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A better understanding of seawater reverse osmosis brine: Characterizations, uses, and energy requirements

Mariam Khan [a], Rana S. Al-Absi [a], Majeda Khraisheh [b], Mohammad A. Al-Ghouti [a,*]

[a] *Environmental Sciences Program, Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, State of Qatar, Doha, P.O. Box: 2713, Qatar*

[b] *Department of Chemical Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar*

A R T I C L E I N F O

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Reverse osmosis

A B S T R A C T

Before investing in any optimizing technology for the recovery and reuse of brine resources, it is of importance to study the full physicochemical characteristics of the brine. In the current study, the physicochemical characteristics of Qatari seawater reverse osmosis (SWRO) brine were fully investigated. The current study intends to lead to a better understanding of the nature of SWRO brine given the economic significance for the country that can be benefited from recycling and reusing various components. The characterization includes physical and chemical composition, as well as mineralogical and morphological investigation. The chemical analysis revealed that the seawater reverse osmosis brine contains various valuable elements and metals such as Ca (77120 mg/L), Na (343500 mg/L), Li (238800 mg/L), Ba (3.3 mg/L), Cs (3.4 mg/L), Fe (30.5 mg/L) and Mg (238800 mg/L). The pH of the brine was 8, while the electrical conductivity and salinity were 90.56 mS/cm and 61.4 ppt, respectively. The scanning electron microscopy-energy-dispersive and energy-dispersive X-ray revealed the placement of various valuable metals on the salt surface. X-ray diffraction showed eight XRD peaks. Interestingly, one peak at 2θ of 31.7° is significantly more intense than the other seven peaks obtained, while all the eight peaks are extremely narrow. The Fourier-transform infrared spectroscopy analysis of the brine sample showed the presence of various functional groups. The narrow and intense peak around 1408 cm^{-1} confirms the presence of the S═O bond in the brine sample, which could correspond to the presence of sulfonyl chlorides or sulfates as indicated by the ICP-OES results. Furthermore, a comparison between the energy requirements for the widely used seawater desalination technologies was presented. Additionally, this study showed the economical and environmental advantages and potential for recovering valuable metals from seawater reverse osmosis brines.

1. Introduction

The increase in water supply-demand can be associated with various factors including increased pollution rates, increased water demand, economic growth, limited availability of water resources, and climate change has escalated water shortage issues globally [1]. According to studies, 40% of the world's population is already experiencing acute water shortages, with the number anticipated to climb to 60% by 2025 [2]. Such distressing data show that current water supplies such as aquifers, rainfalls, snowmelts, and river runoffs are no longer sufficient to support human demands, especially in water-scarce areas [3]. Countries that are susceptive to water scarcity should minimize the exploitation of unconventional water resources to maintain sustainability. Desalination plants are one of the most common methods practiced in many water-scares areas to meet water demands for domestic and municipal uses. Seawater desalination is an effective technology that is widely used around the world to obtain fresh potable water [4].

Qatar is one of the world's driest countries, with a limited water supply, minimal annual rainfall, and groundwater is the only natural source of freshwater. The rate of natural recharge (calculated at 58.1 Mm^3) is several times larger than the rate of annual groundwater withdrawals (estimated at 22.2 Mm^3) [5]. Qatar relies on seawater to provide the huge majority of its municipal water needs. Since the 1970s, when Qatar first set up its multi-stage flash (MSF) desalination plant, the country has continuously upgraded and expanded its treatment plant in response to the growing population demand. An estimate indicates that Qatar's water desalination plants can hold a capacity of 1.5 m^3 supplied

* Corresponding author.
E-mail address: mohammad.alghouti@qu.edu.qa (M.A. Al-Ghouti).

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through a thermal process. Borasni & Rebagliati [6] stated that in the past 10 years, MSF desalination plants have only gained popularity in the Middle East because of the low fuel cost and its reliability.

Apart from expansion, Qatar has also opted for other alternatives to fulfill the huge water demand through the implementation of reverse osmosis (RO) technology. The increased interest in RO desalination plants has raised concerns related to potential environmental problems. Moreover, RO plants create a considerable volume of water as well as brine, a concentrated saline solution that is disposed of in aquatic settings [7]. The disposal of seawater reverse osmosis (SWRO) brine back into water bodies remains an unsolved challenge. Rejected brine usually has high salt content, temperature, and consists of various compounds that were used in various pre-treatment to prevent biofouling. The presence of such content can be detrimental for marine and underground habitats [8]. It is widely suggested that brines discharged from RO plants have the potential to have a significant physicochemical and ecological influence on the receiving environment. Additionally, the presence of such chemicals further reduces clean water outputs [9]. Despite the fact that desalination plants have been a mainstay in many parts of the world for many years, brine management remains a technological, economic, and environmental problem [10].

There are various studies that highlight brine management to mitigate its environmental impacts [11,12]. Disposal of brine is usually 5%–33% of the total desalination cost. The cost is mostly determined by the quality of the concentrate, level of treatment, disposal method, and volume or quantity of concentrate [13]. Well injection, evaporation ponds, discharge into surface water bodies, solid salt concentration, and irrigation of high-salinity-tolerant plants are some of the common treatments available for brine disposal. Due to the various problems associated with brine disposal, various renewable technologies have been proposed such as the use of evaporation ponds to produce salts or chemicals for the industry [14].

However, before investing in any optimizing technology for the recovery and reuse of brine resources, it is important to characterize the brine. In the current study, the physicochemical characteristics of Qatari SWRO brine were fully investigated. The characterizations include physical and chemical composition, as well as mineralogical and morphological investigation. The current study intends to lead to a better understanding of the nature of SWRO brine given the economic significance for the country that can be benefited from recycling and reusing various components.

