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ENVIRONMENTAL IMPACT OF SEAWATER DESALINATION PROCESSES IN CHINA - A REVIEW

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ABSTRACT: The aim of the present review is to report and discuss the relevant literature on environmental impact of sea water desalination in China. China, especially its coastal provinces, is facing a serious shortage of fresh water resources and a water pollution issue, restricting further development. To address the serious imbalance between water resource supply and demand, in addition to efficiently utilizing the regular water resources, China has strived to develop alternative water resources to combat the water crisis, among which seawater desalination plays an important role. This paper reviewed the current situation of the utilization of desalinated seawater in China, including the points outlined below. In order to reduce the detrimental effects of desalination technologies on the environment and to make them sustainable it is of fundamental importance to develop "circular" approaches aimed at valorizing the concentrate streams requiring disposal, with the ultimate goal of zero liquid discharge. It was found that extensive research has been performed on Mg extraction (mainly as brucite) from seawater brines using different technologies; although a few demonstration-scale studies exists on Mg recovery processes both from seawater from industrial brines, most of the recovery technologies are still performed at laboratory scale. In the long term, it is of significant importance to develop desalination technologies to face the challenges of global water crisis. Desalination technologies in China are vital both in the field of freshwater extraction from the sea and the improvement of water environment and ecology. Specifically, emphasis should be put on the following aspects as follows: (1) Technology innovation: Further improve the performance of large-scale SWRO plants. Efforts include the enlargement of single unit capacity, decrease of energy consumption, improvement of system integration, operational stability and reliability, and desalination cost. Further endeavors should be made towards pretreatment and system instrumentation, high-performance RO membranes and elements, high-pressure pumps and energy recovery devices, etc. (2) Utilization of chemical resources from seawater: The extraction and reuse of chemical resources from seawater desalination is an attractive topic from a scientific point of view. Better technologies need to be explored to recover chemicals and reduce possible cost. Moreover, the extraction of strategic elements such as lithium and uranium is more challenging and needs better technologies. (3) Green pretreatment methods ; Attention should be paid to the development of green pretreatments involving green antiscaling agents and agent-free biological methods. It is advisable to investigate electrocoagulation and dissolved air flotation techniques.(4)Emerging desalination technologies: Apart from the traditional SWRO desalination technologies, emerging technologies including MD, CDI, and ED desalination processes require more research efforts, from the exploitation of novel membrane materials to the fabrication of core components and equipment. In addition, hybrid systems coupling the traditional technologies and the emerging technologies should be further promoted to make the most of the less-popular technologies. Overall, with the ongoing research and development of desalination, China is believed to play a more and more important role in the international desalination market with remarkable openness and inclusiveness, providing state-of-the-art desalination technologies, facilities and services, benefitting the water-stressed countries and regions in the world.

Key words: China, current status, seawater desalination, environmental impact,

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INTRODUCTION

China is facing increasing pressure on fresh water supplies (**Yi *et al.*, 2011**). Its per capita water resource quantity was 2,354.9 m^3 in 2016, approximately a quarter of the world's average level, and therefore it has been recognized as one of the 13 lowest water-availability countries throughout the world (**Bai *et al.*, 2007**). Furthermore, the majority of the water resources is concentrated in southern China, leaving the northern and western regions to experience drought (**Yi *et al.*, 2011; Lyu *et al.*, 2016**). Some rivers, lakes and underground aquifers have dried up due to the overdraft. Some surface waters have been polluted so that they are no longer suitable for human use (**Lyu *et al.*, 2016**). With population growth, accelerated urbanization and global climate change, shortages of water resources are becoming a key factor restricting economic development in China.

Desalination is considered as a viable solution to address the issue of global scarcity of fresh water (**Panagopoulos *et al*., 2019; Ramasamy, 2019**). From a desalination process, two streams are obtained treating the seawater feed: freshwater and brine. The salinity of brine is more than three times than the salinity of feed water. Being concentrated flows, brines should be considered as an important source of materials and no longer as a waste to be disposed of. From this comes the importance of developing processes to supply the economy with a constant flow of minerals at reasonable costs, in order to close the industrial cycles and achieve sustainability. In particular, magnesium (Mg) is the most interesting cation in terms of industrial importance and value contained in waste brines. In Europe it is classified as a "critical raw material" from the European Commission among the 30 most critical raw materials, which are subjected to a high risk of supply interruption and a high economic importance, thereby recognizing the importance of searching for alternative ways for its supply (**COM, 2020**).

