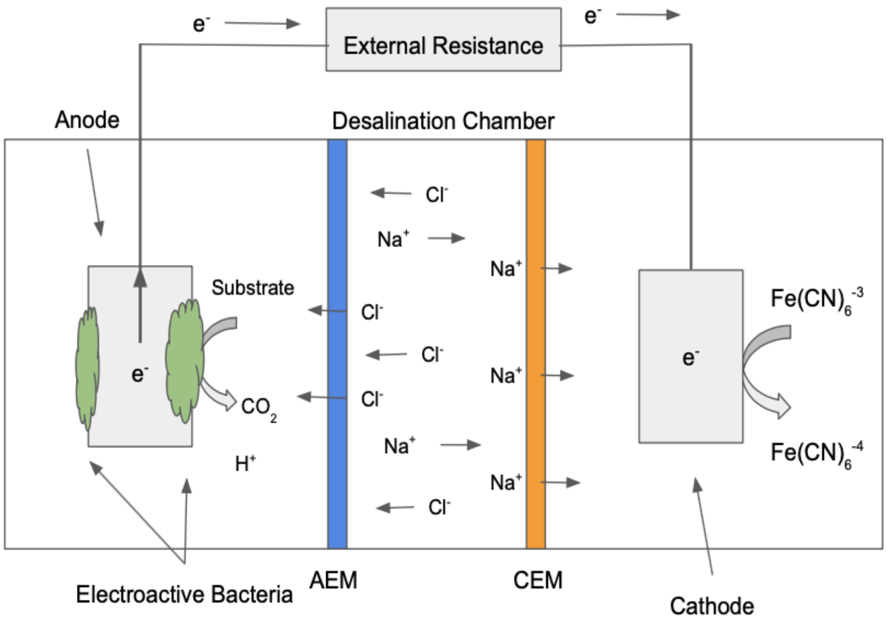


Figure 13. Three chambered MDC based on Cao et al.,

To activate the MDC, anode inoculum is obtained from an active MFC, and acclimated by running the MDC as an MFC by using only one cation exchange membrane. The volumetric ratio of anolyte to desalinated sample in this experiment was 100:3, so the change in the ionic concentration of the anolyte was negligible (Cao et al., 2009). During operation, the MDC produced a maximum voltage of ~600 mV and a maximum current of 3 mA using an initial salt concentration of 20 g/L (Cao et al., 2009). The maximum desalination capacity of the MDC was 93 ± 3% salt removal for an initial salt concentration in the desalination chamber of 35 g/L (Cao et al., 2009). The MDC designed by Cao et al., (2009) was a proof of concept that demonstrated the potential of MDC technology, however the researchers stated that the design choices for the original model, like the ferricyanide catholyte, would not be suitable for commercial desalination. Therefore, it is important to explore the different configurations discussed in this paper.

The desalination capacity and energy generation of this MDC is the benchmark by which we are comparing the other configurations of the MDC.

Air Cathode

The air cathode MDC has a similar basic construction to the traditional MDC (Figure 14). The air cathode MDC designed by Mehanna et al., (2010) has three cylindrical chambers that make up the anode, cathode, and desalination chamber. An anion exchange membrane joins the anode and desalination chambers, while a cation exchange membrane joins the cathode and desalination chambers. Ammonia-treated carbon cloth was used for the anode and a platinum and polytetrafluoroethylene-coated carbon cloth was used for the cathode. In this configuration, the cathode is left exposed to the air, so oxygen in the air serves as the final electron acceptor for the reduction reactions within the cell, thus driving desalination.

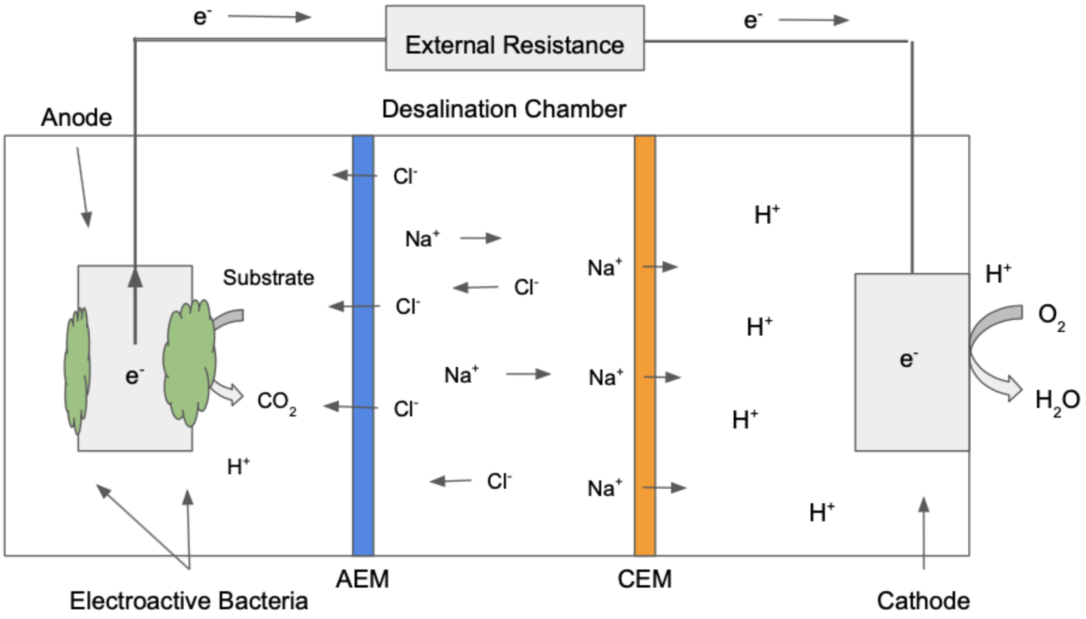


Figure 14. Air cathode MDC configuration.

