Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 27(3): 443 – 459 (2023)
www.ejabf.journals.ekb.eg

Application of Electrodialysis Desalination Technique of the Red Seawater to Utilize in Aquacultural, Industrial, Agricultural and Municipal Usages

Kawthar A. Omran[1, 2], Amr S. El-Shamy[2], Mohamed E. Goher[2]*

[1]Department of Chemistry, College of Science and Humanities, Shaqra University, Saudi Arabia
[2] Freshwater& Lakes Division, National Institute of Oceanography, Fisheries (NIOF), Cairo, Egypt

***Corresponding Author: smgoher@yahoo.com ORCID ID 0000-0001-9377-2429**

ARTICLE INFO

Article History:
Received: May 15, 2023
Accepted: June 4, 2023
Online: June 10, 2023

Keywords:
Electrodialysis,
Reverse osmosis,
Red Seawater desalination,
Energy consumption,
Removal efficiency,
Solar energy

ABSTRACT

The global shortage of freshwater resources worldwide, particularly in KSA, has tremendously influenced the development of desalination technologies, with electrodialysis desalination (ED) being one of the most well-known and respected techniques. In this study, a module was designed for an experiment on electrodialysis desalination. Under batch mode, operation factors including applied voltage, flow rate and feed concentration were investigated. The optimal operating parameters were 20 V of applied voltage, 200 ml/min of flow rate, and 40000 mg/L of dosage. With a high saline concentration of 40000 mg/L NaCl diluted to 1560 mg/L, the ED achieves a removal efficiency of 97.05% and an energy consumption of 2.03 Wh/L. In Jeddah, Saudi Arabia, where the salinity of the Red Seawater is 42420 mg/L, we utilize these optimal conditions to desalinate the water and produce water with a salinity of 1272 mg/L valid for aquacultural, industrial, agricultural, and municipal usage with a removal efficiency of 97 %, a recovery percentage of 83.33% and an energy usage of 2.03 Wh/L. The RO unit we utilize generates water with a removal efficiency of 97.74%, a recovery percentage of 64% and an energy consumption of 3.2 Wh/L. We observed that the ED unit uses less energy, costs less, and wastes less water when we compared its performance to that of a RO unit. If solar energy is used instead of DC electricity, we can save more money and energy.

INTRODUCTION

Almost 97.2% of the world's water resources are saline or brackish water bodies, despite the fact that water covers over 75 percent of the planet's surface **(Elsaie *et al.*, 2023)**. More than 2.1% of the 2.8% of freshwater still in supply is dependent on ice caps, glaciers, the atmosphere and soil moisture **(Peavy *et al.*, 1985)**. Hence, the remaining 0.7% of the freshwater supply found in lakes, rivers and groundwater is what is necessary for human survival as well as a number of agricultural technologies and procedures **(Elsaie *et al.*, 2023)**. Thus, there is a significant lack of potable water in many nations around the world, particularly in developing countries and countries in the Middle East **(Aljohani *et al.*, 2023)**. Egypt is one of the developing countries that suffer water shortage; although 97% of its annual renewable water resources come from the Nile River, this quantity is under threat due to climatic changes and the building of new dams upstream **(Shakweer & Youssef, 2007)**. Thus, the yearly capita share decreased from 800 to 550m^3 per capita each year between the years

2004 and 2022 **(Elsaie *et al*., 2023)**. Wastewater reuse, saltwater desalination, rainfall collection, and brackish groundwater desalination are examples of non-conventional water supplies **(Elsaie *et al*., 2023)**. Moreover, the KSA is one of many Middle Eastern nations that suffer from severe water scarcity, climatic changes and population increase **(Frenken, 2009)**, all of which have an impact on the sustainability of water resources and resulted in the depletion of numerous renewable and non-renewable resources **(Ghanim, 2019)**. The country's climate is described as having particularly harsh climatic conditions because the average annual rainfalls are approximately 59mm, and the summer temperatures can reach as high as 55°C **(Ghanim, 2019)**. More than 90% of Saudi Arabia is covered with desert, and there are no lakes or rivers in the country **(Abderrahman, 2006)**.

One of the most important solutions to Saudi Arabia's water shortage is desalination. Desalination is a method used to eliminate dissolved minerals from brackish or seawater. According to USSB, (2021), since the 1950s, the kingdom has relied on desalinated water and has grown to become the world's largest producer of the substance, producing 7.6 million m^3 of it daily, or 22% of the world's total%. As of 2019, desalination accounts for 60% of the nation's water supply, with nonrenewable groundwater accounting for the majority of the other 40%. The total water consumption for the Kingdom is currently estimated to be 25.29 billion m^3 per year, but is only expected to slightly increase to 25.79 billion m^3 by 2025 **(USSB, 2021)**. In Saudi Arabia, there are 30 desalination plants (Table 1) **(Al-Shail & Ordoñez, 2019)**. The technologies used for the desalination of water are subdivided into two types that are phase and non-phase change processes **(Al-Shail & Ordoñez, 2019)**. Reverse osmosis is regarded as a non-phase change process (including membrane), while multi-effect distillation (MED), multi-stage flash (MSF), and mechanical vapor compression (MVC) are phase -change processes (thermal ones) **(Fthenakis *et al*., 2016a)**. Reverse osmosis is the method that is most frequently used to desalinate water **(Al-Shail & Ordoñez, 2019)**. While, MSF is the second most popular method and is utilized in more than 23% of desalination plants worldwide (Fthenakis *et al*. 2016b). It is still only employed in 63% of those facilities **(Fthenakis *et al*., 2016)**. MSF and MED are particularly well-suited for insertion into cogeneration schemes because they can produce fresh water by using the waste thermal energy that is released from the turbine **(Rambo *et al*., 2017)**. High energy is used in evaporators in thermal desalination plants. Membrane-based desalination facilities employ electrical energy rather than thermal energy in all of their components **(Jurgenson *et al*., 2016)**. Electrical energy is mostly employed in reverse osmosis plants to power pumps **(Mohammed & Alkhafaja, 2023)**.

Electrodialysis is an effective and commercially feasible desalination technique that uses an electric field to remove salts and other minerals from seawater or brackish water sources **(Al-Amshawee *et al*., 2020)**. The process involves placing a series of positively and negatively charged ion exchange membranes between two electrodes . The seawater or brackish water is then passed through the membranes under the influence of an electric field. The negatively charged membranes attract positively charged ions, while the positively charged membranes attract negatively charged ions. This electrical repulsion causes the salt and mineral ions to migrate away from the feed water stream and towards a concentrated brine stream **(Kukučka & Stojanović, 2022)**.

