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Article

Analysis of electrodialysis as a method of producing potable water

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SUMMARY

Only 1 percent of the water on Earth is available for human consumption and usage, and scientists predict that this severe shortage will affect the entire planet by 2050. To resolve this problem, we collected samples of ionized seawater from along the coasts of the San Pedro Channel and Santa Monica Bay and measured their respective total dissolved solids (TDS) every hour as it underwent electrodialysis until the measurement was under the acceptable TDS for drinking water. Our objective was to produce large amounts of purified water through the separation process of electrodialysis, which if successful, would be advantageous to improving the water shortage crisis. Our hypothesis was that after saltwater undergoes electrodialysis, the time it takes for the Na^+ cations to pass through the cathode exchange membranes and Cl^- anions to pass through the anode exchange membranes will decrease as the voltage from the Direct Current (DC) power circuit is increased, which in turn increases the electric current. Our experimentation showed that the final recordings of the deionized water's TDS were under the acceptable TDS for consumable water for all experiment trials. The results of this experiment may be beneficial in increasing the percentage of water available for human consumption.

INTRODUCTION

One of the most destructive global issues affecting all of Earth's inhabitants is water contamination and shortage, a problem that has existed since the 1800s during the Industrial Revolution when heavy supplies of clean water were needed (1). Whereas only 9% of the global population experienced chronic water shortages in 1960, the number surged to 35% in 2005 (1). To this day, global water crises persist, affecting every region of the planet that serves as a habitat for billions of organisms and species. Solutions are needed to restore the Earth before its water is exhausted.

With just 1% of Earth's water available, scientists aim to increase this supply through synthetic water production (2). While mixing hydrogen and oxygen theoretically creates water, the need for an external energy source makes large-scale production unviable. Freshwater generators use the energy from mixing freshwater and saltwater to drive the reaction, but it carries risks akin to experimental nuclear fusion reactors, making it unsafe for large-scale water production (3, 4).

Since it is not realistic to manufacture water on a large scale, scientists began investigating safer methods of producing water. Solar distillation is one possible method, where water is first heated to the point of evaporation using the sun's energy, and then water vapor rises and condenses on the glass surface, which allows for collection (5). During this process, heavy metals and salts are separated from the water (5). Other studies involve using nanoparticle polymer membranes to absorb specific valuable particles altogether (6). Although these methods undeniably produce clean water, such methods are flawed. For one, solar distillation only works during the hours of the day when sunlight is detectable. The materials can also be difficult to obtain, especially since areas that are most affected by global water deprivation are those in poverty (7). Finally, the distillation process's waste stream, which contains high concentrations of salts and impurities can contribute to environmental pollution if not properly disposed of (5). Processes that do dispose of waste, such as reverse osmosis, where the waste stream is often injected into deep wells, are then prone to other issues including membrane fouling, where particles are deposited onto the membrane pores, restricting the flow of liquids through these pores (8,9). Thus, scientists have turned to water electrodialysis as a feasible method to produce usable water without additional damage and inconveniences.

Electrodialysis involves separating the differently charged ions found in water through the use of ion exchange membranes (10). Taking advantage of this, we wanted to know if it was possible to separate the high levels of salt in seawater and how changing the voltage parameters of the process would affect the speed and performance of electrodialysis. We predicted that after saltwater enters the technique of electrodialysis, the time it takes for the Na+ cations to pass through the cathode exchange membranes and Cl- anions to pass through the anode exchange membranes will decrease as the voltage from the Direct Current (DC) power circuit is increased, which in turn also increases the electric current through Ohm's law that states that electrical current flowing through an electrical circuit is directly proportional to the voltage (11). A DC power circuit is necessary to alter the initial voltage conditions, as well as to facilitate our experiment because the electrical potential forces the salt particles to move through exchange membranes, separating the ions from freshwater (12). The Total Dissolved Solids (TDS) of saltwater ranges from 10 ppt to 30 ppt (13). Through experimentation, we found that for all experiment trials, the final recordings of the deionized water's TDS were under the acceptable TDS for consumable water, which is anything under 0.5 ppt (14). The results of this experiment provide scientists with a probable method of generating usable water from seawater by filtering out the prevalent ions of seawater that make it unconsumable.