Similar to the MDC designed by Cao et al., (2009), the anode chamber in the air cathode MDC was inoculated from an existing MFC, and the anolyte consisted of sodium acetate in a phosphate-buffered saline (PBS) solution (Mehanna et al., 2010). The air cathode used a catalyst (platinum), which is an expensive addition to the system and could be impractical to use on a large scale due to the inflated cost (Wen et al., 2012). The air cathode MDC designed by Mehanna et al., (2010) was able to achieve a maximum of 63% reduction in water salinity from a solution with an initial salt concentration of 20 g/L. The system was also able to produce a maximum voltage of ~450 mV and a maximum current density of 2.80 ± 0.1 A/m^2 (Mehanna et al., 2010). One of the benefits of the air cathode MDC is that it demonstrates the feasibility of oxygen as an oxidizing agent at the cathode. This is important because oxygen is relatively cheap and abundant, which would help with the feasibility of scale up. Conversely, the air cathode made use of a platinum catalyst at the cathode, which is relatively expensive and would not be feasible for implementation in a larger scale system.

Biocathode

The biocathode has a similar construction as the traditional MDC proposed by Cao et al (2009) (Figure 15). The design includes a cathode, anode, and desalination chamber, each separated from one another by an ionic exchange membrane. The electrodes were composed of uncoated graphite or carbon cloth and the cathodic biofilm replaced the expensive catalyst or ferricyanide catholyte.

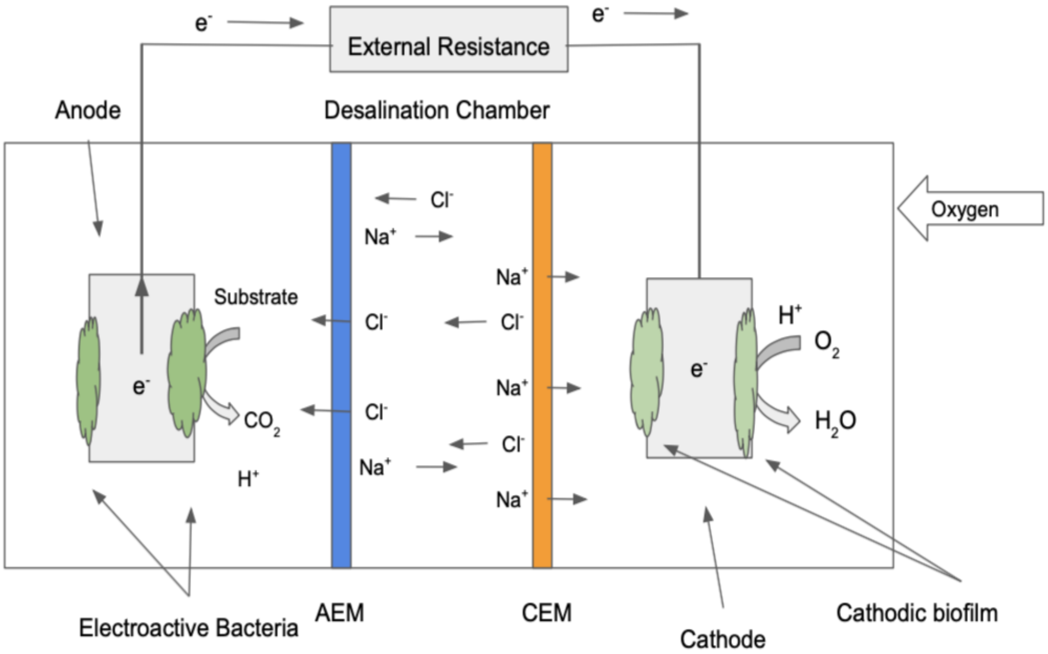


Figure 15. Biocathode MDC configuration.