Table 1. Plants for desalination presently in service in the Kingdom of Saudi Arabi **(Al-Shail & Ordoñez, 2019)**

No.[a]	**Service area**	**Location**	**Technology used**	**Water production (m^3/day)**
1	Tabuk	Haql-II	RO	5,760
2		Duba-III	RO	5,760
3		Al-Wajih-III	MED	9,000
4		Umlujj-II	RO	4,400
5		Umlujj-III	MED	9,000
6	Makkah	Rabigh-II	MED	18,000
7		Al-azizia	MED	4,500
8		Laith	MED	9,000
9		Al-qunfudah	MED	9,000
10	Jizan	Farasan-II	MED	9,000
11	Makkah	Jeddah-IV	MSF	221,575
12		Jeddah-I	RO	56,800
13		Jeddah-II	RO	56,800
14		Jeddah-III	RO	240,000
15	Makkah	Shoaiba-I	MSF	223,000
16	Al-baha	Al-baha Shoaiba-II	MSF	455,000
17	Makkah	Yanbu-I	MSF	100,800
18		Yanbu-II	MSF	143,808
19		Yanbu	RO	127,800
20	Al-madinah	Yanbu-Exp	MED	68,190
21	Asier	Shoqaiq	MSF	97,014
22	Jizan			
23	Al-sharqiah	Al-Jubail-I	MSF	137,729
24	Al-Riyadh	Al-Jubail-II	MSF	947,890
25	Al-qasim	Al-Jubail-III	RO	90,909
26	Al-sharqiah	Al-Khobar-II	MSF	223,000
27		Al-Khobar-III	MSF	280,000
28		Ras-Al-kair	RO	310,656
29	Al-Riyadh	Ras-Al-kair	MSF	740,656
30	Al-sharqiah	Al-Khfji	MSF	22,886

a: 1-10 West Coast (Satellite Plant), 11-22 West Coast (Large Plant), 23-30 East Coast (Large Plant).

The electrodialysis process is highly efficient for removing ions from seawater or brackish water. It requires no heating or chemical treatment, making it a relatively low-cost and environmentally friendly option. The process is also highly scalable and can be used in small or large-scale desalination facilities **(Obotey & Rathilal, 2020)**. One of the significant benefits of the ED process in seawater desalination is that it requires less energy compared to RO. ED requires only a small amount of electricity to create an electric field that separates the ions from seawater **(Knust *et al*., 2014)**. In contrast, RO requires high pressure to force water through a semi-permeable membrane, which requires a large amount of energy **(McMordie *et al*., 2013)**. Moreover, the lower energy consumption of the ED process leads to lower operating costs. The reduced energy input results in lower electricity bills, which are translated to significant savings for the desalination plant. Additionally, the ED process is simpler and requires less maintenance, which further reduces operating costs **(Bhat & Prakash, 2009)**.

This study aimed to investigate ED performance for the desalination of high salinity water. The effects of several parameters including applied voltage, feed concentration and the flow rate were investigated. In addition, this work focused on applying the optimum conditions of ED process to desalinate the Red Seawater in Jeddah- Saudi Arabia and compare it with RO application taking into account power and cost saving.

MATERIALS AND METHODS

Chemicals and instruments

A commercial NaCl salt was purchased from AMISA company, and it was used to prepare the feed solutions (dilute and concentrate) and the electrolyte solution. The solutions of salts were prepared using a tap water. NaOH and HCl were purchased from Sigma-Aldrich chemical companies and used to adjust the pH value. Parameters of pH, EC, salinity and total suspended solids were measured using multiparameter Ion Analyzer 399A, Orion Research, Cambridge, MA, USA.

Set-Up of ED unit

The details on the ED cell were illustrated in the study of **Omran *et al.* (2023)**. However, briefly, the total volume of the ED unit was equal to 0.018 m^3, with an activated membrane area of 0.04 m^2 in each room. (Fig. 1). The ED unit contains 2 stainless steel, 316 electrodes [cathode (-) and anode (+)], 3 anionic exchange membranes -Pention-AEM-72-05-5% crosslinking ion exchange membranes- (AEM), 2 cationic exchange membranes -Ralex® Membrane CMHPP – Mega- EU- (CEM), 4 pumps USA GRUNDFOS (10 L/ min), low-density polyethylene spacers, a rectifier A.M with an automatic range of 0–70 V and 0–20 A. flow meters (100 – 2000 ml/min), and 3 tanks for electrolyte solution (6 L), concentrate solution (6 L) and dilute solution (6 L).

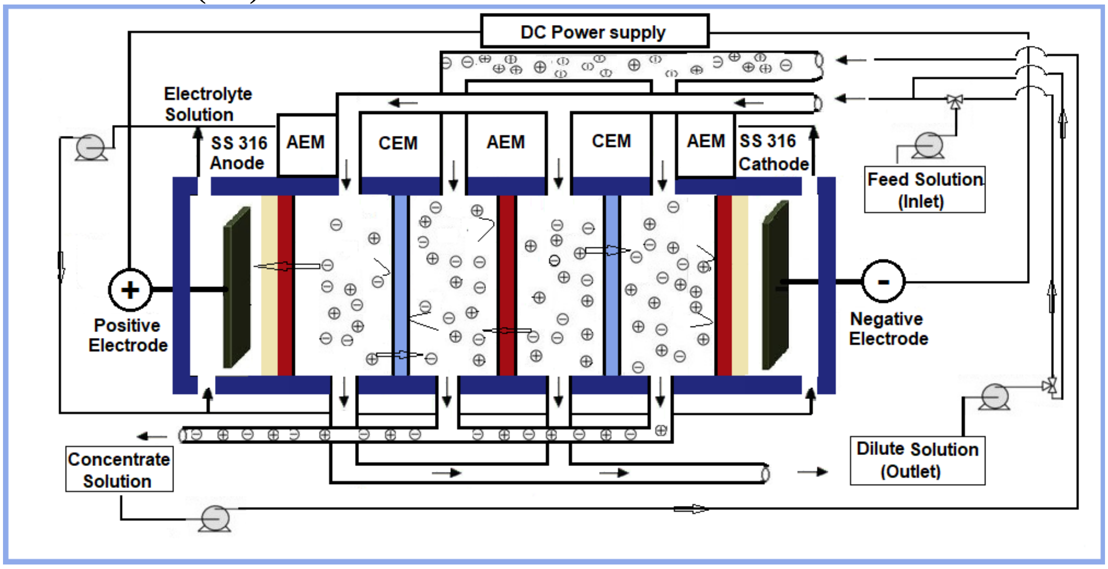

Fig. 1. Schematic diagram for parts of ED unit

Batch experiments and operation parameters

The batch recirculation mode was used to detect the optimum conditions of ED process to desalinate a different concentrated saline water (10000 – 40000 mg/L). The batch experiment was achieved under conditions of 5-30 V of applied voltage, operation time of 0.5 – 3 h, and flow rate from 100 ml/min to 400 ml/min. In all experiments, the 0.5 M NaCl solution was used as an electrolyte solution.

In general, once the electric current is connected to the electrodes, the cations (Na^+) and anions (Cl^-) move toward the cathode and anode through the CEM and AEM, respectively. On the other hand, both sodium and chloride ions are blocked by AEM and CEM, respectively. Accordingly, the concentration of Na^+ or Cl^- is increasing in one chamber which is known as the concentration chamber, and its stream is known as the concentrate solution. In contrast, the concentrations of ions are decreasing in the adjacent chamber which is known as the dilute chamber, and its stream is known as the dilute solution.

There are 2 important calculated parameters in the ED operation system od desalination process, which evaluate the performance factors. These two factors are the removal efficiency and the energy consumption.

A- The removal efficiency (RE) is a parameter that determines the removal percentage of salts from the saline water at the end of the experiment.

$$\boldsymbol{RE}\ (\%) = \frac{(\boldsymbol{C_o} - \boldsymbol{C_t})100}{\boldsymbol{C_o}}$$

Where, RE is the removal efficiency %, C_o: the initial TDS concentration of dilute solution (mg/L), and C_t: the outlet TDS concentration of dilute solution at time t (mg/L).