RESULTS

To test our hypothesis, we conducted 3 separate trials for this experiment. We assembled an apparatus with 7 (10 cm x 10 cm x 10 cm) cubic chambers, where a graphite anode was fixed next to the leftmost chamber and a stainless steel cathode was fixed next to the rightmost chamber. Then, for each trial, we filled each of the 7 chambers with the collected water and measured the total dissolved solids (TDS) of the chambers every hour until we reached a value of less than 0.5 parts per thousand (ppt), the acceptable range for consumable water (14). An odd number of containers was used since it was necessary to have one exchange membrane of each type (one for anions and one for cations) on both sides so that the container in between is composed of purely clean water. Although this experiment would also be feasible with 3 or 5 chambers, we wanted to test the variability of electrodialysis and whether different chambers would have varied ppt values.

We first conducted two trials using the same initial voltage parameter of 55 volts, but with independent samples of seawater from different locations (San Pedro Channel and Santa Monica Bay), to test the variability of our experiment. The initial TDS measurement of seawater was 25.6 ppt for the San Pedro Channel seawater sample **(Figure 1)**. The initial TDS measurement of seawater was 27.1 ppt for the Santa Monica Bay seawater sample **(Figure 2)**. By using a TDS meter to measure the ppt of the water in each of the 7 chambers at the end of every hour, we found that for both locations, the Na^+ cations and Cl^- anions contained in the seawater did pass through the cathode and anode ion exchange membranes, respectively **(Figure 3)**. Consumable deionized water was produced as a result in the concentration chambers between the exchange membranes, specifically in chambers 2, 4, and 6, since out of the 7 total chambers, the TDS values decreased in chambers 2, 4, and 6 but increased in chambers 1, 3, 5, and 7. For the San Pedro Channel sample, the final ppt values of chambers 2, 4, and 6 were measured to range from 0.2 to 0.4 ppt **(Figure 1)**. The same applied to chambers 2, 4, and 6 for the Santa Monica Bay seawater sample **(Figure 2)**. Because the ppt of chambers 2, 4, and 6 were all below 0.5 ppt, the data from any of these chambers all represent consumable water, so we are only discussing results from chamber 2 for the remainder of our experiments. Despite having varied initial TDS values, both experiments at 55 volts concluded after 9–10 hours, resulting in deionized water of 0.2 ppt in both trials' second chambers. This demonstrates how using the same voltage conditions results in electrodialysis behaving alike in both trials, regardless of the differing initial TDS conditions of the two saline feeds.

We further analyzed the effects varying voltage parameters would have on the time it takes for seawater to deionize by performing another trial using the same sample of seawater from the San Pedro Channel, but with the initial voltage being 82 volts. By increasing the voltage to a maximum of 82 volts, we investigated whether a higher voltage had any effect on the time required for electrodialysis to reduce the seawater's ppt to less than 0.5 ppt, all while ensuring that no damage occurred to the DC power circuit. We found that at the end of hour 5, the TDS value reached 0.2 ppt, which is within the appropriate range of consumable water **(Figure 4)**. At this