In a study conducted by Arana and Gude (2018), the microalgae *Chlorella Vulgaris* was selected as the biological component in the biocathode because of its tolerance to high levels of CO_2 and its ability to efficiently convert CO_2 using photosynthesis (Arana & Gude, 2018). This biocathode MDC used a microbial sludge from a wastewater treatment plant in a synthetic wastewater solution for the anolyte. The catholyte consisted of *Chlorella Vulgaris* in a sodium bicarbonate solution. The biocathode MDC produced a maximum voltage of 256 mV from an initial salt concentration of 35 g/L with a microalgae suspension in the cathode chamber with 0.2 absorbance (Arana & Gude, 2018). One of the main benefits of the biocathode MDC over the other MDC models is that *C. vulgaris* can be harvested for different uses such as the production of biofuels like biodiesel. Arana and Gude (2018) recorded a maximum biomass growth rate of 72.6%, which indicates that the biocathode MDC can produce a useful amount of biomass to be harvested. The study also mentioned that based on the specific energy of the biomass, the energy produced by the MDC, and the energy saved by desalination, the net energy benefit of the biocathode MDC is on the order of a kWh/m^3 (Arana & Gude, 2018). When comparing the energy benefit of the MDC to the 2.2 kWh energy requirement of reverse osmosis technology to desalinate the same volume of water, the biocathode MDC is a viable means of desalination from an energy use perspective. One potential drawback of the biocathode system is that the biological component in the cathode chamber can be sensitive to pH changes in the cathode which could affect the biomass growth rate or the biological contribution to the efficiency of the cell.

Stacked Membranes

The final MDC configuration examined by the team was the stacked desalination chamber setup shown in Figure 16. The stacked desalination chamber MDC that was constructed by Chen et al., (2011) was adapted from an air cathode MDC. It uses a platinum and polytetrafluoroethylene coated carbon cloth cathode, and a carbon cloth anode. The anolyte was composed of sodium acetate in a nutrient buffer and the catholyte was a potassium buffer solution.

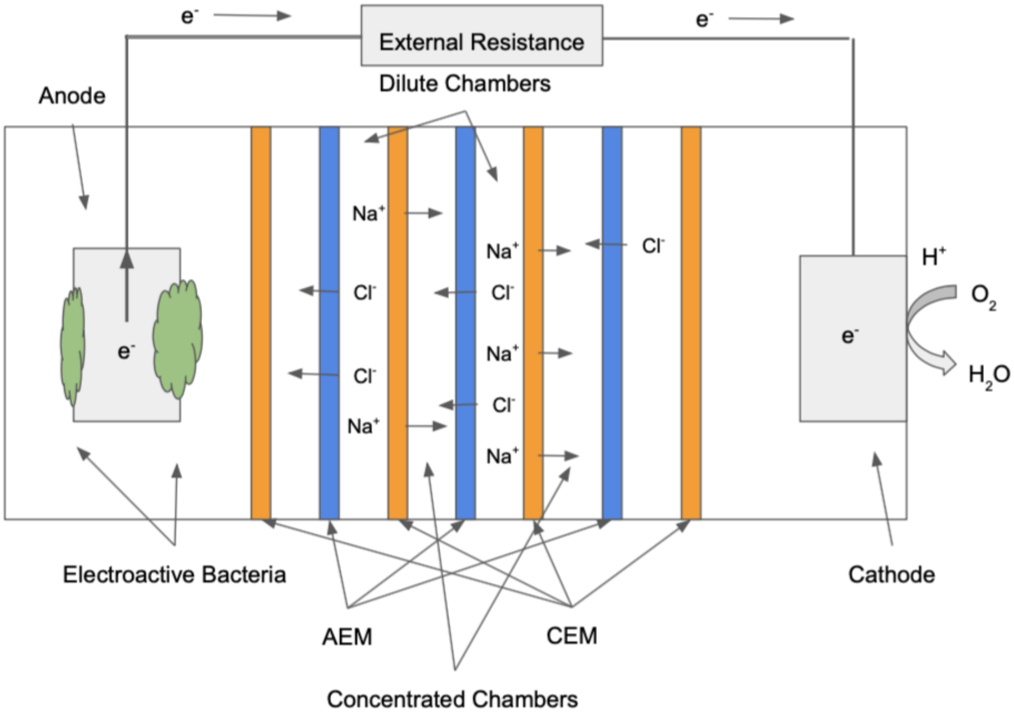


Figure 16. Stacked MDC configuration.

According to Chen et al., (2011), the concept including multiple desalination chambers was introduced in order to mimic electrodialysis, which is a membrane desalination technique involving the use of an electrical potential gradient to move ions out of solution (Gude, 2018). Electrodialysis cells are known as stacks and typically contain at least a few cell pairs in bench-scale experiments (Mohammadi et al., 2021). The 3-MDC chamber stacked configuration generated a maximum current of 4.67 mA and a maximum desalination capacity of 72.1% (Chen et al., 2011). The researchers noted that the electron transfer efficiency of the cell and the total volume of the salt solution that is being desalinated increases with the number of desalination cells in the system. The main drawback of increasing the number of stacks is the increase of the internal resistance of the cell which would decrease the current that the system produces

The stacked desalination chamber MDC that was constructed by Chen et al., (2011) was adapted from an air cathode MDC. It uses a platinum and polytetrafluoroethylene coated carbon cloth cathode, and a carbon cloth anode. The anolyte was composed of sodium acetate in a nutrient buffer and the catholyte was a potassium buffer solution.