2. Materials and methods

2.1. SWRO brine sample collection and preparation

The SWRO brine was collected and sampled from a local desalination plant in Qatar, which uses an RO membrane system. Approximately 3 L of RO brine were collected for this study. After collection, all the collected samples were mixed together to create a representative homogenous sample of the SWRO brine. The sample was then stored in a plastic bottle and stored in a dark, dry, clean, and isolated area to prevent any contaminations or reactions with the surroundings. Brine water was dried for 4 days at 60 °C to obtain dried crystals to perform surface characterization and Fourier-transform infrared spectroscopy (FTIR) [15]. Prior to any analysis, the brine was first filtered using a 20 μm membrane filter to remove any suspended solids.

2.2. Elemental and mineralogical composition of the SWRO brine

The sample was filtered using a 20 μm pore membrane and the filtrate was diluted, due to the high concentration of ions in the solution. An inductively coupled plasma optical emission spectrometer (ICP-OES) was used to evaluate the sample after dilution (PerkinElmer Optima 3000V, or Shimadzu ICPS-7510 Sequential Plasma Spectrometer, Japan). The anion and cation content of the brine was determined using ion chromatography (IC) (METROHM model 850 professional). Powder X-ray diffraction (XRD) was used to determine the mineralogical composition of brine (PANalytical Empyrean/Netherlands). The scan was performed on a scale of 5–85 (2-theta-scale). The morphological, elemental, and quantitative compositional information were determined using scanning electron microscopy-energy-dispersive X-ray spectroscope (SEM-EDX) (NovaTM Nano SEM 50 Series, FEI Company).

2.3. Physical and chemical characterizations of the SWRO brine

Several physical and chemical characterization tests were used to characterize the collected SWRO brine sample. The pH of the solution ($pH_{solution}$), conductivity, salinity, temperature, and TDS were determined using HQ440d multi (Ames, Iowa, USA). Fourier Transform Infrared Spectroscopy (FTIR) (Shimadzu IR Spirit, Japan) was used to identify the functional groups on the surface of the brine by using spectra ranging from 400 cm^{-1} to 4000 cm^{-1}. The SWRO brine pellets were prepared for the FTIR analysis by mixing 1 mg of powdered samples with 300 mg of potassium bromide.

2.4. Economic feasibility

The economic feasibility of using multistage flash (MSF), multi-effect distillation (MED), and SWRO for obtaining pure portable water were evaluated and compared with other alternatives in terms of energy consumption.

3. Results and discussion

3.1. Elemental and mineralogical characterization of the SWRO brine

3.1.1. Inductively coupled plasma optical emission spectrometry (ICP-OES)

The concentrations of the metals present in the collected SWRO brine sample are reported in Fig. 1. The trace metals include barium (Ba), calcium (Ca), cesium (Cs), indium (In), iron (Fe), lead (Pb), lithium (Li), magnesium (Mg), potassium (K), sodium (Na), vanadium (V), zinc (Zn) and strontium (Sr). Results indicated that the collected SWRO brine showed significant enrichment of Ca (77120 mg/L), Na (343500 mg/L), Li (238800 mg/L), and Mg (238800 mg/L). The results also indicated that the SWRO brine had a low concentration of Ba (3.3 mg/L), Cs (3.4 mg/L), In (4.5 mg/L), Fe (30.5 mg/L), and Pb (44.2 mg/L). The concentration behavior of trace metals in brine is influenced by a number of factors such as the chemistry of brine, the desalination technology employed along with the used chemicals, and the region's geological setting [16]. The concentration of strontium and zinc can be due to the presence of carbonates in the brine, chemical, and physical weathering, as well as the leaching of rocks and soils [17]. While the presence of lead is due to enrichment and the production of stable chloride complexes that hinder their removal into the sediments. Interestingly, zinc in seawater is often found to be associated with other metals like lead, which explains the presence of lead in the brine sample [18]. Furthermore, because there were no outflows, it is probable that the bottom sediments have a high potential for serving as a trace metal sink. Moreover, vanadium presence in the collected reverse osmosis brine could be due to natural reasons like soil erosion and weathering of rocks as well as anthropogenic sources such as the burning of fossil fuels [19]. The relatively high concentration of lithium in the brine is due to the fact that the seas are major reserves for lithium around the world [27]. As mentioned previously, desalination plants often employ various kinds of chemical treatments during the desalination process, which may be a great contributor to the presence of various kinds of trace metals like iron, lanthanide, cesium, and barium. Kasedde and coworkers (2014) studied the characterization of brine lake in Uganda and found that the lake dominated with Na^{+}, K^{+}, Cl^{-}, CO_3^{2-}, SO_4^{2-} and HCO_3^{-} ions while Mg^{2+}, Ca^{2+}, Br^{-} and F^{-} are present in smaller concentration. The study explained the high concentration of CO_3^{2-} and SO_4^{2-} was primarily due

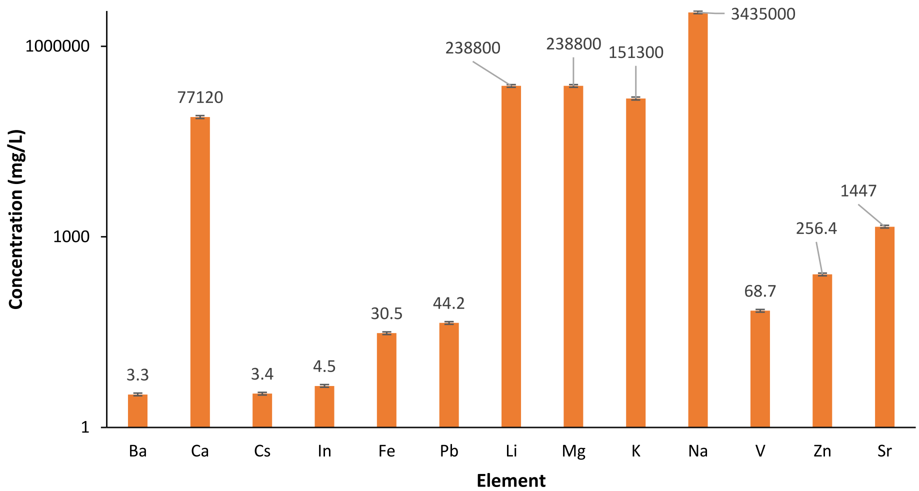


Fig. 1. Elemental compositions of the SWRO brine according to ICP-OES analysis.

to the geological setting such as high trona, thermonatrite, and burkeite. Table 1 compares the current data with various other brine water.