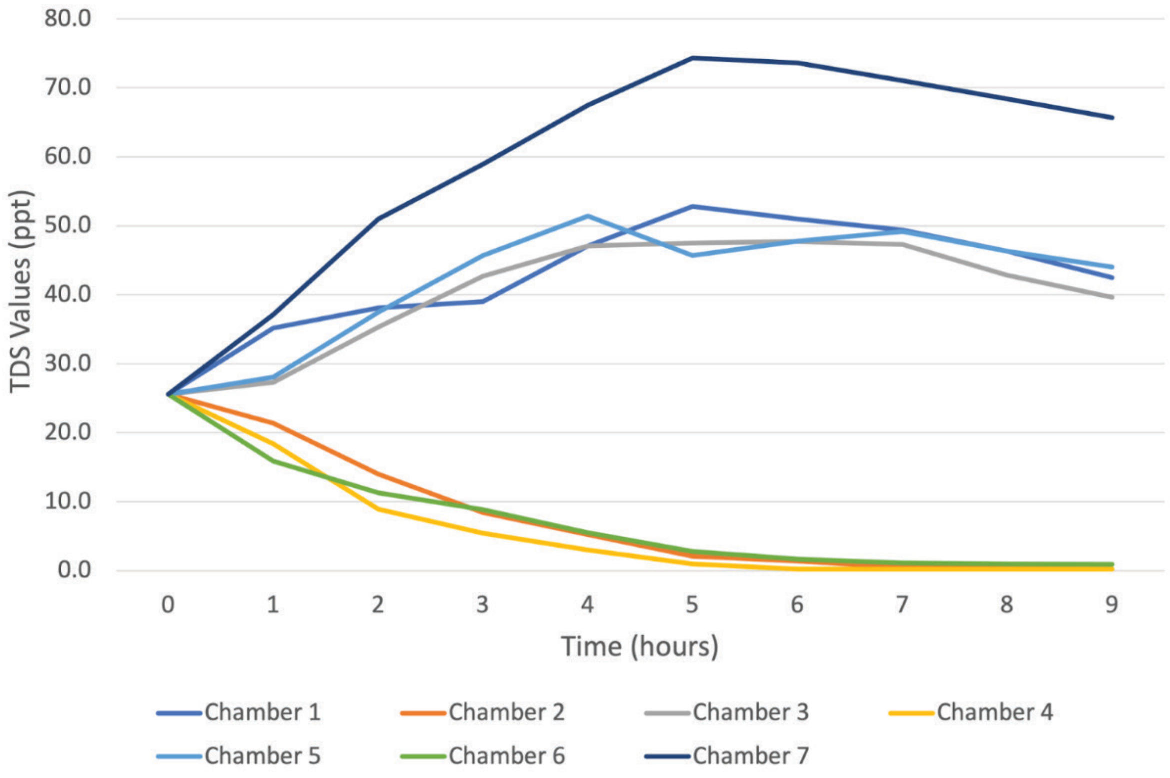

Figure 1: Changes in the TDS values of San Pedro Channel seawater as time increased at 55 volts. Line graph of TDS values from the Santa Monica Bay seawater sample in each of the 7 chambers at a voltage of 55 volts over a 9-hour period. A TDS meter was used to determine the ppt of the saltwater in the electrodialyzer every hour of the experiment until the value reached less than 0.5 ppt.