The main difference between the air cathode and stacked configurations is the use of multiple desalination chambers between the anode and cathode chambers. For this study, a desalination chamber was defined by a chamber with an anion exchange membrane on the side closest to the anode chamber and a cation exchange membrane on the side closest to the cathode chamber. In between each of the desalination chambers is a chamber where the ions moving out of the desalination chambers migrate to. According to Chen et al., (2011), the concept including multiple desalination chambers was introduced in order to mimic electrodialysis, which is a membrane desalination technique involving the use of an electrical potential gradient to move ions out of solution (Gude, 2018). Electrodialysis cells are known as stacks and typically contain at least a few cell pairs in bench-scale experiments (Mohammadi et al., 2021). The 3-MDC chamber stacked configuration generated a maximum current of 4.67 mA and a maximum desalination capacity of 72.1% (Chen et al., 2011). The researchers noted that the electron transfer efficiency of the cell and the total volume of the salt solution that is being desalinated increases with the number of desalination cells in the system. The main drawback of increasing the number of stacks is the increase of the internal resistance of the cell which would decrease the current that the system produces (Chen et al., 2011). Based on this drawback, there is an optimum number of stacked cells which balances the volume of desalinated water with the cell's current generation (Chen et al., 2011).

Comparison of Configurations and Conclusions on Novel MDC Design

Upon review of the literature relevant to the design and construction of a typical MDC, the types of electrodes, ion exchange membranes, electroactive bacterial species, and three major MDC configurations have all been evaluated. In order to maximize the desalination and energy-producing potential of an MDC that is suitable for implementation within water-stressed countries of sub-Saharan Africa, the cost and the feasibility of the MDC's construction have been prioritized. As a result, the following tables (Table 7-9) summarize the results of this selection process and the decided upon design of an ideal MDC system given the scope and target region of this project.

Table 7. A comparison of the materials and construction for each MDC configuration explored.

Configuration	Cathode	Anode	Anolyte	Catholyte
Traditional (Cao et al., 2009)	Carbon Felt	Carbon Felt	Sodium acetate in nutrient buffer	Potassium ferricyanide
Air Cathode (Mehenna et al., 2010)	Platinum polytetrafluoroethylene coated carbon cloth	Ammonia treated carbon cloth	Sodium acetate in nutrient buffer	Potassium buffered saline solution
Biocathode (Arana & Gude, 2018)	Carbon cloth	Carbon cloth	Synthetic wastewater (glucose in nutrient buffer)	*Chlorella vulgaris* in sodium bicarbonate solution
Stacked Membrane (Chen et al., 2011)	Platinum and polytetra-fluoroethylene coated carbon cloth	Carbon felt and graphite rod	Sodium acetate in nutrient buffer	Potassium phosphate buffer

Table 8. A comparison of the parameters of importance for each MDC configuration explored.

Configuration	**Desalination Capacity**	**Voltage Generation**	**Current Generation**
Traditional (Cao et al., 2009)	93 ± 3% salt removal (35 g/L)	600 mV (20 g/L)	3 mA (20 g/L)
Air Cathode (Mehanna et al., 2010)	63% salt removal (20 g/L)	450 mV (20 g/L)	2.80 A/m^2 (5 g/L)
Biocathode (Arana & Gude, 2018)	47.1% salt removal (35 g/L)	256 mV (35 g/L)	325 mA/m^3 (35 g/L)
Stacked Membrane (Chen et al., 2011)	~70% salt removal (20 g/L)	-	4.67 mA (20 g/L)

Table 9. A summary of the components and configuration selected for a novel MDC design.

Component	**Selection**
Electrodes	Carbon felt/paper/plates
Membranes	Non-fluorinated/partially fluorinated polymers (i.e., synthetic polyimides)
Electroactive Bacteria	*Actinobacteria* or *Proteobacteria*
Configuration	Traditional, three-chambered MDC

Based on the data available and the comparisons made between multiple MDC configurations and material profiles, an ideal design for an MDC system to be implemented into water-stressed regions within sub-Saharan Africa should minimize cost and design complexity while maximizing the desalination and energy production of the cell. Carbon electrodes are not only inexpensive on small and large scales, but they can be fashioned into many different shapes and forms (i.e., plates, felt, paper) in order to maximize the effective surface area available to the electroactive biofilm for electron transport throughout the cell. Carbon electrodes are also good electrical conductors, resistant to corrosion, and highly durable attesting to their suitability for reliable long-term desalination systems. These electrodes are among the most commonly used in microbial desalination so their inclusion in a novel MDC system for sub-Saharan Africa appears to be the most ideal considering the abundance of information available on their construction, use, and implementation in desalination technology.

Based on the high cost of membranes, the overall financial expense associated with the MDC system is determined greatly by the cost of its membranes. Therefore, this review has concluded that partially or non-fluorinated membranes, specifically synthetic polyimides membranes, are an ideal solution for minimizing the cost of the MDC. Furthermore, flat, smooth membrane surfaces have yielded higher rates of desalination and power output due to their high ionic conductivities compared to membranes with topological patterns/non-smooth surfaces. The overall high mechanical strength and stability of these membranes also makes them appropriate materials for the design of a sustainable, long-lasting MDC system. Furthermore, the electroactive bacteria selected for the MDC system include *Actinobacteria* or *Proteobacteria* based on their excellent desalinating and energy producing capabilities in the context of MDCs.