3.1.2. Ion chromatography (IC) analysis

The major cations and anions found in the studied brine samples were Na^{+}>Ca^{+}>K^{+} while SO_4^{2-} > Cl^{-} > Br^{-} (Fig. 2 A and B). Additionally, it can be noted that the brine salts were dominated by sodium and chloride along with other impurities. While calcium, potassium, sulfate, and bromide make up the rest bulk constituents in the salts. These results are predictable for a reverse osmosis seawater desalination brine solution. This is because seawater is characterized by its salinity, which corresponds to the presence of high salt content. Salt in this context is known as calcium and sodium chloride, and as seawater is desalinated to produce freshwater, the calcium and sodium chloride should be removed in the form of brine. Therefore, the highest concentrations of cations and anions were calcium, sodium, and chloride, respectively. Other types of salts in the forms of potassium and magnesium chlorides may be present in seawater and brine solutions as well. Kasedde and coworkers (2014) performed the brine characterization using the Piper tri-liner diagram, the results indicated that high sulfate content, ion exchange, and an intermediate link between Na–Cl and Na–HCO_3 water types were found in the Lake Katwe and Lake Kitagata brines (Fig. 2C). The study discussed that the brine originated from highly saline marine groundwater. The current study showed similar results of high sulfate content and ion exchange (Fig. 2 B). This demonstrates the similar characteristics of saline marine brines.

3.1.3. X-ray diffraction (XRD) analysis

Fig. 3 illustrates XRD patterns of different compounds composition present in brine samples. Amongst with sodium chloride was found at 7 different peaks at 2 θ values of 27.36, 31.73, 45.45, 54.94, 56.44, 75.33, and 83.99. Similarly, a small peak was observed which denoted the presence of calcium at 31.89. While 74.57 and 63.45 at 2 θ confirmed the presence of lithium chloride. Lastly, 26.38 and 30.47 confirmed calcium strontium compounds. Additionally, strong peaks for hanksite, and burksite were found [20,30]. As a general principle, the spacing between the atoms or crystals of the sample is represented by the 2θ values of an XRD graph. The degree of the crystallinity of the sample could be understood from the peak intensity in the XRD graph as shown in Fig. 3, where lower intensity corresponds to lower crystallinity and vice versa. Moreover, the width of the graph's peak represents the size of the crystals in the sample being tested [31]. For example, eight XRD peaks can be observed for the SWRO brine sample at the study (Fig. 3). Interestingly, one peak at 2θ of 31.7° is significantly more intense than the other seven peaks obtained, while all the eight peaks are extremely narrow. This means that at 2θ of 31.7°, the crystallinity of the atoms is significantly high with small-sized crystals. The peaks observed at 2θ of 45.5°, 56.4°, and 66.3° are almost similar in their width's (narrow) and intensities. The peak at 2θ of 45.4° has an intensity of 6439 a.u., whereas the peak at 2θ of 56.4° has an intensity of 6767 a.u. However, the peak at

Table 1
Chemical composition of brine in various studies.

Ca	Mg	Na	K	Sr	Li	Rb	Reference
Element, mg/L							
521	1738	18,434	491	NR	NR	NR	[21]
891.2	2877.7	24649.2	888	NR	NR	NR	[22]
790	2379	21921	32127	NR	NR	NR	[23]
789.30–804.20	2390.50–2524.10	23,100.00–24,800.00	790.20–810.10	15.42–16.11	0.39–0.41	0.19–0.23	[24]
610	1870	15680	NR	NR	NR	NR	[25]
9220	4180	111000	3700	258	<5	NA	[26]
788	2600	20077	838	NR	NR	NR	[27]
713.3	2128.5	21432	1034.1	NR	NR	NR	[28]
7300	1140	78320	1819	458.5	78.6	6.5	[29]
535	1497	13112	429	6.4	NR	NR	[30]
77120	238800	3435000	151300	1447	238800	NR	**Current study**

NA: Not applicable result.
NR: Non-reportable result.