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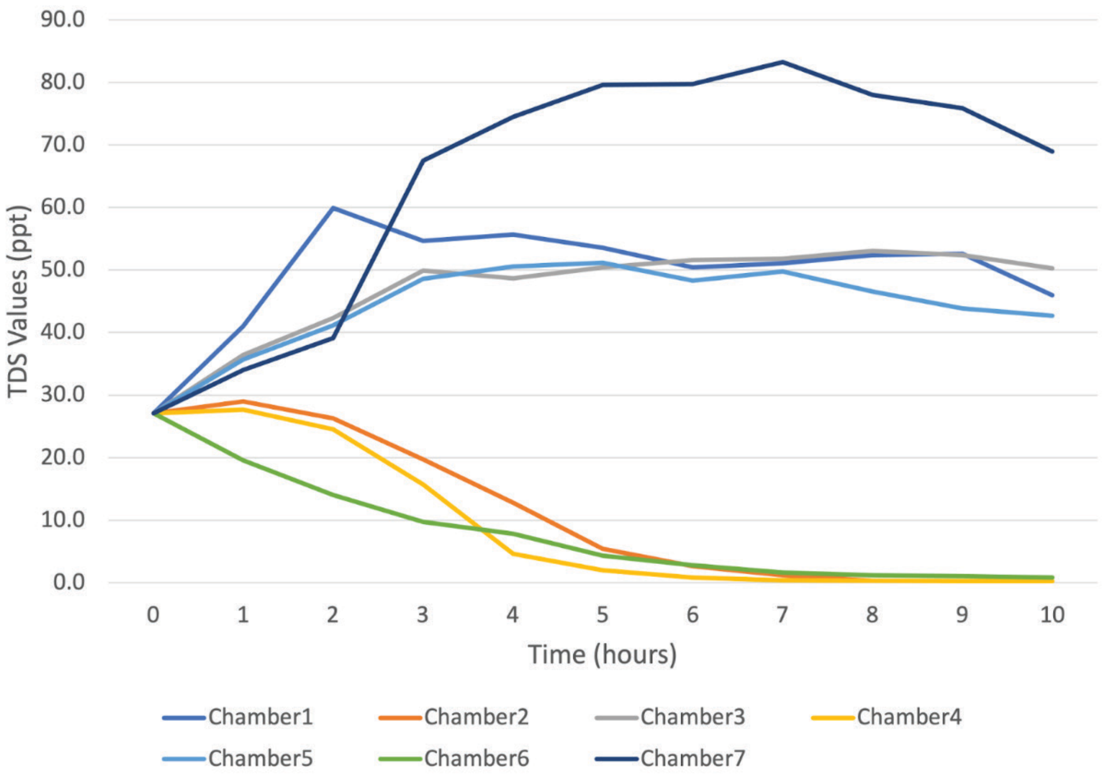

Figure 2: Changes in the TDS values of Santa Monica Bay seawater as time increased at 55 volts. Line graph of TDS values from the Santa Monica Bay seawater sample in each of the 7 chambers at a voltage of 55 volts over a 10-hour period. A TDS meter was used to determine the ppt of the saltwater in the electrodialyzer every hour of the experiment until the value reached less than 0.5 ppt.