To address the serious disparity between water resource supply and demand, China has taken many measures to conserve and augment the limited water resources to meet the growing demands (**Yi *et al.*, 2011; Lyu *et al.*, 2016**). These measures include implementing a very stringent water management system that specifies water efficiency objectives (**Wang *et al.*, 2015**), adjusting the inner structures of primary, second and tertiary industries for a series of water-saving targets (**Chao *et al.*, 2006**), and implementing trans-basin water diversion projects across the country (such as the South-to-North Water Diversion Project) and (**Zhao *et al.*, 2017**).

As an overview, 43% of China's population lives in its 11 coastal provinces with a 1,800 km coastline occupying 13.7% of China's territory (by the end of 2010) (**China Statistical Year Book, 2010**), and the average water resources per capita in these 11 coastal provinces are only 1,915 m^3 (in 2010), much less than the national level Bulletin of Water Resources in **China (2010)**. Furthermore, urbanization, economic development and industry are much more advanced in coastal areas compared with those in Chinese inland areas, leading to strong water resources pressure in coastal regions. From the **Chinese Statistical Year Book (2010)**, the Gross Domestic Product (GDP) was 24.6 trillion yuan in 2010 in coastal provinces, accounting for 61.3% of the national GDP. However, the total water resources in coastal provinces only comprise 28.6% of the total national water resources. The total water use in coastal areas is 248 trillion m^3, accounting for approximately 41.2% of the total national water use. In coastal areas, 28.1% of the water resources have been used, while the national average water use efficiency is only 19.5% (Bulletin of Water Resources in **China (2010)**.

The three commonly used technologies worldwide for seawater desalination include multi-phase flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO). MSF was adopted for water generation in the 1950s, and has advanced significantly since the 1980s. This technology was employed for 26% of total seawater desalination capacity worldwide (**Ghaffour *et al.*, 2013**). MED was the primary technique for desalinating seawater before the 1960s, and this technology has been applied in more large desalination plants (**Feng and Xie 2010**). RO was applied in seawater desalination in the 1950s. With the advancement of high performance membranes, and installation of energy recovery devices, the cost and energy consumption for this technology has decreased significantly during past decades (**Elimelech and Phillip, 2011**).

Present Condition of Utilization of Seawater Desalination

It is clear that the development of seawater d esalination plants in China has entered a rapid gr owth phase since 2006. By the end of 2015, ther e were 139 seawater desalination plants put into operation in China, with a total production capac ity of 1 × 10^6 m^3/d Utilization Report of Seaw Ater in **China (2015**). Table 1 lists the 10 largest seawater desalination plants present in China. Furthermore, by the end of 2015, 31 seawater dealination plants with capacities of over 10^4 m^3/d were constructed throughout the country with a total capacity of 8.9 × 10^5 m^3/d. Approximately 7.2% (10) and 19.4% (27) of the total seawater desalination plants have a capacity from 5,000 to 10,000 m^3/d and from 1,000 to 5,000 m^3/d, respectively, producing approximately 1.2 × 10^5 m^3/d in total. There were 71 seawater desalination plants with capacities below 1,000 m^3/d across China, yielding a new water resource quantity of 1.6 × 10^4 m^3/d (Utilization report of seawater in **China (2015**).