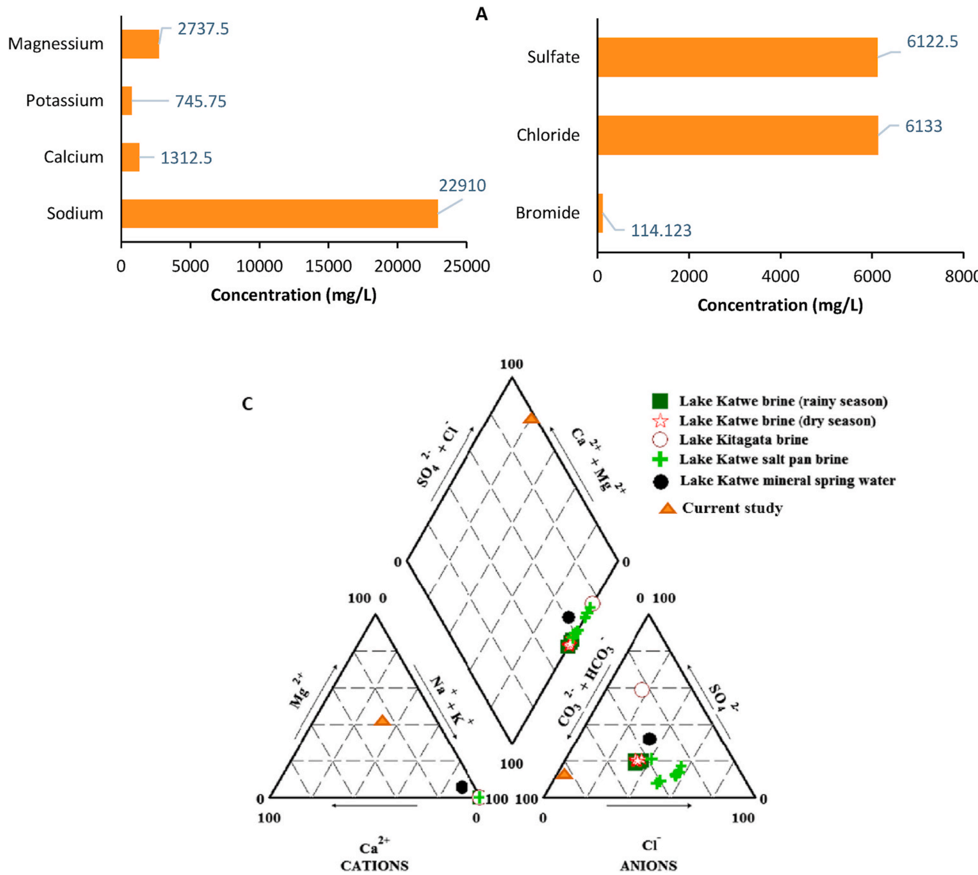


Fig. 2. The composition of the major (A) Cations (B) Anions (mg/L) in the SWRO brine using ionic chromatography (C) Piper tri diagram of brine water (Modified from [28]).

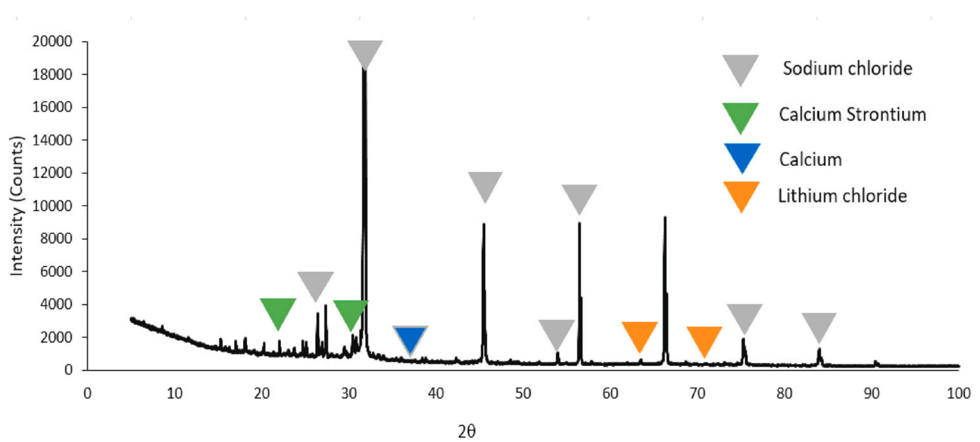
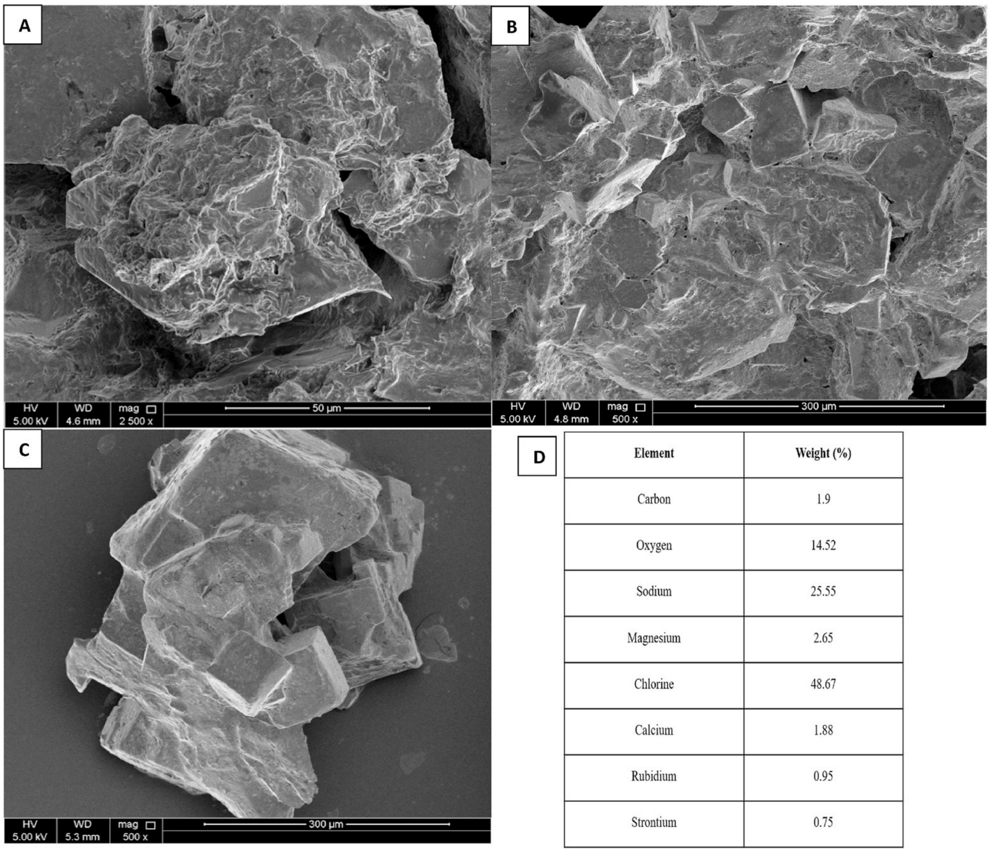


Fig. 3. X-ray diffractrogram of brine water.