B- The energy consumed (EC) is the amount of energy consumed to complete the desalination process in the electrodialysis cell.

$$\boldsymbol{EC} = \frac{(\boldsymbol{W} * \boldsymbol{t})}{\boldsymbol{V_d}} \qquad \boldsymbol{W} = \boldsymbol{V} * \boldsymbol{I}$$

Where, EC is the energy consumed (Wh/L) or Specific energy consumption, W is the electrical power (watt); V is the applied voltage (Volt), I is the electrical current (Amber), t is the time in hours (h), and V_d is the volume of the dilute solution (L), which is 6 liters in the present work.

RO Unit

In the present study, RO unit was used to remove salts from the Red Sea water collected at the beach of Jeddah city – Kingdom of Saudi Arabia. The RO process was done to compare the ED unit to find the most efficient for removing salts, the highest recovery in used water, the least energy consumption and the lowest cost. The RO unit is made in Taiwan Globe well at Chieh Sheng Co. (RO / N – 6 plus) For heavy duty has Production:20 gal/day, and the unit has USA RO membrane materials that are polyamide thin film composites (TFC). Diaphragm pump YZY-800-A^2 hasVolts 24 VDC working pressure 70 PSI, Amps 0.8 A working flow 800 ml and in pressure 28 PSI open flow 2000 ml. Membranes: FILMTEC_ TW30-2514 Small Commercial. Elements are characterized with the following specifications: Membrane type: Polyamide thin-film composite, active area (m^2): 0.7 applied pressures (bar): 15.5 and stabilized salt rejection (%): 99.5 permeate flow rate (m^3/d): 0.7.

Desalination of samples of the Red Sea water

Subsurface water samples from the Red Sea were collected from Jeddah Beach in the summer of 2022. The water samples were kept in cleaned stopper plastic bottles. Before the desalination process, the water samples were filtered using a sand filter to remove all impurities and suspended matter. The Red Sea water samples with TDS of 42420 mg/L (42.4 %) were desalinated using the designed ED unit under the obtained optimum conditions. In the same manner, the seawater was treated by the RO unit (RO / N – 6 plus). Triplicate desalination operations were done by both RO and ED units to achieve the accuracy of the desalination results. Saving energy and thus reducing costs is one of the most important global goals in all industrial project planning and research experiments. Therefore, the solar cell was used as a source of power to treat the samples of the Red Sea as an alternative to the use of electric current. The solar cell that is used as a DC power source in our pilot system consists of two units of Monocrystalline - Model MG-PV-100M2 (100 W) produced by MICROGREEN Co., Canada. Every one set contains crystalline cells, a charging regulator, a battery, and an inverter. The stages of seawater desalination utilizing ED and RO units, the paths of diluted (pour) and concentrated water, the choice of power source (AC or solar cell), and the filtration of seawater by the sand filter are all depicted in detail in Fig. (2).

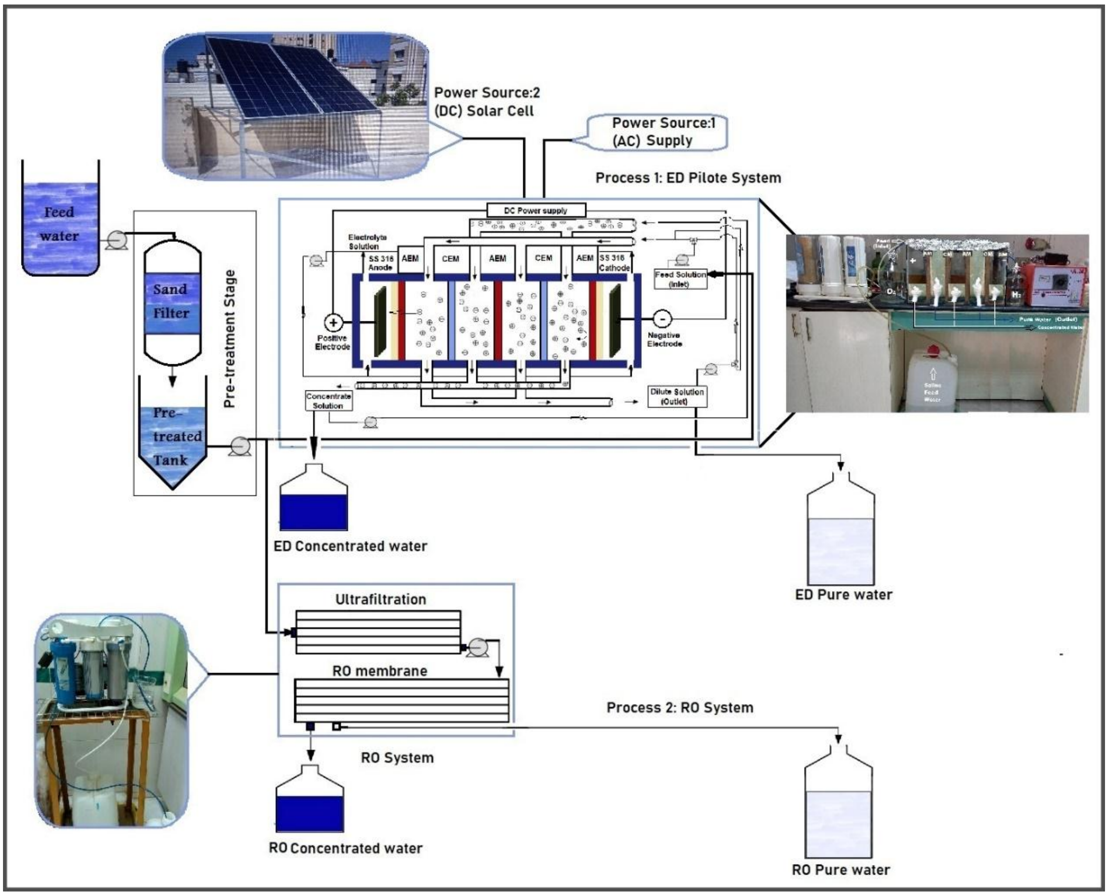

Fig. 2. Schematic diagram for the desalination of the Red Sea water utilizing ED and RO units. The AC supply serves as power source 1, while the solar cell serves as power source 2. Before the desalination process, the seawater is filtered in the diagram.

RESULTS

Factors affecting performance of electrodialysis

Here, the effectiveness of ED cell under various process conditions is examined with the aim of optimizing the process by choosing the most effective operating conditions. Under these optimal conditions, the desalinated model wastewater ought to be harmless or even appropriate for discharge into the environment **(Vítěz *et al*.,**

2012; Gherasim *et al*., 2014), with the desalination process also being characterized by removal efficiency (RE) and low energy consumption (EC). The effects of the following objective parameters were taken into account: the applied voltage, the flow rate, the operation time and the initial concentration in the feed.

Effect of applied voltage

First, a voltage between 5.0 and 30.0 volts was individually supplied to a 40000 mg/l NaCl solution at pH 7.4 in order to measure the limiting current density (LCD). The current-voltage curve is in the ohmic zone, as shown in Fig. (3), and the current density for this ED cell does not approach the LCD when a voltage between 5.0 and 30.0 volts is applied.