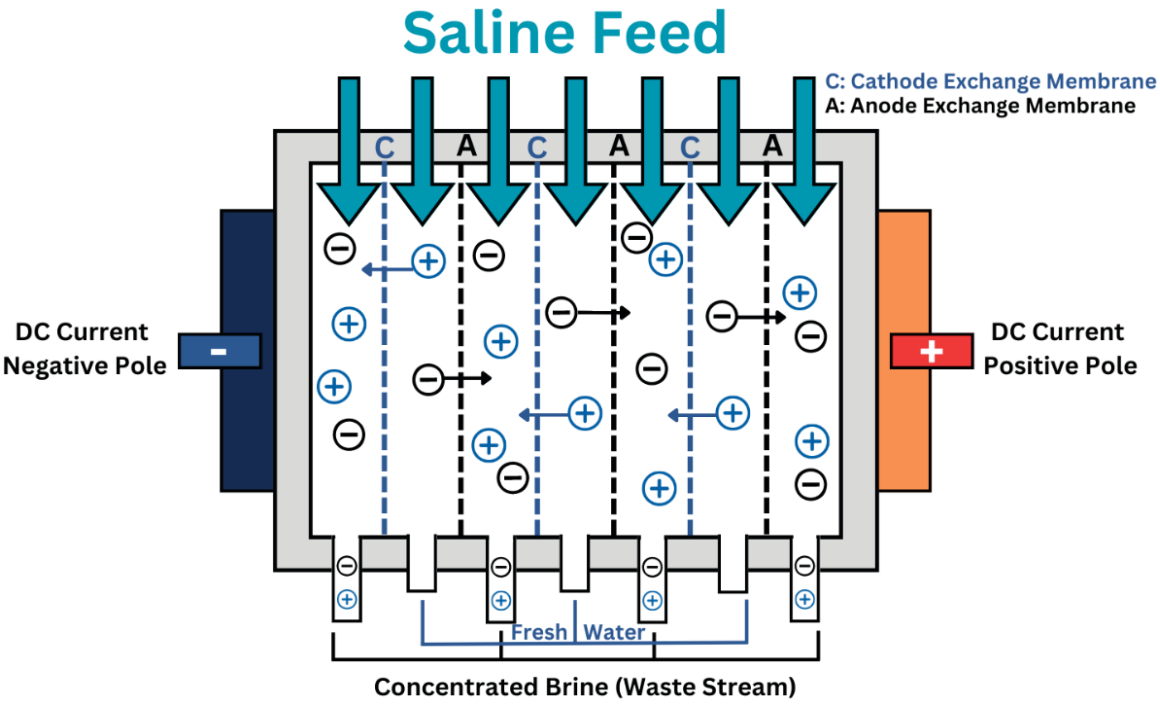

Figure 3: Illustration of the electrodialysis process for experiment trials 1, 2, and 3. Diagrammed view of what occurs inside the apparatus during electrodialysis at the molecular level. Cations (blue circles with pluses) pass through blue dotted lines labeled C (cathode exchange membrane). Anions (black circles with minuses) pass through black dotted lines labeled A (anode exchange membranes). Freshwater results in the 2nd, 4th, and 6th columns between dotted lines, and concentrated brine results in the 1st, 3rd, 5th, and 7th columns.