2θ of 66.3° was found to have an intensity of 6789 a.u. This shows that at these 2θ phases or spacing between the sample's atoms, the sizes, as well as the degree of crystallinity of the brine sample, is almost the same, low number of small-sized crystals. The lowest degree of crystallinity could be observed for the collected reverse osmosis brine sample at 2θ of 26.6°, 27.5°, 74.8°, and 84.5°. Abdou and Moharam [32] studied the characterization of marine salt samples, which involved the application of an XRD analysis. The peaks obtained for the sample were very similar to the peaks obtained by this study for the characterization of the reverse osmosis brine sample. Interestingly, the peaks obtained by both studies correspond to the same characteristic peaks of the NaCl standard, which demonstrates the salt nature of the sample at the present study.

3.1.4. SEM-EDX analysis

Fig. 4 shows images of the brine sample taken with a scanning electron microscope (SEM). The sample was dried at 100 °C for 24 hours prior to the SEM-EDX analysis to obtain the surface morphology and chemical characteristics of the crystals. The metals that were identified from various analytical equipment were found in SEM-EDX as well. The result showed the presence of hexagonal crystals on the surface which is throughout the samples. The surface of the salts is laden with various salt crystals as seen in Fig. 4 (A, B, and C). Furthermore, the morphology of



Element	Weight (%)
Carbon	1.9
Oxygen	14.52
Sodium	25.55
Magnesium	2.65
Chlorine	48.67
Calcium	1.88
Rubidium	0.95
Strontium	0.75

Fig. 4. SEM morphology of the dried SWRO brine sample at (A) 2500x magnification (B) 500x magnification (C) 500x magnification and (D) The elements by weight (%) in the brine crystals.

brine crystals is somewhat cubic, agglomerated, non-smooth, and contains few cavities or cracks. Quilaqueo et al. [33] showed similar SEM morphological results for various types of salts. The EDX analysis revealed that the collected reverse osmosis brine crystals contained mainly chlorine and sodium (Fig. 4 D), which was shown previously by the IC and ICP-OES analysis. Moreover, some of the elements are present in minute amounts may be lost or evaporated during the drying process of the brine, which explains the remaining 3.13% by weight from the brine sample.

3.1.5. Fourier-transform infrared spectroscopy (FTIR) analysis

The FTIR spectrum of the brine sample is shown in Fig. 5. The presence of O–H stretching and trace N–H amino acidic group may be seen in the broadband around 3250 cm^{-1} - 3356 cm^{-1}. The asymmetric stretching of the methyl group caused the peak to appear around 2950 cm^{-1} (-CH_3). The bands at 2920 cm^{-1} and 2860 cm^{-1}, on the other hand, correspond to asymmetric and symmetric stretching of –CH_2, respectively. Deformation vibrations of aliphatic groups and deprotonated symmetric stretching of carboxylic groups created the peak around 1460 cm^{-1} -1400 cm^{-1} [34]. Moreover, C=O stretching of the protonated carboxylic acid functional group was linked to the peak

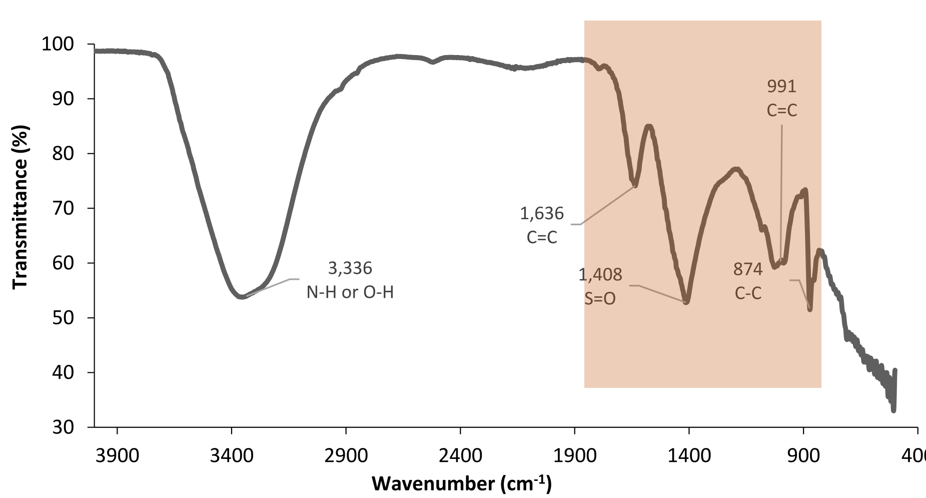


Fig. 5. The FTIR spectrum of functional groups present in the SWRO brine sample.

around 1710 cm^{-1}. The peak around 1630 cm^{-1} owed it to the presence of aromatic C═C vibrations [35]. Moreover, the narrow and intense peak around 1408 cm^{-1} confirms the presence of the S═O bond in the brine sample, which could correspond to the presence of sulfonyl chlorides or sulfates as indicated by the ICP-OES results shown previously [36]. Furthermore, the existence of -C-OH stretching of aliphatic alcohols was revealed by the peak around 1170 cm^{-1} [44]. The peaks at 1080 cm^{-1} and 950 cm^{-1} were linked to vibrations from polysaccharide and carbohydrate C–O and C–H bonds [37]. A strong peak around 872 cm^{-1} revealed the aromatic CH bend. Lastly, the peaks at 991 cm^{-1} and 874 cm^{-1} are related to C═C bending due to alkene compounds and C–C stretching, respectively [38].