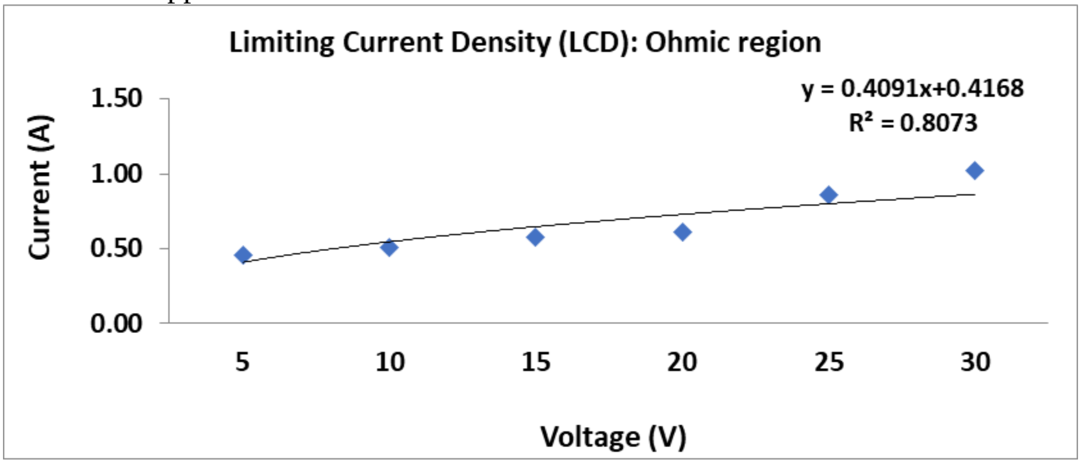

Fig. 3. Limiting current density (LCD): Ohmic region

To determine the effectiveness of ions removal, a series of experiments were conducted at various applied potential differences ranging from 5.0 to 30.0 volts. The following conditions were maintained as follows: 60 minutes were spent on electrodialysis in total, flow rate 200 ml/min, pH 7.4 and feed concentration 40000 mg/L. The variation of RE and EC at various applied voltages is depicted in Fig. (4). It is noteworthy that, the removal efficiency increased from 18.8% to 97.05% at 5 V and 20 V, respectively. It is noticeable when the applied voltage is increased to 30 V recording a minor increase in RE; this is seen when it reaches 99.43%. On the other hand, as the voltage rises, the rate of energy consumption rises continuously, reaching 0.38, 2.03, and 5.10 Wh/L at 5, 20, and 30 V, respectively. From the obtained results, although the highest removal efficiency was recorded at the applied voltage of 30 volts, the optimum value of the applied voltage is 20 volts for the desalination process in the designed ED unit. This applied voltage (20 V) saves approximately 60% of the energy consumed when using 30 V.

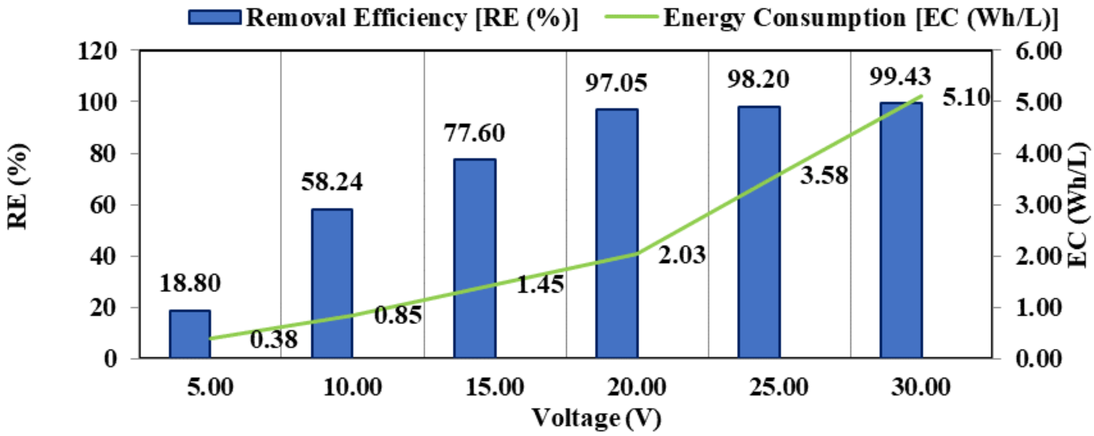

Fig. 4. Effect of applied voltages on RE and CE for NaCl (t= 60 min; Ci=40000 mg/L; pH = 7.4; Fr = 200 ml/min, at T 25 °C).

Effect of feed concentration

With a range of salinity (10000-50000 TDS) in the recirculated batch mode, the influence of initial feed concentration on the efficacy of the ED was examined. The experiment is carried out at 25°C for 60 minutes, with a flow rate of 200 ml/min and an applied voltage set to the 20 V value that was previously determined to be the process's optimum conditions. Fig. (5) shows that as concentration increases from 10,000 mg/L to 40,000 mg/L, respectively, elimination efficiency decreases from 99.60% to 97.84%. However, as concentration climbs from 10,000 mg/L to 40,000 mg/L, respectively, energy consumption rises from 1.57 Wh/L to 2.03 Wh/L. The RE decreased from 97.05% at 40000 mg/L to 95.20% at 50000 mg/L when the feed concentration was increased from 40000 mg/L to 50000 mg/L. The results of this study unequivocally demonstrate that 40000 mg/L is the optimum initial input concentration for cost-effective and efficient desalination. With an applied voltage and flow rate of 20 V and 200 ml/min, the produced ED cell outperforms **(Shi *et al.*, 2022)**. In their research, they desalinate 35000 mg/L using 20 V and 250ml/ min. Although there is a relative preference for each of the RE and EC when using a feed solution of 10000 mg/L, the use of a concentrated solution of 40000 mg/L is preferable from the economic point of view, as well as because it is the closest to the nature of salinity of the Red Sea.

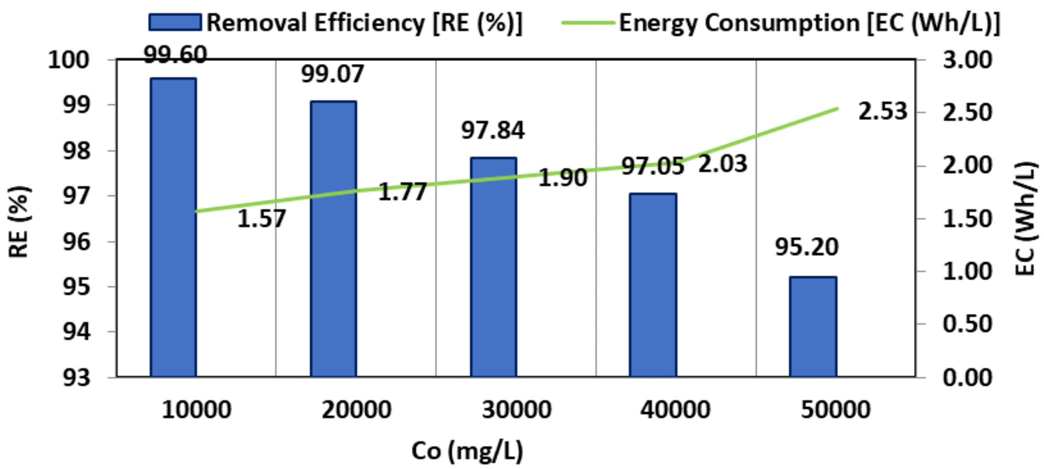

Fig. 5. Effect of initial concentration on RE and CE for NaCl (t= 60 min; Fr=200 ml/min; pH = 7.4; applied voltage 20 V, at T 25 °C).