The major materials necessary for these construction of MDCs of this design, mainly the carbon electrodes and membranes, would have to be provided from some outside source, as this method would prove to be far more efficient and feasible than importing the raw materials and producing the needed supplies locally. The technology required to generate these components of the MDC would not be suitable for the coastal communities that this desalination system intends to support. The synthesis of the membrane material alone would require specialized infrastructure to produce these materials en masse. Ideally, the materials for the MDC would be manufactured at the same site, thereby improving the efficiency of their production and transport to target regions. Identifying possible suppliers and manufacturers of these materials would be the primary goal of future research aiming to implement this proposed technology.

That being said, acquiring cultures of Proteobacteria or Actinobacteria may be able to become a more localized practice. One study in particular has highlighted the abundance of Actinobacteria in Algerian ecosystems, thus avoiding the need for intercontinental support (Djinni et al., 2019). Also, Proteobacteria are often found in abundance in soil, providing yet another source for the collection of this bacterial species (Spain et al., 2009). Therefore, identifying local sources of bacteria to be used within the MDC system may prove to be more feasible than manufacturing other materials like electrodes or membranes locally.

The traditional MDC proposed by Cao et al., (2009) had the best desalination performance out of all of the configurations reviewed. Based on its desalination capacity, this is the configuration that would be selected for scale-up testing, however the researchers mentioned that the use of ferricyanide would be inacceptable for practical use of the MDC. This is likely due to its cost and its aquatic toxicity. In order to implement the traditional MDC at production scale, work would need to be done to find a catholyte that functions like ferricyanide by allowing for the control of the potential of the cathode chamber. This catholyte material would ideally be inexpensive and nontoxic, like the oxygen used in the air cathode.

The startup process for the MDC involves establishing the electroactive biofilm. This first step is to either inoculate the MDC with bacteria from an existing MDC or MFC, or to encourage the growth of any electroactive bacteria present in a wastewater sample by using an external power source to run a current across the MDC circuit (Cao et al., 2009). This encourages electroactive bacteria that are in solution to aggregate on the anode and form the biofilm that will be the source of the cell's power. The biofilm establishment, or acclimation process lasts until the cell produces a stable and reproducible peak voltage (Cao et al., 2009).

Once the MDC is running, the organics in the wastewater will become depleted as the cell continues running. Similarly, if the electron acceptor used is solution based, as in the traditional MDC, the chemical oxidizing agent will become depleted as well. So at regular time intervals the solutions from all three chambers will need to be cycled out and replaced with fresh solutions to keep the cell running at its best performance (Cao et al., 2009). One approach to managing the cycling of the solutions would be to use large reservoirs of each solution and pump them at a constant rate through the MDC to turn this traditionally batch process into a semi-continuous process (Carmalin Sophia et al., 2016).

In order to keep the MDC running at its maximum capacity, it will also be important to replace or treat the membranes to prevent any fouling that may occur. This fouling could be in the form of biological growth from the bacteria in the anode chamber or scaling caused by the buildup of ions that are unable to pass through the membrane (Carmalin Sophia et al., 2016). The membranes would need to be treated or replaced on a regular basis to keep the desalination cell running at maximum desalination capacity.

SOCIAL IMPACT

Public Health

Human Health and Disease

Water is a vital and daily necessity for people all over the world. In sub-Saharan Africa, water use includes bathing, domestic activities, cultural, and religious practices (Osunla et al., 2017). A major concern of water contamination is disease transmission. The global MDG target for water sanitation has not been met for almost 700 million people (WHO, 2015). Furthermore, in sub-Saharan Africa less than 50% of the population uses improved drinking water sources for daily use (WHO, 2015). Improved drinking water sources secure the water from exterior contamination, specifically from fecal matter.

Accessibility to water and sanitation is an essential human right. However, a large quantity of people around the world still are unable to access these basic needs. Poor drinking water and sanitation is the world's second leading cause of death in children (Armah et al., 2018). Roughly 10,000 people die daily from water and sanitation related diseases, and thousands more suffer from a wide variety of impairing illnesses (Armah et al., 2018). The most common health risks associated with contaminated drinking water include typhoid fever, diarrheal diseases, cholera, dysentery, and cryptosporidiosis (Anthonj et al., 2018).

Additionally, the act of open defecation contributes to poor water sanitation and contamination in various regions of the world, including sub-Saharan Africa. Open defecation is the practice of discharging bowel movement in fields, trenches, and waterways with lack of proper disposal. Around 892 million of the world's population practice open defecation (Saleem et a., 2019). In sub-Saharan Africa, open defecation is a major source of pathogen transmission that causes diarrheal diseases, with *Escherichia coli* being the most common pathogen; human gastrointestinal tract infections are also caused by the consumption of contaminated drinking water (Gwimbi et al., 2019). Furthermore, poor socio-economic status of communities further exacerbates open defecation rates and unsanitary practices that increase the transmission rate of bacterial pathogens in water drinking sources (Gwimbi et al., 2019). Poor socio-economic status contributes to the lack of infrastructure as well, eventually leading to increases in practices of improper sanitation and higher rates of diarrheal diseases (Figure 17).