Geographic Distribution

Fig. 1 show the geographic distributions of the number and the capacity of seawater desalination plants along the Chinese coastline by the end of 2015 Utilization report of seawater in **China (2015)**. There are many seawater desalination projects with a wide geographic distribution, ranging from the eastern sea of Liaodong Island (to the north) to the South China Sea (to the south). In terms of number, most of the desalination plants were located in four provinces: Zhejiang, Shandong, Liaoning and Hainan. From the perspective of capacity, the majority of the desalination plants were concentrated in the six provinces of Tianjin (an autonomous city), Zhejiang, Hebei, Shandong, Guangdong and Liaoning. Forty-five seawater desalination plants were put into operation in Zhejiang, with a total capacity of 2 × $10^5 m^3$/d. Only nine desalination plants were in Tianjin, but the total capacity reached 3.2 × $10^5 m^3$/d, showing there were some large-scale plants in Tianjin. There were 30 desalination plants in Shandong, with a total capacity of 1.6 × $10^5 m^3$/d, whereas only nine seawater desalination plants were constructed in Hebei, but they had a capacity of 1.7 × $10^5 m^3$/d. There were 16 and eight desalination plants in Liaoning and Guangdong Provinces, yielding 6.8×10^4 and 8.2×$10^4 m^3$/d of water, respectively. The other 22 seawater desalination plants were set up in Fujian, Jiangsu and Hainan Provinces, but they produce a smaller total capacity of 2.8 × $10^4 m^3$/d. The desalination plants in northern China focused on large-scale projects for industrial needs, whereas the desalination plants in southern China focused on island projects for domestic living objectives (**Zhu *et al.,* 2012**).

Desalination Technology

Fig. 2 shows the distributions of the number and the capacity of seawater desalination plants with different desalination technologies by the end of 2015 Utilization report of seawater in **China (2015)**. Most desalination plants have employed RO and/or MED technologies. For the number of desalination plants, 120 seawater desalination plants have adopted RO technology, and 17 desalination plants have employed MED technology to desalinate seawater. There was only one of each type of desalination plant that used MSF or ED technology. In terms of the capacity, the capacity of desalination plants with RO technology is 6.6 × 10^5 m^3/d, accounting for approximately 63.9% of the total capacity, whereas the desalination plants using MED technology have a total capacity of 3.6 × 10^5 m^3/d, even though there are only 17 plants, showing that MED technology is generally used for large-scale desalination plants. The capacities of seawater desalination plants using other technologies such as MSF and ED are 6,000 and 200 m^3/d, respectively, accounting for only 0.6% and 0.02% of the total capacity.

The major drawback of RO technology is that the semipermeable membrane in the RO system is very sensitive to oxidants, organisms, algae, bacteria, and other pollutants contained in the seawater, as well as the pH of the seawater. Hence it is necessary to carry out rigid pre-treatment towards seawater. Scale and fouling easily happen on the surface of the semipermeable membrane, consequently leading to a declining ratio of desalinization and unstable water quality. Therefore it is necessary to wash and replace the semipermeable membrane in a timely manner (**Zheng *et al.,* 2016**).

Table 1. Ten largest seawater desalination plants in China (Utilization report of seawater in China, 2015)

Plants	Capacity (m^3/d)	Technology	Start-up year	Energy source	Provinces
Tianjin Dagangxinquan SDP	10^5	RO	2009	Electric power	Tianjin
Tianjin SDP of the Beijiang Electric Power Plant, first batch	10^5	MED	2010	Electric power	Tianjin
Tianjin SDP of the Beijiang Electric Power Plant, second batch	10^5	MED	2012	Electric power	Tianjin
Phase I Tianjin SDP of the Beijiang Electric Power Plant	10^5	MED	2012	Electric power	Tianjin
Caofeidian Beikongakeling SDP	$5*10^4$	RO	2011	Electric power	Hebei Province
Yuhuan Huaneng SDP of an Electric Power Plant	$3.5*10^4$	RO	2006	Electric power	Zhejiang Province
Iron and Steel Base SDP in Zhanjiang, Guangdong	$3*10^4$	MED	2015	Electric power, Steam power	Guangdong Province
Shougang Jingtang Iron and Steel SDP, first phase II	$2.5*10^4$	MED	2010	Electric power, Steam power	Hebei Province
Shougang Jingtang Iron and Steel SDP, first phase I	$2.5*10^4$	MED	2009	Electric power, Steam power	Hebei Province
Guohua Huanghua SDP of an Electric Power Plant, III	$2.5*10^4$	MED	2014	Electric power	Hebei Province

Notes: SDP, seawater desalination project; MED, multi-effect distillation.

Source: **Zhu *et al.* (2019)**.