Effect of operation time

To desalinate 40000 mg/L of 6 L NaCl, a recirculated batch experiment is run. 200 ml/min flow rate, pH 7.4, and applied voltage of 20 V are the parameters used to evaluate the influence of operating time. Fig. (6) demonstrates how the ED process improves as operation time increases. The removal efficiency rises from 53.13% to 97.05% as the operation time increases from 0.5 h to 1 h, as shown in the Fig. (6). Similarly, as the operation duration goes from 0.5 to 1h, the energy usage rises from 1.02 to 2.03Wh/ L. Additionally, the removal rate will increase from 97.05% to 99.45% when more ions are passed over the membranes over longer residence (operating) times of 1 to 3h, while the energy cost will increase from 2.03 to 6.10Wh/ L, correspondingly. Performance of separation and energy usage therefore worsen. Therefore, 1 hour of operation is enough to desalinate 40g/ L effectively and cheaply.

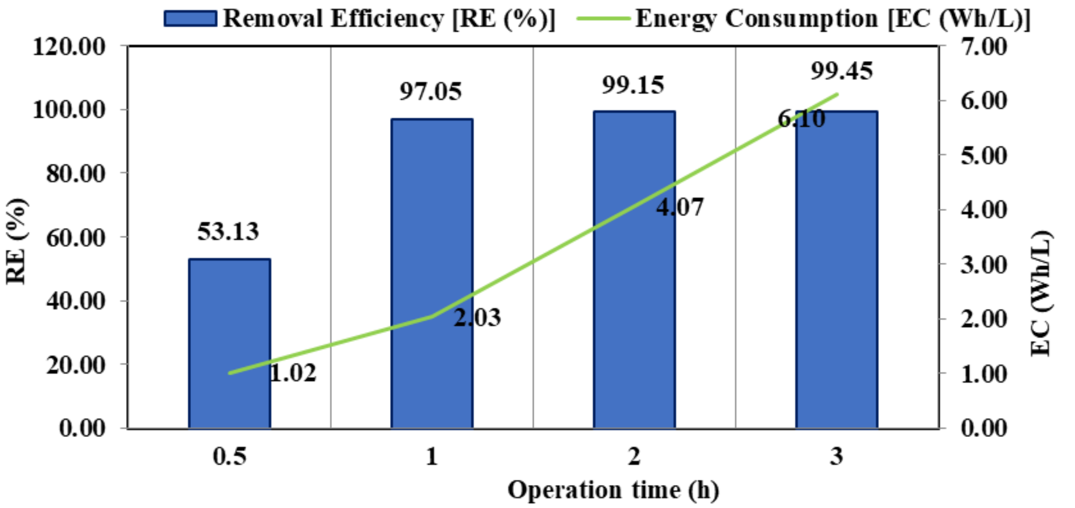

Fig. 6. Effect of operation time on RE and CE for NaCl (Ci=40000 mg/L; Fr=200 ml/min; pH = 7.4; applied voltage 20 V, at T 25°C).

Effect of flow rate

The impact of flow rate (100, 200, 300, and 400 ml/min) of concentrate and diluted solutions was investigated at 20V applied voltage, pH 7.4, and 40000 mg/L NaCl. Fig. (7) shows that with a flow rate increasing from 100 to 200ml/ min, the removal efficiency increased from 75.45% to 97.05%. However, as the flow rate increased from 100 to 200ml/ min, the energy consumption dropped from 2.27 to 2.03Wh/ L. The removal efficiency decreases from 97.05% to 74.35% and the energy consumption rises from 2.03 to 2.70Wh/ L as the flow rate is increased further from 200 to 400ml/ min. Based on these results, the optimum rate of flow to desalinate water with a salinity of 40g/ L is determined to be 200ml/ min. When compared to the 250ml/ min flow rate utilized by **Shi *et al*. (2022)**, 200ml/ min provides a greater removal efficiency.

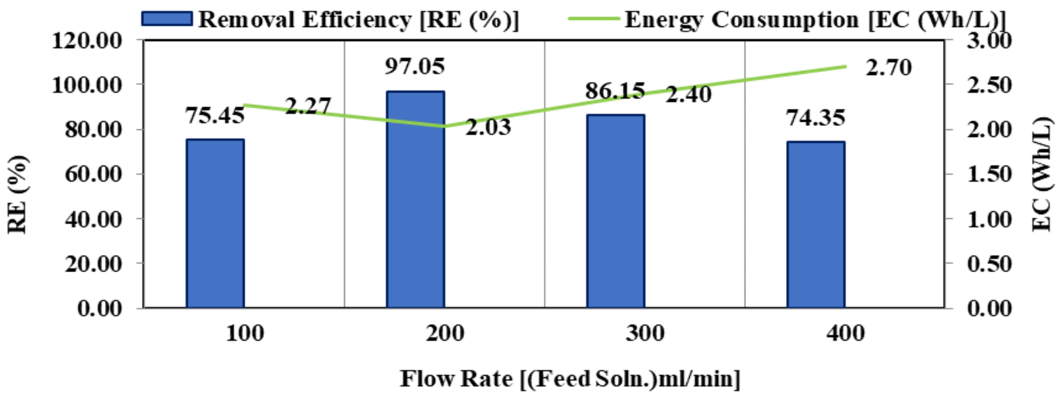

Fig. 7. Effect of flow rate on RE and CE for NaCl (t= 60 min; Ci=40000 mg/L; pH = 7.4; applied voltage 20V, at T 25°C).

The optimal operating conditions for an ED cell operating in batch mode are summerized in Table (2) based on the results of all the above experiments.

Table 2. The optimum operating conditions of ED cell

Parameter	Value
Applied volage, V	20 V
Initial feed concentration, mg/L	40000 mg/L
Operation time, h	1 h
Flow rate, ml/min	200 ml/min
Type of electrolyte	Sodium Chloride
Electrolyte concentration, M	0.5 M NaCl

Appling the optimum conditions of ED process to desalinate Red Seawater of Jeddah - Saudi Arabia and compare it with RO technique

We used two recycling tests and the optimal ED process parameters (Table 2) to desalinate 6L of the Red Sea water. The removal efficiencies for ED and RO are 97.0 % and 97.74%, respectively (Table 3). According to Table (4), in this experiment, 36% of the desalinated Red Sea water was rejected, while 64% of the original product was recovered using a RO system, with a removal efficiency of 97.74%, salt rejection of 97.74%, or 41.461 g/L, and energy usage of 3.2Wh/ L. The results presented in Table (4) for the ED system reveal that 83.33% of the primary output was recovered while 16.67% of the water was discarded, with energy consumption of 2.03Wh/ L, removal efficiency of 97.0% and salt rejection of 97.0 %, which equals 41.15g/ L. It is evident that RO requires more energy to operate while recovering less water, despite generating water of a higher quality.