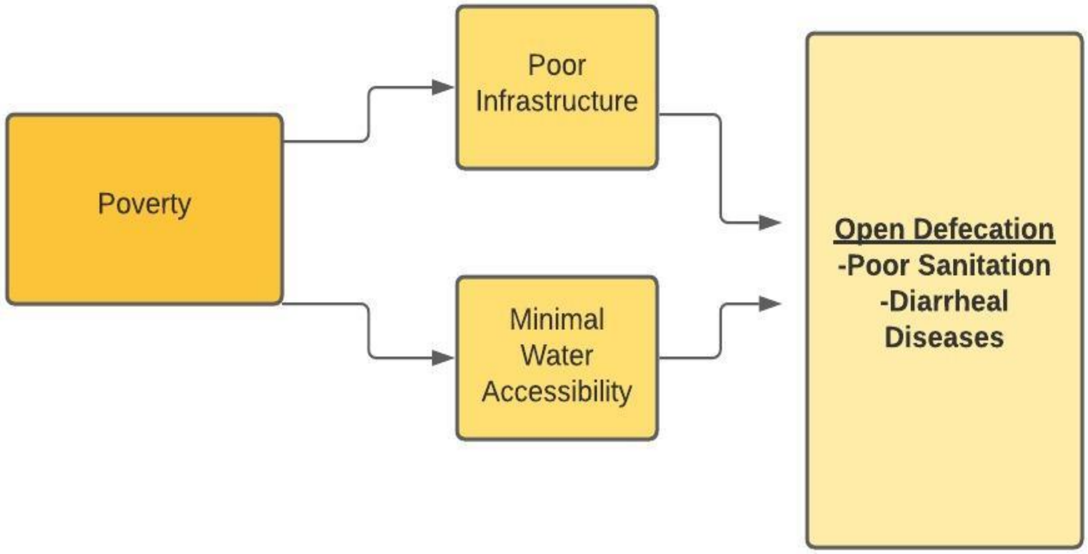


Figure 17. Flow chart displaying the effects of poverty on water sanitation, hygiene, and health.

Women's Health

Research by the United Nations Millennium Project indicates that within households, the responsibility of collecting water falls primarily on women (Figure 18). In addition, studies have estimated that 3.36 million children and 13.53 million young adults were responsible for collecting water for their households, with a collection time greater than 30 minutes (Graham et al., 2016). Daily water collection has a huge impact on the health and mental well-being of both women and children. Many children faced high levels of fatigue and trouble concentrating in school due to the daily requirement of water collection (Graham et al., 2016). In addition to fatigue negatively impacting health, musculoskeletal damage, early degenerative bone, and signs of soft tissue damage can occur overtime due to carrying heavy water consistently (Graham et al., 2016). The act of walking long distances holding large quantities of water is a highly time consuming process and requires lots of energy. Water transport places a major constraint on metabolism, and places pressure on the skeletal system which can later result in arthritis (Graham et al., 2016). The stress from transporting water activates the body's sympathetic nervous system, and consequently releases hormones such as cortisol and betatrophin that slow down metabolism and increase abdominal fat.