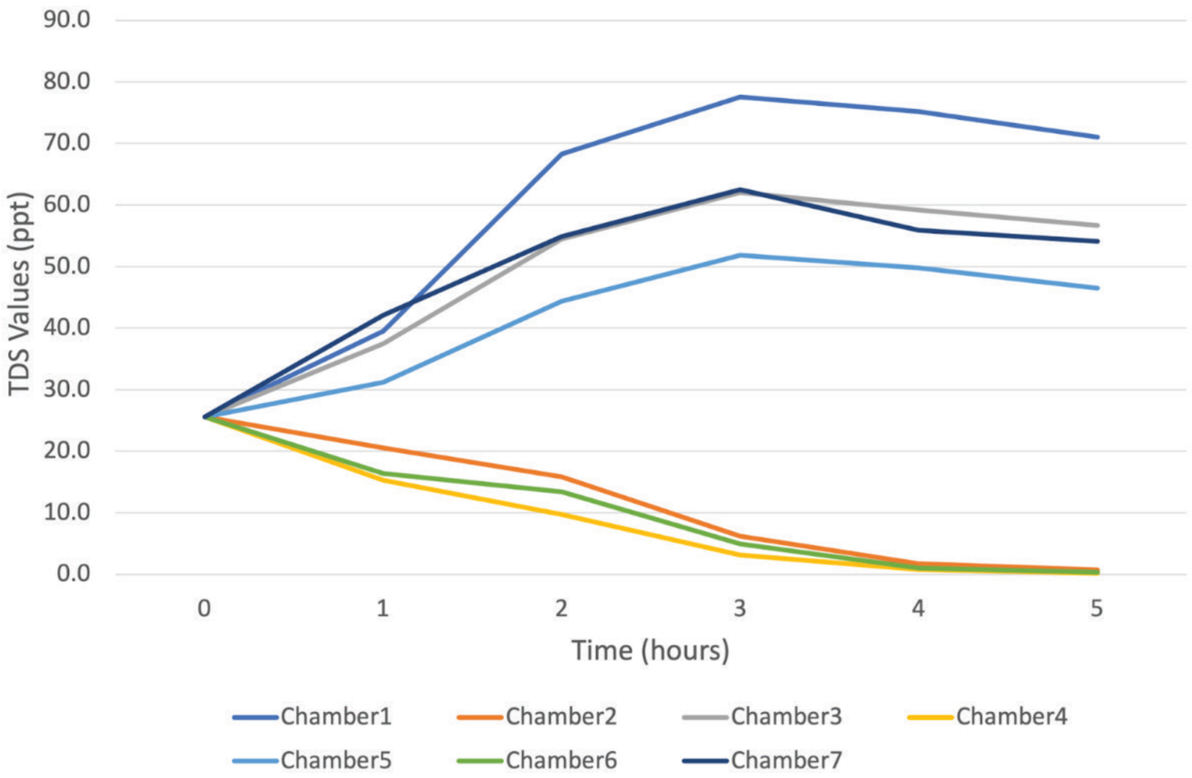

Figure 4: Changes in the TDS values of San Pedro Channel seawater as time increased at 82 volts. Line graph of TDS values from the San Pedro Channel seawater sample in each of the 7 chambers at a voltage of 82 volts over a 5-hour period. A TDS meter was used to determine the ppt of the saltwater in the electrodialyzer every hour of the experiment until the value reached less than 0.5 ppt.

voltage, electrodialysis was able to reduce the seawater's TDS to less than 0.5 ppt within 5 hours, whereas trials using a voltage of 55 volts required 9–10 hours **(Figure 5)**. Altering the initial voltage conditions through the DC power circuit played a central role in our experimentation since the greater the voltage, the higher the electrical potential energy available to drive the seawater ions through their corresponding exchange membranes. A greater voltage parameter thus led to a faster electrodialysis process, meaning more freshwater was produced from the same initial saline feed in a much shorter time.

DISCUSSION

In all experimental trials, the final TDS levels of deionized water remained within acceptable limits, with usage of 82 volts achieving this standard five hours faster than a voltage of 55 volts. Since ppt indicates the mass of a chemical per unit volume of water, the decrease in ppt from an initial measurement of 25.6 and 27.1 ppt to 0.2 and 0.4 ppt illustrates the reduction of ions and contaminants in the original sample of ocean water, which is made possible by the DC power circuit's provision of the electrical drive needed to separate ions from consumable water.

In all trials, chambers 2, 4, and 6 produced water with final ppt values of less than 0.5, indicating the electrodialysis process affected each chamber to relatively the same degree. However, there were variations in the degree to which the TDS decreased at each hour of the experiment. For example, the trial with the feed solution from San Pedro at 55 volts experienced the largest decrease in ppt from hour 2 to hour 3, at the beginning of the experiment. This observation correlated with previous research on electrodialysis, which found that longer work times led to decreases in the number of free electrons available, and fewer free electrons indicated slower movement of ion passage (15). Since we found that faster experiments correlated with higher DC power circuit voltages and that the electric current decreased with the number of free electrons, it is possible that in later parts of the experiment, the ppt did not decrease to the same degree as in earlier hours because of the reduction in the system's conductivity ability to transport electrons across membranes (14).

The best method to improve the efficiency of the electrodialysis process is to increase the voltage through the DC power circuit. Through experimentation, we found that increasing the voltage from 55 volts to 82 volts decreased the time needed by half. We chose such values as our parameters because increasing them even further would easily damage our device. However, at even 82 volts, we understand that a massive amount of electricity was needed to produce every liter of potable water (16). Not to mention, if we upscaled this project to produce enough water for a large population, even more electricity would be needed. To combat this issue, we could find the optimal voltage for producing the most amount of freshwater in the shortest amount of time. We could do so through the usage of mathematical models, such as possible Riemann sum approximations for different voltages. Additionally, to comply with larger demands, we can stack layers of ion exchange membranes on top of each other to increase efficiency, an idea noted by researchers at MIT