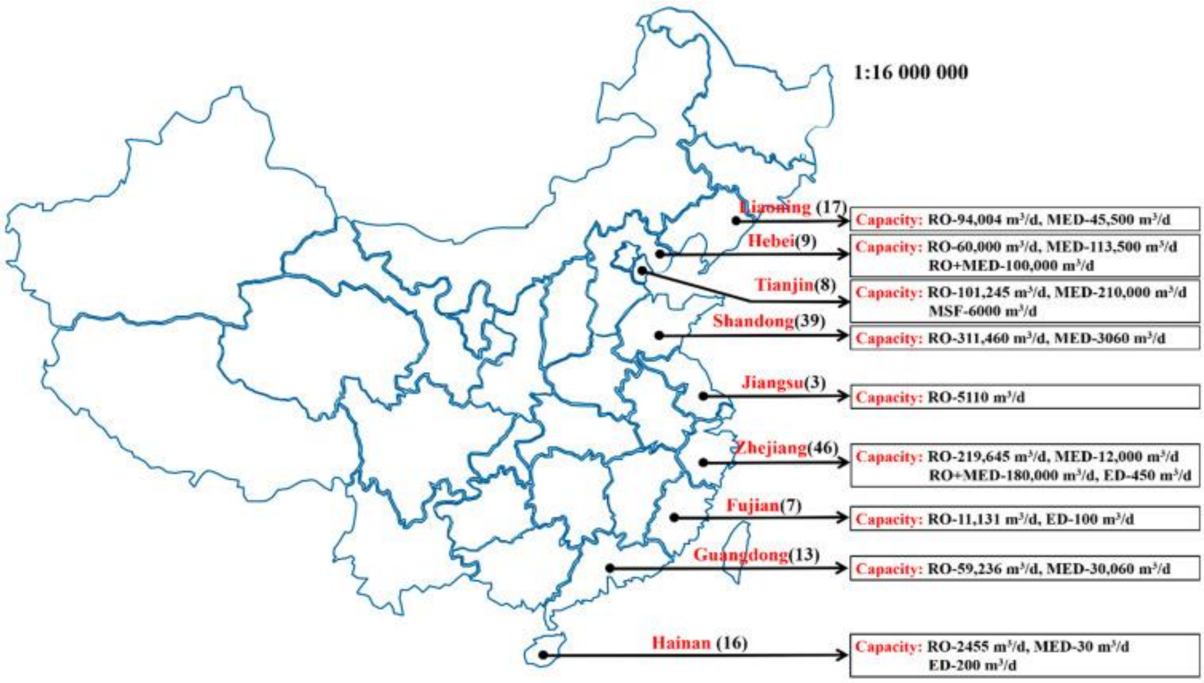

Fig. 1. The detailed number and capacity range for local seawater desalination projects in China.

Source: Ruan *et al.* (2021)

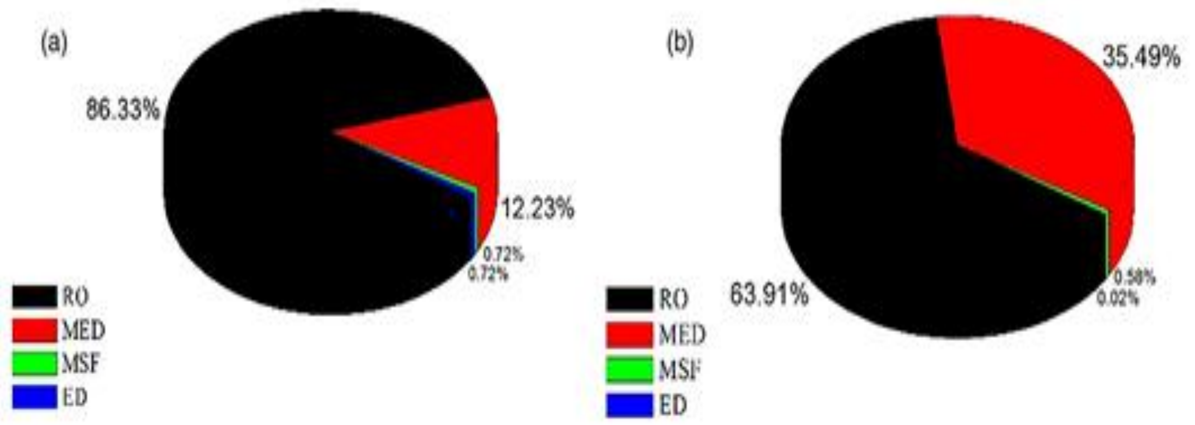

Fig. 2. (a) Number and (b) capacity (m^3/d) of seawater desalination plants with different desalination technologies by the end of 2015 (MSF is multi-stage flash distillation technology).