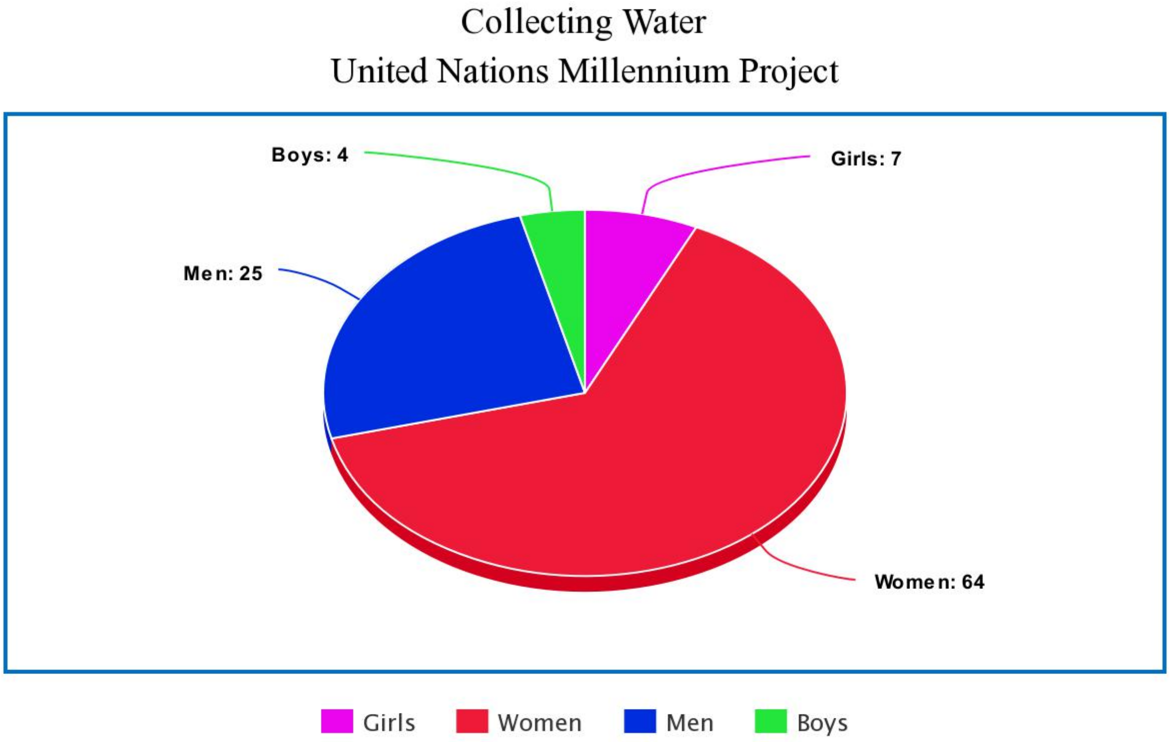


Figure 18. Research findings report that the household responsibility for collecting water falls primarily on women in the household. Adapted from the United Nations Millennium Development (2015)

Contaminants within drinking water pose significant health threats to pregnant females. Studies show that high levels of arsenic found in drinking water can led to abortion, stillbirth, and infant mortality (Campbell et al., 2015). Furthermore, high levels of fluoride in drinking water increases chances of low birthweight and skeletal fibrosis in newborn infants (Campbell et al., 2015). Industrial contaminants found in drinking water, such as metals, have severe adverse effects on neurodevelopment. Pregnant women who are exposed to potassium, mercury, and lead not only face increased chances of spontaneous miscarriages, but also congenital malformations in the fetus. These metals overtime can also cause renal failure, gout, hypertension, and decreased fertility within affected females (Campbell et al., 2015).

Violence Against Women

The effects of poor accessibility to water extend to both women's physical health and mental health. During their water-fetching routines, women are often exposed to physical and sexual violence. This risk is particularly exacerbated when women are walking alone and for long distances (Pommells et al., 2018). Since water is a vital human need, in regions that are water scarce perpetrators have ample opportunity to subject women to violence. Moreover, the routes that women take to go get water are widely known, further exposing them to these attacks. Women in water-scarce regions in sub-Saharan African nations often report that along their trails men would be waiting for them, particularly if rape is an accepted practice in their culture (Pommells et al., 2018).

The risk of sexual violence is also present in regions where open defecation is widely practiced. Open defecation is the practice of defecating in an open area without proper disposal of human waste. This is typically practiced in water scarce regions due to the lack of sanitation facilities in the household (Saleem et al, 2019). To preserve their privacy and maintain their dignity, women often walk to remote, dark places where they may defecate privately.

However, this leads women to be isolated and vulnerable (Ngwu, 2017). Similarly to when women go to fetch water, the men prey on the fact that women will want to preserve their privacy and wait to prey on them. As such, studies have shown that women are twice more likely to experience non-partner sexual violence due to open defecation (Jadhav, 2016). While having household access to clean water will not remove the socially acceptable nature of rape, it will remove the opportunity that men have to subject women to the impacts of rape.

Finally, the lack of accessibility to water exacerbates pre-existing gender roles. In many sub-Saharan African countries, gender roles are an important factor in the social structure. Women are seen as responsible for providing their families with sources of water (Pommells et al., 2018). Because water is such a vital resource for daily life, women have a huge responsibility to ensure that their families can continue to effectively function. In many studies, women have reported that when they are unable to provide water to their families, they have been at risk for spousal abuse (Pommells et al., 2018).

Impact of Climate Change

Women in these studies have reported that whenever water is more scarce, due to the drying season or climate change, it becomes more difficult to find consistent sources of water for their families' consumption. In addition, water is required for women to fulfill many of their socially required duties, such as cleaning, cooking, and bathing. Thus, when water is scarce, women become unable to fulfill their husbands' expectations and face increased risk of spousal abuse (Sommer et al, 2015).

Due to the increased reports of climate change, this risk of domestic violence may very well increase for these women. This is because climate change has significantly decreased the availability of freshwater in rural sub-Saharan African countries. According to the British Geological Survey, climate change will result in large local changes in rainfall; rainfall is expected to decrease 30% in southern Africa (Bailey, 2011). In focus groups, women have described the domestic violence by “slapping, kicking, and hitting” and noted that both pregnant and non-pregnant women experienced this abuse (Pomells et al, 2018). It is important to note that climate change exacerbates the risk of violence to women. Though it does not inherently create the opportunity for women to be domestically abused, tackling its causes may decrease the opportunity of women being subjected to sexual abuse and domestic violence.

CONCLUSION

In order to combat the social impacts that regional lack of potable water has on coastal-Sub Saharan African communities, it is important that desalination efforts be made accessible. The combination of low-cost prefiltration methods with an optimized microbial desalination cell configuration and materials could prove to be a viable way to convert seawater into a localized source of potable water in these communities. The hypothesized desalination system has a prefiltration system acting as an initial step to filter seawater prior to routing it toward a microbial desalination cell. The simplified model in Figure 19 shows the flow and distribution of water in the proposed system.