Table 3. Comparison between ED and RO techniques for desalination of the Red Sea water in Jeddah – Saudi Arabia

Parameter	Red Seawater, Jeddah - Saudi Arabia				
	Feed water	ED Unit		RO unit	
		After Desalination	Removal %	After Desalination	Removal %
EC µS/cm	67752	2033	97.00	1530	97.74
TDS mg/L	42420	1272	97.00	960	97.74

Table 4. Comparison between ED and RO performances for the Red Sea water desalination in Jeddah-Saudi Arabia (TDS = 42420 mg/L)

Parameter	RO performance	ED performance
Removal Efficiency %	97.74	97.00
Salt Rejection %	97.74	97.00
Salt Rejection g/L	41.46	41.15
Salt Passage g/L	0.96	1.27
Water Recovery %	64	83.33
Energy Consumption	3.2 Wh/L	2.03 Wh/L

Evaluation of the ED process's power and cost savings

As we deduced from the results of the comparison between the ED method and RO (Tables 3, 4) to desalinate the Red Sea water, the ED consumes 1.17Wh/ L less energy than RO. The power saving of 1.17Wh/ L (1.17 kWh/m^3). The equivalent cost reduction is 0.21 SAR/m^3 based on the current energy consumption price in the Kingdom of Saudi Arabia, which is equal to 0.18 SAR/kW. On the other hand, according to **SWCC (2023)**, the cost of energy consumption is equal to 0.5 SAR/m^3, and the average amount of electricity needed to create 1m^3 of desalinated water is 2.75 kWh/m^3. Thus, compared to the KSA's present desalination process, utilizing the ED approach can save about 0.72 kWh/m^3 and 0.13 SAR/m^3. Furthermore, switching from DC electricity to solar energy can improve our capacity for energy and cost conservation. The solar cell has a daily operating time of 12 hours. As a result, the cost of power can be minimized by 50% to reach 0.183 SAR/m^3, saving about 0.31 SAR/m^3 compared to the current production in the Desalination Plants (in view of the cost of electricity consumption). Table (5) shows details concerning the characteristics of an ED system at a TDS inlet of 42000–43000 mg/L that produces water less than TDS of 1500mg/ L (which is suitable for most usages) with energy consumption of about 2.03kW/ m^3 (without solar cell) and 1.015 kW/m^3 with using the solar cell, respectively, as a power-saving measure when using an ED system rather than the RO system.

Table 5. Properties of piloted ED system

No.	Properties	ED system
1	Total Production capacity	6 L/h = 144 L/d
2	Max. TDS Inlet	40000-43000 mg/L
3	TDS Outlet	< 1500 mg/L
4	Salt Passage %	1-2 %
5	Energy Consumption	2.03 Wh/L = 2.03 kW/m^3
6	[a]Cost of Energy Consumption	0.37 (SAR/m^3)
7	Power Save	1.17 W/L (1.17 kW/m^3) in compare to the RO 0.72 kWh/m^3in compare to the *DP in KSA
8	Cost Save without Solar cell	[b]0.21 SAR/m^3 in compare to The RO unit 0.13 SAR/m^3in compare to the DP in KSA
9	Power Save with Solar cell	1.74 kWh/m^3 in compare to the DP in KSA
10	Cost Save with solar cell	[b]0.31 SAR/m^3in compare to the DP in KSA
11	Application	Desalination (Seawater-Brackish water) and industrial wastewater treatment.

[a]The cost of production of cubic meter desalinated water is calculated according to the cost price of the kWh (0.18 SAR/kWh) in 2023 for the industrial purposes (SEC, 2023); [b]Cost save is calculated according to the cost (1.2 SAR/m^3) of energy consumption (2.75 kWh/m^3) in the DP of KSA, not to the total cost to produce 1m^3 desalinated water according to SWCC (2023); *DP is the desalination Plant in KSA.

DISCUSSION

As mentioned in the literature, desalination is a process used to remove salts and other minerals from seawater or brackish water in order to make it suitable for human consumption or use in agriculture. The process can be done through various methods like reverse osmosis and electrodialysis. It is generally more expensive than traditional fresh water sources due to its high energy consumption but is becoming increasingly important in water-scarce regions like KSA as a rainfall-independent water resource **(Shatat & Riffat, 2014)**. ED uses an electrical potential to remove ions from a solution, while RO applies pressure to a semi-permeable membrane to separate ions and other impurities from water. The performance of ED for desalination is likely to depend on a variety of factors, including applied voltage, flow rate and feed concentration. In electrodialysis (ED), the effect of applied voltage can be significant on the performance of the process. Firstly, it is important to determine the limiting current density. The limiting current density (LCD) is the highest permitted current density at which the concentration of salt ions at the membrane surface in the dilute cell of the ED stack is zero. With a rise in applied voltage at the electrodes of the electrodialyzer, current density rises throughout the cell. The salt ion concentration within the dilute diffusion boundary layer approaches zero at the membrane surface if current density increases beyond the LCD **(Walker *et al.*, 2014)**. If current density increases beyond the LCD, the dilute diffusion boundary layer's linear concentration gradient becomes steeper (or thinner) **(Walker *et al.*, 2014)**. Identification of the LCD aids to determine how much voltage application is required for an effective ED operation. To avoid water splitting, energy waste, and ED equipment damage, ED systems should be run below the LCD (Fig. 3).

Increasing the applied voltage can improve the efficiency of ED by driving ions across ion-exchange membranes and promoting the separation of salts from water (Fig. 4). However, high applied voltage can cause concentration polarization phenomena to occur and also lead to membrane fouling as well as increased energy usage and cost **(Patel *et al.*, 2020)**. The optimal applied voltage for ED will depend on factors such as the properties of the treated water and the desired level of desalination **(Hyder *et al*., 2021)**. Therefore, a value of 20V was chosen as the optimum value to satisfy the conditions.

The impact of the initial feed concentration in the feed is crucial for determining the suitable range of application for the ED process under investigation and for carrying out a highly efficient ED process. Using the recirculated batch mode, different initial concentrations of TDS (10000-50000 mg/L) in the feed solution were utilized to examine how the initial feed concentration affected the effectiveness of the ED. The experiment is run for 60 minutes at 25°C with pH 7.4, flow rate and applied voltage adjusted to the values previously observed as optimum for this procedure. Fig. (5) demonstrates how energy consumption and removal efficiency both decline as concentration rises. This is related to the medium's high ion concentration. Additionally, the concentration increase suggests a rise in conductivity, yet the removal efficiency fell in spite of this rise. Similar to concentration polarization, the removal efficiency can decrease. The situation may also be impacted by the membranes' limited ability for separation. Since extra ions might lead to resistance and pollution with growing concentration, ED cell will have an adverse effect in this situation, leading to accumulation and stratification in the membranes and a reduction in removal efficiency **(Kırmızı & Karabacakoğlu, 2023)**. At high concentrations, ion removal is problematic either due to the excessive ion concentration in the medium (more conductivity) or concentration polarization, but the efficiency decreases **(Kırmızı & Karabacakoğlu, 2023)**. Moreover, due to the ion abundance in the medium, the time is maintained for a long time to ensure removal, and energy consumption’s increase **(Kırmızı & Karabacakoğlu, 2023)**. This is undesirable in both laboratory scale systems and industrial activities. As in Fig. (5), the most suitable initial feed concentration which can be removed efficiently (97.05 %) with low energy consumption (2.03 Wh/L) is 40000 mg/L value. The desalination of seawater with a salinity of 40000 mg/L, with this high removal efficiency and an energy consumption of only 2.03 Wh/L demonstrated the efficiency of the ED method.