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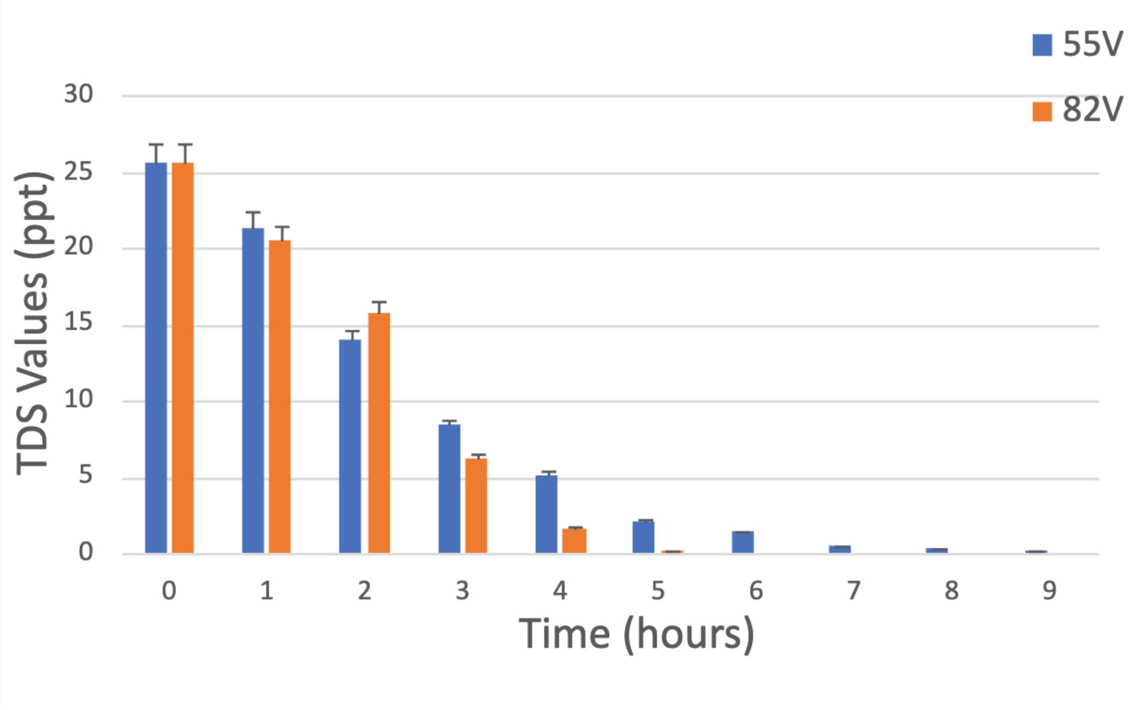

Figure 5: Comparison of the changes in the TDS values of San Pedro Channel seawater as time increased at 55 volts and 82 volts. Bar graph of the different TDS values found in chambers where deionized water was produced for trials 1 and 3. San Pedro Channel water entered the electrodialysis process at 55 volts for trial 1 (blue) and 82 volts for trial 3 (orange). Error bars represent the Standard Error of the Mean. A TDS meter was used to determine the ppt of the saltwater in the electrodialyzer every hour of the experiment until the value reached less than 0.5 ppt.

(17). By doing so, we would also be able to decrease the compartment sizes, turning the electrodialysis process into portable units that can supply families in times of need.

An additional downside to electrodialysis is its buildup, which can make maintenance an issue. In our experiment, we observed that chamber 1 produced a yellow hue and had a strong chlorine odor. We speculate that the yellow color can be attributed to the fact that cuprous oxide, often yellow, is deposited when concentrated amounts of chloride ions are exposed to the copper electrodes (18, 19). Future experiments must be conducted to validate this hypothesis. Additionally, we observed that the chamber nearest the cathode (chamber 7) obtained a milky white precipitate. We suspect that this was the $Mg(OH)_2$ precipitate because the Mg^{2+} cations, found in seawater (20), would have passed through the cathode exchange membranes and would be heavily concentrated in chamber 7. Future experimentation, such as collecting samples of the white residue and melting it to see if it corresponds with the melting point of $Mg(OH)_2$, should take place to verify this postulation.