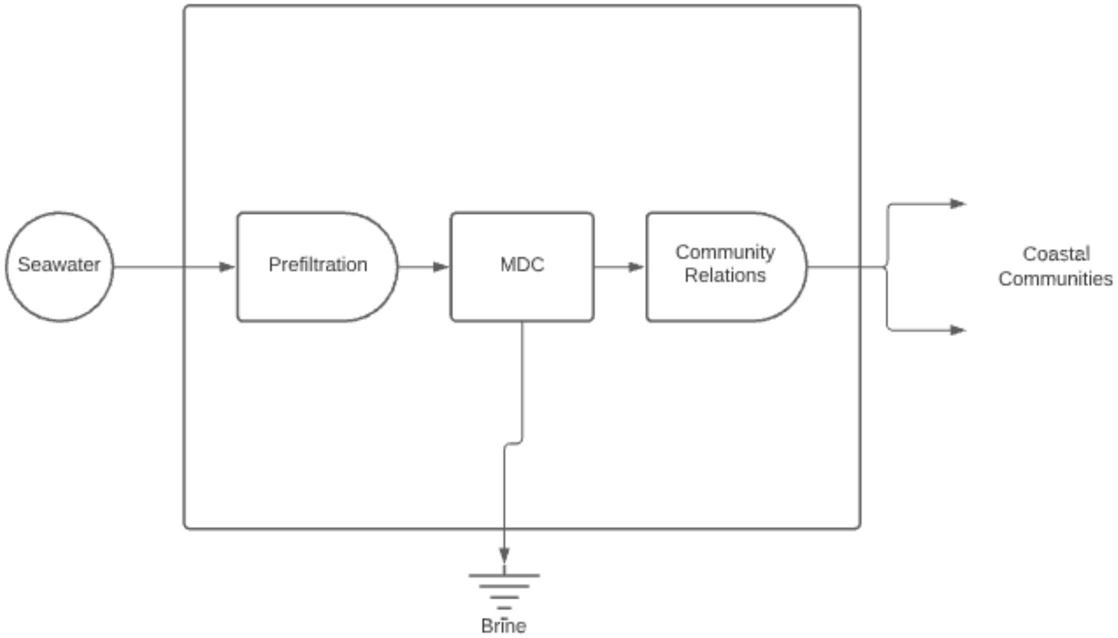


Figure 19. A process diagram for the proposed desalination system presented in this review.

The prefiltration and microbial desalination technologies we propose in this paper have not previously been tested in conjunction; therefore, the scale of the proposed solution is undetermined at this time. If further research is able to determine the appropriate scale, along with an optimized relationship among volume of water desalinated, cost, and maintenance requirements, the system may be specialized for implementation in sub-Saharan communities. If an effective system comes at a higher cost but can desalinate at a level sufficient for a community, the focus of the system can be to provide a central potable water source for larger regions.

For each component of the diagram in Figure 19, there are research questions to be addressed. Seawater composition of the coastal sub-Saharan African region must be analyzed for contamination levels of each water contaminant as detailed in the World Health Organization Guidelines for Drinking Water Quality (World Health Organization, 2017). Prefiltration system materials must be experimented with to determine the most effective contaminant removal. For the microbial desalination cell, various configurations and materials need to be tested to determine which result in the optimal system for minimizing cost and maximizing desalination rate and volume. Additionally, more sociological research is required to determine the type of system most likely to be adopted in the regions of interest and at what scale.

One additional consideration is the creation of a hypersaline brine byproduct by the MDC. Globally brine production from desalination plants exceeded commercial desalination volume by 50% as of 2019 (Jones et al., 2019). This brine may be harmful in large quantities if released into marine environments. Particular concern has been raised for the *P. oceanica* species of seagrass (Morillo et al., 2014). Luckily, the smaller volumes that are to be expected of a smaller-scale desalination system make solar evaporation a possible solution to this issue. Solar evaporation is the process of salt recovery from brine by the evaporation of water in shallow pools lined with clay or other impermeable substances (Morillo et al., 2014). Using solar evaporation, the liquid component in the brine would simply evaporate into the atmosphere leaving behind sea salt which may be sold commercially depending on the salt type (Pramanik et al., 2017).

As mentioned previously, our team had plans to begin researching some of these questions prior to the spread of COVID-19, which prevented us from collecting laboratory data. However, the sociological research that we then pivoted toward informed us greatly about the specifications that would be required of a system to use desalinated water in sub-Saharan Africa. Initially, we had thought to design a biological method of desalination to perform a similar function to traditional reverse osmosis desalination plants. Rather than addressing large-scale water scarcity, however, we learned that desalination would be better suited in our target region as a localized, smaller-scale solution for water access. Water scarcity, specifically in sub-Saharan Africa, has more to do with the lack of infrastructure to access freshwater available to the area than lack of freshwater itself (Fraiture, 2005). Additionally, as mentioned previously, problems such as sexual violence happen while women are walking long distances to get access to water (Pommells et al., 2018). This key information about the target region for implementation led the team toward discussions of a smaller, less centralized system design than had been previously considered. Future research on solutions for water scarcity in sub-Saharan Africa must take these facts into account as well. Consultation with water scarcity-affected communities beforehand will prove to be essential to finding the best technologies to address their needs.

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