Operation (retention) time can be an important operating parameter in electrodialysis (ED) processes, as it can impact the overall efficiency of the system. The duration of the feed stream staying in the ED system is referred to as operation or retention time, and it can affect how well ions are transferred through the ion-exchange membranes. Since flow rate and retention time are closely related, increases in retention time frequently led to better ion removal efficiency. Whereas, increasing energy consumption also results in higher expenses **(Liu *et al.*, 2010)**. Extended retention intervals; however, can also lead to poorer membrane performance as a result of fouling and scaling, which can reduce the overall efficacy of the ED process **(Iorhemen *et al.*, 2016)**. The effect of operation time on RE and EC is displayed in Fig. (6). It is clear that, one hour is the optimal operation time for achieving maximum removal efficiency with minimal energy usage. An important process parameter that can be controlled to limit concentration polarization phenomena is the flow rate of the aqueous solution in the dilute and concentrate compartment. This flow rate, along with the use of high voltages, is what causes concentration polarization phenomena to occur **(Strathmann *et al.*, 2004)**. As a result, it is recognized that in ED processes, ions are transported through ion exchange membranes more quickly than they are in solutions while they are going towards the electrodes **(Gherasim *et al.*, 2014)**. Low flow rates cause the ions' retention times to get longer, concentration profiles to form, boundary layers to be built up near the membrane surfaces, and this concentration polarization phenomenon determines an increase in the resistance of the diluted due to the high resistance of the depleted boundary layer **(Długołęcki *et al.*, 2010)**. By reducing the thickness of the boundary layers at the membrane surfaces during batch ED, the use of appropriate flow rates can lessen the concentration polarization phenomena and increase the transfer of ions via the ion exchange membranes **(Wang & Yang, 2001)**. Data in Fig. (7) demonstrate that, the removal efficiency improved with a flow rate increase from 100 to 200ml/ min. By strengthening the hydrodynamics with an increase in flow rate, this behavior is described by the drop in concentration polarization phenomena **(Aytaç & Altın, 2017)**. The desalination of the diluted solution becomes less effective as the flow rate is raised further from 200 to 400ml/ min. In this situation, upon decreasing the ion retention time, an opposite effect was detected on the ion transfer between the membranes, lowering the removal efficiency **(Omran *et al.*, 2023)**. Consequently, the results of the experiment show that a flow rate of 200ml/ min is the optimum rate.

When we used the ED method under optimal conditions to desalinate water from the Red Sea in Jeddah- Saudi Arabia and compared its effectiveness to the RO approach, we came to the conclusion that, both reverse osmosis (RO) and electrodialysis (ED) are used for seawater desalination, but they differ in their mechanisms and application areas. RO is more effective in removing ions from water, while ED is more energy efficient (Tables 3, 4). ED uses ion exchange membranes and an electric field to separate ions from water, while RO uses pressure to push the water through a semi-permeable membrane to separate salts and other impurities from the water. ED is generally used in industrial applications for handling high-strength brine streams or in situations where complete desalination is not required, whereas RO is used for household drinking water purification and in larger-scale desalination plants. ED typically has lower energy consumption, operating costs and can produce higher water recovery rate than RO, but RO has a more well-established industry.

The quality of produced water by the ED process is 1272mg/ L. According to standards and specifications for water types that were set by the Ministry of Environment Water & Agriculture, KSA (MOEWA, 2021), the water produced by ED process is suitable for agriculture (TDS = 2000 mg/L). It is also valid for industrial and aquaculture purposes. Additionally, the produced water may be used for the most domestic uses, except the drinking purpose. The TDS of drinking water must be less than 1000mg/ L, as reported by the Ministry of Environment, Water and Agriculture of the Kingdom of Saudi Arabia in 2021 **(MOEWA, 2021)**. Thus, the produced water for drinking purposes requires an additional stage of desalination processing.

Electrodialysis is a membrane-based separation process that is commonly used for desalination, purification of solutions with high ionic strength and recovery of valuable materials. Compared to other separation processes like reverse osmosis, electrodialysis has the potential to be more energy-efficient and cost-effective. One way that electrodialysis can be more energy-efficient is by utilizing renewable energy sources to power the process. Since electrodialysis is an electrochemical process, it requires the use of an external energy source to drive the separation of ions. If this energy source comes from renewable sources such as solar energy, then electrodialysis can be a more sustainable and environmentally friendly technology. In terms of cost savings, electrodialysis can be more cost-effective than other separation technologies such as reverse osmosis if the feed solution has a high ionic strength or a high concentration of impurities. Electrodialysis can achieve high water recovery with less energy than reverse osmosis, which can result in lowering operating costs over the lifetime of the process. Additionally, electrodialysis can be combined with other separation technologies such as nanofiltration or ultrafiltration to create hybrid processes that can further improve the efficiency and cost-effectiveness of the overall separation system.

CONCLUSON

In this study, an electrodialysis desalination unit was constructed. The factors affecting the performance of ED unit was discussed like applied voltage, flow rate and feed concentration. The optimum operating conditions to desalinate high salinity synthetic water of 40000 mg/L NaCl were 20V and 200ml/ min and dilute it to 1560 mg/L, with 97.05 % removal efficiency and energy consumption of 2.03Wh/ L. The ED process proved its effectiveness for desalination of the Red Sea water in Jeddah, KSA, with high salinity content of 42420mg/ L to convert it to water with salinity of 1272 mg/L, which is valid for agricultural, industrial and municipal usage according to Ministry of Environment Water & Agriculture, KSA, 2021 guidelines **(MOEWA, 2021)**. Additionally, when we compare the performance of ED unit with RO unit, we observed that ED is more energy efficient and higher recovery percent. In addition, we can save more energy and money if we replace DC electricity by solar energy.

Statements and declarations

Funding: The authors extend their appreciation to the deanship of scientific research at Shaqra University for funding this research work through the project number (SU-ANN-202217).

Competing interests: The authors have no relevant financial or non-financial interests to disclose

Author contribution: Conception and design, all authors. Material preparation, data collection, analysis and experimental study were performed by all authors. Writing of the first draft and final text were contributed by all authors. Review, editing and approving of the final text, all authors.

Ethical approval: Not applicable

Code availability: Non applicable.

Consent to participate: All authors voluntarily agree to participate in this research study.

Consent to publish: All authors voluntarily approved the publication of this research study.

REFERENCES

Abderrahman, W. (2006). Groundwater Resources Management in Saudi Arabia. Special Presentation and Water Conservation Workshop, Al Khobar, Saudi Arabia.

Al-Amshawee, S.; Yunus, M.; Azoddein, A.; Hassell, D.; Dakhi,l. and Hasan, H. (2020). Electrodialysis desalination for water and wastewater: A review. Chem Eng J. 380: 122231.