Source: Zhu *et al*. (2012).

For MED technology, because the heat transfer coefficient for phase transition increases with rising temperature, a low top-brine temperature will hinder the improvement of heat efficiency. Scale deposits easily form on the outer wall of the heat exchange tube of MED systems. Hence it is important for a timely cleanout of the heat exchange tube to dislodge the scale, in order to maintain the effective operation of the desalination system (**Zheng *et al.,* 2016**).

The major drawback of MSF desalination technology lies in the fact that structural materials are prone to corrode, and seawater is easily leaked into the condenser pipe when corrosion failure happens. Additionally, the MSF system needs an amount of seawater to circulate, leading to a large power consumption for the pump (**Zheng *et al.,* 2016**). For ED technology, ions will gather on the surface of the electrode and the ion exchange membrane, consequently leading to the formation of scale deposits. Additionally, it should be noted that there are some new methods (such as microbial desalination cells) for water desalination in the literature (e.g. **Cao *et al.,* 2009; Chen *et al.,* 2011**).

Desalination technologies have recently been reviewed by several authors (**Elsaid *et al***.**, 2020; Jones *et al***.**, 2019; Qasim *et al***.**, 2019; Zarzo and Prats, 2018**). They can be classified into two main categories: evaporation-based processes and membrane-based processes (**Zarzo and Prats, 2018**). Evaporation processes work by heat supply-as in MSF and MED processes-or through electric energy supply by mechanical compression-as in VC technologies. Membrane technologies works primarily by providing electrical energy. In particular, RO and NF operate by membrane pressurization while EDR processes work by a direct current between electrodes. Other processes which can be used for salt removal, such as ion exchange, precipitation or freezing, are not used for large scale desalting (**Zarzo and Prats, 2018**). Evaporation processes have been considered the most viable processes, but are known to be energy intensive (**Elsaid *et al***.**, 2020**). Energy requirements for membrane desalination depend on the water supply sources. For example, for RO technologies they are usually higher, as RO operates at pressures higher than 60 bars.

RO is the cheapest technology compared to several commercial-scale desalination technologies and for this reason it dominates this market with a share of 65% of the installed capacities (**Amy *et al.,* 2017**). The RO processes can be also grouped in different categories in relation to the salinity of the feed (**Qasim *et al.,* 2019**): as an example, BWRO plants and SWRO plants process feeds with salinity of 500–10,000 mg

L^{-1} and 30,000 mg L^{-1}, respectively. BWRO plants are further grouped into low salinity plants (feed water salinity: 500–2500 mg L^{-1}) and high salinity plants (feed water salinity: 2500–10,000 mg L^{-1}).

Environmental Risks Due to Concentrated Seawater and High Waste Heat from Desalination Plants

In the process of seawater desalination, a large amount of concentrated seawater (brine) will be produced. At present, there are two kinds of comprehensive utilization methods for brine. The first kind is direct discharge of brine: discharge brine into ocean, surface water and sewage treatment systems directly through the pipeline, or lead it into an evaporation tank or bore. This method does not need any treatment measures, and can only be applicable for small-scale discharge of brine (**Yu *et al.*, 2017; Dai *et al.*, 2018**). The direct discharge of brine will damage the coastal water environment (**Zhang *et al.*, 2010**). Additionally, the waste heat discharged from the seawater desalination process could increase the seawater temperature of regional waters, resulting in rapid reproduction and highly dense phytoplankton, and sometimes a phenomenon termed ‘harmful algal blooms’ occurs in some coastal waters (**Nie and Tao, 2008**). The increasing seawater temperature lowers the concentration of dissolved oxygen in seawater, influences the metabolism of organisms, and finally causes deterioration of the living environment of organisms (**Zhou, 2009**).