3.2. Physical and chemical characterization of the SWRO brine

The physical and chemical properties of the SWRO brine samples are reported in Table 2. The brine was observed to be alkaline as indicated by the pH which was around 8 and was similar to Naidu et al. [23] and Liu et al. [30] findings. While the electrical conductivity and salinity were 90.56 mS/cm and 61.4 ppt, respectively. It is worth noting that, that the salinity of the brine is 1.6 times higher than the average salinity of the seawater as illustrated in Table 2. The conductive ions usually come from dissolved salts and inorganic materials such as alkalis, chloride, sulfides various other compounds [39]. Thus, the higher the ion concentration the higher the conductivity of water. Similarly, sodium and chlorine ions are the main charge carriers for the electrical conduction in brine water along with other ionic derived species. As observed from elemental analysis sodium and chloride both are present in a very high amount in the brine water. Furthermore, salinity is considered a vital contributor that influences the conductivity of the solution. The salinity of brine is usually dependent on various major ions, alkali, and alkaline earth metals salts including calcium, magnesium, sodium, and various carbonates. It is important to point out the high salinity of Qatar's brine can also be influenced by the high evaporation that takes place due to the high temperature observed in the country. Similarly, total dissolved solids (TDS) can also have an adverse impact on aquatic life and water quality. It is one of the parameters which determines the conductivity of the water along with temperature and salinity. In a study by Bindel et al. (2020) TDS and conductivity were found to be similar as well. Table 2 illustrates that the average temperature of the SWRO brine involved in other studies and it was observed that the current study has a lower temperature than the temperature of seawater. This is because the collected SWRO brine cooled down during shipping and storage.

3.3. Potential uses of seawater desalination brine streams

3.3.1. Production of sodium hydroxide and hydrochloric acid

It is reported by studies that sodium hydroxide can be produced through a process called the Chloralkali process followed by an electrochemical reaction [47]. The following reaction can also be used to produce electrolysis Cl^- and Na^+,

$$2H_2O + 2Na^+ + 2e^- \rightarrow H_2 + 2NaOH \quad (1)$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (2)$$

Additionally, by incorporating a process called bipolar membrane electrodialysis (BMED) or Electrodialysis with bipolar membranes (EDBM), NaOH and HCl can be acquired. The membrane on the cathode and anode will isolate the chemicals, preventing the ions to be detached back to the solution. However, this process is limited to pilot scale and not practiced industrially due to its complex design, high maintenance, and high running cost [48]. Direct electrosynthesis, in which oxygen gas is created in the anode, is another option for producing HCl and NaOH, while hydrogen gas is produced in the cathode. This reaction can be expressed if brine water is mixed with NaCl (Eq (3)),

$$2H_2O + 4Cl^- \rightarrow O_2 + 4HCl + 4e^- \quad (3)$$

3.3.2. Agricultural and irrigation use

Another use of the SWRO brine can be in the agricultural sector. However, there are certain limitations to such use. For instance, prior to its use in the agricultural sector, the brine should be free of hazardous components and have a low TDS level that meets the country's health regulations. Currently, several facilities are using waste from brine streams to produce liquid fertilizers. Usually, a mix of hardness and sodium is preferred. Therefore, to provide such brine waste, brine is treated using an ion-exchange process to remove sodium ions while keeping the hardness [49].

3.3.3. Recovering solid salts

The solid waste from SWRO brine can be beneficial to the economy. By implementing zero liquid discharge (ZLD) solid salts can be recovered from brine. However, this will require additional various steps, including brine concentration, crystallization, and dewatering of the solids. Various industrial sectors can use brine solid salts for different chemical production processes such as curing, de-icing, dyeing, water treatment. However, various researchers have reported pilot studies proving that salts may be extracted from brine using a variety of methods. Quist-Jensen et al. [50] investigated the possibility of using membrane crystallization (MCr) to recover salt and water from RO brine. It was found that to treat 100 m^3 of brine, 50% of water recovery was achieved using the RO unit, while MCr was able to recover more than 90% of water. The study concluded the possibility of exploring an integrated conventional membrane with MCr to obtain high water recovery, low energy consumption, and higher salt recovery. Panagopoulos [51] achieved a ZLQ system by preparing a brine treatment system with solar power, to recover high purity solid salt. The system incorporated techno and economic assessment of solar collectors and cells with MED-thermal power compression (MSD-TVC) into a single system. The study concluded that this system can be an economically viable solution for brine management. Additionally, another study was

Table 2
The physical and chemical characterization of seawaters and SWRO brine.

Saline solution	pH	Salinity (ppt)	TDS (g/L)	Conductivity (mS/cm)	Temperature (°C)	Reference
Seawater	8.1	NR	42.5	59.5	28	[29]
Seawater	7.8	NR	40.5	57500	20.5	[40]
Seawater	8.15–8.0	NR	39.01	0.08	NR	[41]
Seawater	8.1–8.2	40.4–42.7	35	61.62	13–31.5	[42]
Seawater	7.8 ± 0.7	29.5 ± 1.2	NR	NR	26 ± 2	[43]
Seawater	8.23	~35	71.88	11.21	NR	[44]
SWRO brine	8.2	39.1–39.4	NR	NR	19–21 °C	[45]
SWRO brine	8.0	NR	30.73	77	25	[46]
SWRO brine	8.0–8.12	NR	58.80–58.93	NR	NR	[23]
SWRO brine	8.17	NR	71.827	11.204	NR	[44]
SWRO brine	10	NR	69.17–72.36	88–132	20	[26]
SWRO brine	7.95	61.4	67.46	90.56	19.5	**Current study**

conducted under Zero Brine Project to assess the recovery of valuable concentrates coming from two-pass NF retentate and RO brine. This initial plant was able to treat 400 L/h of a clay mine. The energy consumption of this project was estimated to be 12 kWh/m^3 of brine treated with 82.8% salt recovery. Mitko et al. (2021) [52] and Al-Anzi et al. (2021) [11] investigated the viability of using an electrodialysis (ED)-evaporator hybrid system to treat synthetic brine water to produce coarse salt and freshwater. The study concluded that ED operating with high current density was favorable for producing salts with about 87.87% recovery rate.