Aljohani, N.; Kavil, Y; Al-Farawati, R.; Aljohani, N,; Orif, M.; Ghandourah, M.; Bahshwan, S.; Aloufi, F.; Halawani, R. and Salam, M. (2023). The assessment of environmental parameter along the desalination plants in the Kingdom of Saudi Arabia. Open Chemistry. 21(1): 20220274.

Al-Shail, K. and Ordoñez, J. (2009). Optimum design of PV-RO system solar powered sea water desalination without storage in Saudi Arabia (Case study).

Aytaç, E. and Altın, S. (2017). Influence of Flow Rate on the Removal of Copper, Lead and Nickel from Solutions in Electrodialysis Process. MATTER: International Journal of Science and Technology. 3(3): 24-35.

Bhat, I. and Prakash, R. (2009). LCA of renewable energy for electricity generation systems—a review. Renewable and sustainable energy reviews. 13(5): 1067-1073.

Długołęcki,P.; Ogonowski, P.; Metz, S.; Saakes, M.; Nijmeijer, K. and Wessling, M. (2010). On the resistances of membrane, diffusion boundary layer and double layer in ion exchange membrane transport. J Membr Sci. 349(1-2): 369-379.

Elsaie, Y.; Soussa, H.; Gado, M. and Balah, A. (2022). Water desalination in Egypt; literature review and assessment. Ain Shams Engineering Journal: 101998.

Frenken, K. (2009). Irrigation in the Middle East region in figures AQUASTAT Survey-2008. Water Reports. (34).

Fthenakis, V.; Atia, A.; Morin, O.; Bkayrat, R. and Sinha, P. (2016). New prospects for PV powered water desalination plants: case studies in Saudi Arabia. Prog Photovoltaics Res Appl. 24(4): 543-550.

Ghanim, A. (2019). Water resources crisis in Saudi Arabia, challenges and possible management options: An analytic review. International Journal of Environmental and Ecological Engineering. 13(2): 51-56.

Gherasim, C.; Křivčík, J. and Mikulášek, P. (2014). Investigation of batch electrodialysis process for removal of lead ions from aqueous solutions. Chem Eng J. 256: 324-334.

Gorobchenko, A.; Mareev, S. and Nikonenko, V. (2021). Mathematical modeling of the effect of pulsed electric field on the specific permselectivity of ion-exchange membranes. Membranes. 11(2): 115.

Hyder, A.; Morales, B.; Cappelle, M.; Percival, S.; Small, L.; Spoerke, E.; Rempe, S. and Walker, W. (2021). Evaluation of electrodialysis desalination performance of novel bioinspired and conventional ion exchange membranes with sodium chloride feed solutions. Membranes. 11(3): 217.

Iorhemen, O.; Hamza, R. and Tay, J. (2016). Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling. Membranes. 6(2): 33.

Jurgenson, S.; Bayyari, F. and Parker, J. (2016). A comprehensive renewable energy program for Saudi Vision 2030. Renewable energy focus. 17(5): 182-183. doi.org/10.1016/j.ref.2016.08.006

Kırmızı, S. and Karabacakoğlu, B. (2023). Performance of electrodialysis for Ni (II) and Cr (VI) removal from effluents: effect of process parameters on removal efficiency, energy consumption and current efficiency. J Appl Electrochem. 1-17.

Knust, K.; Hlushkou, D.; Tallarek, U. and Crooks, R. (2014). Electrochemical desalination for a sustainable water future. ChemElectroChem. 1(5): 850-857.

Kukučka, M. and Kukučka Stojanović, N. (2022). Intrinsic Dependence of Groundwater Cation Hydraulic and Concentration Features on Negatively Charged Thin Composite Nanofiltration Membrane Rejection and Permeation Behavior. Membranes. 12(1): 79.

Liu, H.;Ma, J.; Winter, C. and Bayer, R. (2010). Recovery and Purification Process Development for Monoclonal Antibody Production. MAbs. : Taylor & Francis. 2: 480-499.

McMordie Stoughton, K.; Duan, X. and Wendel, E. (2013). Reverse osmosis optimization . https://doi.org/10.2172/1095449.

MOEWA (Ministry Of Environment Water & Agriculture). (2021). Standards and specifications for water types (according to the water system and its implementing regulations) in arabic. 25 p. https://www.mewa.gov.sa/ar/Information Center/DocsCenter/RulesLibrary/Pages/default.aspx

Mohammed, R. and Alkhafaja, R. (2023). Water Desalination Cost. University of Thi-Qar. Journal for Engineering Sciences. 13(1).

Obotey Ezugbe, E. and Rathilal, S. (2020). Membrane technologies in wastewater treatment: a review. Membranes. 10(5): 89.

Omran, K.; Goher, M. E. and El-Shamy, A. S. (2023). Factors affecting electrodialysis uint performance in the removal of copper from wastewater and aquatic environment treatment. Egyptian Journal of Aquatic Biology & Fisheries. 27(3): 35-53.

Patel, S.; Qin, M.; Walker, W. and Elimelech, M. (2020). Energy efficiency of electro-driven brackish water desalination: Electrodialysis significantly outperforms membrane capacitive deionization. Environ Sci Technol. 54(6): 3663-3677.

Peavy, H.; Rowe, D. and Tchobanoglous, G. (1985). Environmental Engineering. : McGraw-Hill New York. 7

Rambo, K.; Warsinger, D.; Shanbhogue, S. and Ghoniem, A. (2017). Water-energy nexus in Saudi Arabia. Energy Procedia. 105: 3837-3843.

SEC (Saudi Electricity Company) (2023). https://www.se.com.sa/ar-sa/Customers/pages/tariffrates.aspx last visit, 12 May, 2023

SWCC Saline Water Conversion Corporation, KSA (2023). Available on line https://www.swcc.gov.sa/en, last visit, 12 May, 2023.

USSB (United States Saudi Business Council). (2021). Water in Saudi Arabia: Desalination, wastewater, and privatization. US-Saudi Business Council (January 7, 2021). https://ussaudi.org/water-in-saudi-arabia-desalination-wastewater- and-privatization/

Shakweer, A. and Youssef, R. (2007). Futures studies in Egypt: water foresight 2025. Foresight . 9(4): 22-32. doi.10.1108/14636680710773803

Shatat, M. and Riffat, S. (2014). Water desalination technologies utilizing conventional and renewable energy sources. International Journal of Low-Carbon Technologies. 9(1): 1-19.

Strathmann, H. (2004). Ion exchange membrane separation processes. Membrane Science and Technology Series, vol. 9, Elsevier, Amsterdam. 106: pp. 227–230,147–181.

Vítěz, T.; Ševčíková, J. and Oppeltová, P. (2012). Evaluation of the efficiency of selected wastewater treatment plant. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis .40: 173-180.

Walker, W.; Kim,Y. and Lawler, D. (2014). Treatment of model inland brackish groundwater reverse osmosis concentrate with electrodialysis—Part I: Sensitivity to superficial velocity. Desalination. 344: 152-162.

Wang, T. and Yang, W. (2001). Factors affecting the current and the voltage efficiencies of the synthesis of quaternary ammonium hydroxides by electrolysis-electrodialysis. Chemical Engineering Journal. 81(1-3):161-169. doi.org/10.1016/S1385- 8947(00)00188-1