This is one area where water filtration has an advantage over electrodialysis since its membranes allow the separation of contaminants and residue (21). To overcome this, we could incorporate a process called electrodialysis reversal, which drives ionic flow in the opposite direction periodically by reversing the negative and positive electrodes' polarities. This prevents buildups from occurring as it acts as a "backwashing" procedure to rid deposits (22). To rid other contaminants found in saltwater, such as other metals/salts and bacteria/viruses, additional procedures would need to be added. Before saltwater enters the electrodialysis process, it needs to first go through other treatments, such as reverse osmosis, which contains 0.1-nanometer pores that can easily filter out bacteria and viruses (14). We could also use nanoparticle polymer membranes designed by researchers at UC Berkeley to selectively remove other metals such as mercury, iron, or copper during desalination (6).

The byproducts of this experiment were H_2 gas, O_2 gas, and Cl_2 gas, though only H_2 gas was collected. Further adjustments to our protocol could be implemented if the other two byproducts O_2 gas and Cl_2 gas are desired to be collected. The gases can be utilized for future usage and experimentation. However, safety is an important consideration for large-scale implementation of our method, as these gas products can be hazardous to human health.

In conclusion, we hypothesized that after saltwater undergoes electrodialysis, the time it takes for the Na^+ cations to pass through the cathode exchange membranes and Cl^- anions to pass through the anode exchange membranes would decrease as the voltage from the DC power circuit is increased. This hypothesis was supported by the negative correlations found between time and the TDS of seawater. Our findings support our objective of producing large amounts of desalinated and purified water through the separation process of electrodialysis, as well as suggesting possible methods to make the process more efficient. Overall, these conclusions demonstrate that electrodialysis can convert seawater into consumable water by eliminating the components of seawater that make it undrinkable through ion exchange membranes.

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MATERIALS AND METHODS

Seawater Sample Collection

First, 5-gallon samples of seawater from the San Pedro Channel and Santa Monica Bay were collected. We took the boat to gather seawater samples from both locations to get samples that are representative of the saline feeds. The EZ-9909 TDS meter, which measures TDS values ranging from 0 to 99.999 ppt, was then inserted into both saline samples to measure their initial TDS values.

Electrodialyzer Assembly

We assembled the electrodialyzer, which served as the apparatus for this process, by cutting out square pieces of the 1⁄4-inch Plexiglass sheets to form 7 (10 cm x 10 cm x 10 cm) cubic solution tanks/chambers. The chambers at the two ends were only hollow (8 cm x 8 cm hole) on one side. The seven chambers were glued together using Weld-on 4 Acrylic Adhesive plastic cement. A graphite anode was fixed next to the leftmost chamber and a stainless steel cathode was fixed next to the rightmost chamber. We connected delivery tubes to both the cathode and anode on either side of the chambers. These were used to collect the H_2(g) from the cathode and Cl_2(g) from the anode. The anode exchange membrane FAA-3-PK-130 and cathode exchange membrane FKL-PK-130 were purchased from Fuel Cell Store and were attached to each chamber using screws.

Seawater Electrodialysis

We filled each of the seven chambers with the collected seawater from the San Pedro Channel. We wired 3 separate DPS 3010U DC power supply circuits (30 volts each) together to connect and combine their power supplies, reaching a total of 90 volts possible. The voltage was set to 55 volts for the initial trial with the San Pedro Channel saline feed. The circuits were then wired to the anode and cathode on either side of the electrodialyzer. We attached one delivery tube to the neoprene stopper on the furthest right chamber and connected the tube to a 500 mL filled water bottle, which was placed in a separate container. Once all the water from the water bottle had been transported into a separate container, the water bottle was delivered with hydrogen gas. The TDS meter was used every hour to measure the ppt of the water in each of the seven chambers. We repeated our measurements every hour until the TDS value was less than 0.5 ppt (acceptable range for drinking water) for all seven chambers. The TDS meter was used one last time to measure the TDS of the saltwater after deionization. We repeated this process using the saline feed from Santa Monica Bay for the second trial. Finally, the voltage was increased to 82 volts for the third experiment, which involved altering the parameters of the independent voltage variable. The same procedure was followed for the third experiment as well.

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