3.3.4. Metal recovery

Seawater is considered a vast source of various valuable metals. With a growing population, the demand for such metals has exponentially increased over the years. Recently, there has been increased attention in recovering valuable and rare metals from brine streams as shown in Table 3. This can be beneficial to the country in various ways such as, it can increase the country's revenue, decreasing water production costs, and preventing various environmental issues that are associated with brine disposal [53]. The current method that is being used for metal recovery in a lab is still undeveloped and requires further investigation to further increase the efficiency of the metal recovery. The common extraction procedure for metals such as bromide and potassium includes precipitation, ion exchange, and adsorption. While, the recovery of trace metals from brine can be challenging due to the complexity of brine, low metal concentration, and limited selectivity. Vassalloa et al. (2021) have attempted to overcome such barriers but still to date the recovery of trace metals remains a challenge. Moreover, due to the advancements in lithium recovery from brine, around 300 mg/dm^3 -1600 mg/dm^3 of lithium is mostly produced from brine. Currently, brine approximately consists of lithium equivalent to 52.3 million tons, while 8.8 million tons are from the mineral resource. Additionally, other valuable trace metals include rubidium (Rb) which has a high economic value (USD 14720.00/kg). Furthermore, Rb is commonly used in fiber optic telecommunication as well as laser technology [12]. According to the US geological survey [54], 156000 × 10^6 tons of Rb^+ are present in seawater.

3.4. Energy consumptions of widely utilized seawater desalination technologies

3.4.1. Energy consumption for multi-stage flash (MSF) seawater desalination process

There are several factors that influence the energy consumption of seawater desalination multi-stage flash (MSF) processes. For example, construction materials, number of desalination stages, heat exchanger design, maximum temperature level for heating source, the temperature of the heat sink, and salt content in a brine solution. By increasing the number of stages, the performance ratio, and heat transfer area, the cost of energy consumption can be lowered [61]. Furthermore, MSF plants consume between 190 and 283 MJ/m^3 of energy at GOR 12 and 12 and 8, respectively. For an MSF plant operating at 30% efficiency, the thermal energy required is between 15.83 kW he/m^3 and 23.5 kW he/m^3. Furthermore, the energy required by the running pump might range from a low of 5 kW he/m^3 to a high of 2.5 kW he/m3. A typical MSF plant's overall energy consumption ranges from 19.58 kW he/m^3 to 27.25 kW he/m^3 (Table 4) [81/62].

Table 3
Compilation of various metals recovered from brine streams.

Metal	Amount (mg/g)	Reference
Uranium	6.22	[55]
Magnesium oxide	78.8	[56]
Rubidium	57.46	[23]
Uranium	0.00028	[57]
Lithium	2.6	[58]
Lithium	37	[59]
Boron ($B(OH)_4^-$)	70	[59]
Magnesium	0.0768	[60]

3.4.2. Energy consumption for multi-effect distillation (MED) seawater desalination process

The energy consumption for MED desalination processes can be calculated using the following equation [11],

$$E = \frac{I \times U \times t}{1000} \tag{4}$$

where E is the energy consumed, I indicate the current (A), U is the voltage (V) and t is the operational time in hours.

The two energy types required for MED are similar to MSF, which are the electricity required for the operation of the pump and low temperatures heating for evaporation. A typical MED plant will require 145 MJ/m^3 at GOR = 16, and 230 MJ/m^3 at GOR = 10 for thermal energy. The pump's electrical consumption ranges from 2.0 kW he/m^3 to 2.5 kW he/m^3 [63]. Similar to MSF, assuming the MED power plant's efficiency is maintained at 30%, the thermal energy required will range from 12.2 kW he/m^3 to 19.1 kW he/m^3. Overall, a typical MED process requires between 14.45 kW he/m^3 and 21.35 kW he/m^3 of energy (Table 4) [62].

3.4.3. Energy consumption for reverse osmosis (RO) seawater desalination process

Unlike the MSF and MED seawater desalination processes, RO is a membrane-based desalination method. As thermal desalination technologies are popular worldwide due to their high water recoveries, they are well-known for their relatively high energy consumptions [64]. Several factors determine the overall energy consumption of a large-scale SWRO desalination plant, such as feeding water's salinity and temperature, as well as equipment efficiencies like energy recovery devices (ERD's) and pressure pumps. In addition, the quality and quantity of the treated water could greatly impact the total energy requirement of an SWRO desalination plant [22]. Less energy consumption for an SWRO desalination plant could be possible if the feedwater temperature is higher and salinity is lower. Moreover, the development of ERD's and employing larger-sized pumps over the years significantly reduced the overall energy consumption of SWRO plants. Furthermore, producing high quality and recovery permeate would require the installation of special RO configurations and require more energy consumption. SWRO desalination plants that produce lower brine quantities significantly require higher energy demands [21]. SWRO desalination technology is considered to be more energy-efficient and cost-friendly than MSF, MED, and other common seawater desalination technologies (Table 4). Because of the recent advancements in the SWRO desalination technology, its energy consumption is decreasing substantially throughout the years [65]. For example, in 1970, the energy consumption of a large-scale SWRO desalination plant was on average equal to 20 kWh/m^3, which was significantly reduced in 2010 to be equal to around 2.5 kWh/m^3. In general, the energy required for a typical SWRO desalination process is between 2 kWh/m^3 to 4.5 kWh/m^3 (Table 4) [66].

3.5. Environmental impacts of brine disposal into water bodies

SWRO has the largest water capacities and hence tends to use a variety of intake mechanisms, including deep-water intakes, canal intakes, surface water intakes, offshore intakes, and passive-screen intakes. The impact on marine life varies with the type of intake system being utilized and the level of treatment prior to discharge [69]. Additionally, the discharge of brine to water bodies could be done directly without pre-treatment and could undergo very intense pretreatment processes. Many of these processors may require strong and high doses of chemicals. Thus, the brine being discharged will also include such harsh

Table 4
Summarizes the required energy for some of the common desalination plants as well as their advantages and limitations.

Properties	Desalination plants					
	Multi-stage flash (MSF)	Multiple-effect distillation (MED)	Seawater reverse osmosis (SWRO)	Brackish water reverse osmosis	Mechanical vapor compression	Electrodialysis (ED)
	Energy consumption					
Unit size (m^3/day)	50,000–70,000	5000–15,000	Up to 128,000	Up to 98,000	100–3000	2–145,000
The amount of electricity utilized (kW h/m^3)	2.5–5	2.0–2.5	2–4.5 with ER	1.5–2.5	7–12	2.64–5.5
The total electricity consumed (kW h/m^3)	19.58–27.25	14.45–21.35	2–4.5 with ER	1.5–2.5	7–12	0.7–2.5 for low TDS And 2.64–5.5 for high TDS
	Advantages and limitation					
Reference	[67]	[67]	[66]		[68]	[68]
Advantages	Brine does not require too much treatment, incorporated with power plant	Operation life is long. Has large capacity. Does not require intensive brine pre-treatment. High recovery for freshwater. Salinity could be controlled depending on the cost invested to construct the plant	For (RO) Energy-efficient. Does not require the plant to be completely shut down for maintenance. Able to remove all pollutants except salts. Requires less energy for operation. Quick start-up. The plant can be improved depending on the budget and requirement.		Resistant to high salinity	Fouling does not occur as frequently as in RO. Can tolerate high salinity Can produce high quality of water
Disadvantages/ limitation	Requires high costs for both maintenance and operation. Requires additional space for the cooling of freshwater.	Requires high cost for operation. High carbon footprint. Requires chemicals to prevent corrosion. Plant requires to shut down while performing maintenance	The membrane has a very short lifetime. Limited range of salinity Common issues related to fouling can occur The maintenance and replacement of the membrane are expensive. Mechanical failure may occur due to high pressure. The brine requires intensive pre-treatment.		High maintenance cost for both maintenance and operation. Requires high energy to operate.	Requires high energy and capital to achieve high quality of water. In High saline feed, low flux is achieved Unable to remove neutrally charged contaminants from the feed.

chemicals either from the desalination process or from pre-treatment stages, which may pose detrimental impacts on marine life. The removal of marine species, usually permanently, due to the installation of an intake system is known as impingement and entrainment. As such impingement and entrainment are two of the major threats faced by marine life. Another key environmental issue that should be considered is the mortality rate of fishes, invertebrate eggs, and larvae that are being impacted.

Seawater desalination brines are characterized by their elevated temperatures and salinity levels. Many studies proved that the disposal of brine streams into water bodies may increase the surface temperatures and salinities approximately to 50 °C and 85 g/L, respectively. Other risks of brine disposal into water bodies include altered pH ranges, decreased oxygen levels, toxicity, and eutrophication [70]. Seawater organisms and plants are adapted to specific environmental conditions and any disruption to these conditions could risk their existence [71]. Qatar is a host to a huge coral community in various parts of the country. A little increase in salinity can adversely affect the coral community. Additionally, corals are known to be one of the productive ecosystems consisting of various biomass. Therefore, an adverse impact on corals can lead to a cascade effect on various tropical levels. In addition, seasonally, Qatar also hosts gatherings of numerous whale sharks and dugong. Shaaban et al. (2018) [72] concluded that the male sharks dominated in the Qatari water in contrast to females. Thus a little change in water conditions can negatively affect marine organisms. Furthermore, seawater desalination brines could contain various types of metals due to the corrosion of desalination heat exchangers or pre-treatment chemicals. The release of metals into water bodies might bring toxic and lethal effects to aquatic species. A study done by Alshahri (2016) [73] revealed that the region surrounding desalination plants at the Arabian Gulf contains significant amounts of iron, copper, and chromium. While Rodríguez-Rojas et al. (2020) [74] reported that the brown algae known as *Ectocarpus* suffered from a decrease in important functional antioxidants, disrupted photosynthesis, uncontrolled enzyme encoding, enhanced peroxidation of lipids, and other effects due to their exposure to seawater desalination brine. Lastly, microalgae are the basis of many aquatic food webs and any disruption in their existence might affect entire food webs.

4. Conclusion

Desalination technologies produce highly saline brines that require management and treatment. The direct discharge of brine into the sea poses a significant threat to marine life and the ecosystem. To achieve a suitable brine management strategy, an understanding of its elemental, mineralogical, physical, and chemical properties must be established. This study examines the physicochemical characteristics of Qatari SWRO desalination brine streams. Several analytical techniques were employed namely ICP-OES, IC, SEM-EDX, FTIR, and XRD. In addition, the pH, salinity, conductivity, temperature, and total dissolved solids of the SWRO brine stream were investigated. Interestingly, the SWRO brine showed the presence of various economically and industrially valuable metals such as lithium, strontium, vanadium, and others. There are various technologies to recover brine including distillation, membrane distillation, solar pond, crystallization, and adsorption. However, some of these technologies require large space and go through frequent fouling and wear and tear which adds additional maintenance costs. Recovery of metals such as lithium, strontium, rubidium and, uranium can be possible by the adsorption process. There are various advantages associated with using adsorption such as minimal energy, cost, and preparation requirements. It is important to highlight, the cost-effectiveness of recovering resources depends on two major things: the market value of the resource recovered and the process used. Though extracting valuable resources from brine is possible, however, it calls for more studies to evaluate the technical and economic feasibility. Thus, more pilot-scale research is required to develop low-cost technology, evaluate process efficiency, metal recovery, and environmental benefits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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