The second method is resource reuse of brine: salt manufacturing, and extraction of chemical raw materials (**Yu *et al.*, 2017; Dai *et al.*, 2018**). Circumfluence and distillation are two common methods adopted for small-scale brine treatment in China. There are some developed technologies for the comprehensive utilization of brine, including multi-effect distillation of brine, softening of calcium and magnesium of brine, salt-making method of brine, and bromine and potassium extraction from brine (**Dai *et al.*, 2018**). Zero discharge technology is an ideal way of brine treatment. It not only protects the water environment and ecological balance of the inner sea, but also recycles brine resources and provides resource guarantee for economic development. This technology adopts the evaporator, brine concentrator and crystallizer to complete the separation of chemical products (such as calcium chloride, calcium carbonate and sodium carbonate) from water. There is potential for zero-discharge technology to be applied to large-scale brine treatment in China (**Yu *et al.*, 2017**).

Disposal of Brines

Brine disposal has negative environmental impacts and poses significant financial burden. RO brine contains up to twice as much salt as seawater. In addition, it often contains chemicals added in the pretreatment and membrane cleaning processes which might be toxic to marine organisms (**Portillo *et al.*, 2014**). Because of the higher density compared to seawater, the brine stratifies in the benthic zone near the outlet, then sliding towards the seabed (**Fernández-Torquemada *et al.*, 2009**). As a result, marine organisms are exposed to the brine from the discharge point to the bottom of the seabed (**Petersen *et al.*, 2018**). A recent review discusses ways to mitigate the environmental problems associated to brine discharge (**Panagopoulos *et al.*, 2019**). The waste management strategy is to minimize the volume of the discharged brine by technologies that achieve ZLD so that the produced salts can be discharged to land or water with reduced environmental impact. The pure fresh water produced by this route (up to 99% water recovery) can find different applications, including agriculture, cooling systems and drinking purposes. Solid waste can be further processed for reuse or disposed of (COM, 2020). Beside ZLD strategies, MLD strategies can be considered as a valuable approach for the utilization, reuse and recovery of wastewater resources (**Panagopoulos and Haralambous, 2020**): the comparison between MLD and ZLD strategies showed that the ZLD system exceeds the MLD system energy requirements by about 2 times; however the total fresh water recovery of the MLD system is 10% less than the ZLD system. Therefore, MLD has the potential to maximize water recovery, minimize operating costs and reduce the amount of energy required.

Waste Brines Valorization through Resources Recovery

Waste brine should be considered as a potential source of valuable materials with the dual-purpose of simultaneous water recovery and salt production, thereby contributing to the Circular Economy implementation. However, such valorization has to be both technically and economically viable. For example, at very low salinity, revenues from the recovered materials could not compensate the costs of transporting seawater through the recovery plant. Furthermore, the addition of chemicals make the disposal of the final volume problematic from an environmental point of view (**Davis, 2006**).

The concentration of metals and salts in the permeate and concentrate streams can be thus determined in order to evaluate their potential value (**Jeppersen *et al*., 2009**). In the review of **Panagopoulos *et al.* (2019)**, typical concentration values of dissolved ions in reject brines are reported. According to the Authors, Mg, Na, Ca and K concentration values in brines coming from RO desalination plants are in the range 1860–2880 mg L^{-1}, 15,300 – 25,240 mg L^{-1}, 520–960 mg L^{-1} and 740–890 mg L^{-1}, respectively. However, the available literature mainly focuses on technical problems and challenges related to mineral extraction and very little information is available on the economic feasibility. **Shahmansouri *et al.* (2015)** addressed this problem by analyzing the extraction methods, gathering economic information concerning potentially commercial salts and metals in seawater and desalination concentrate and performing a preliminary cost assessment analysis. The Authors found out that the economic feasibility is dependent on factors such as proximity to a buyer, extraction efficiency, product purity, safety and costs related to material handling, storage and transport. Recently, **Zhang *et al.* (2021)** reviewed the different techniques for the recovery of minerals, water and energy from desalination brines, providing an economic comparison of operating desalination plants.

It should be mentioned that the exploitation of the potential energy of brine, using technologies which take advantage of the osmotic gradient between brine and a low-saline solution in order to produce energy, should be considered as well (**Tedesco *et al*., 2013**). This approach helps diluting the brine that is released into the sea, minimizing its negative impact on the marine environment. CCU can be considered as another interesting technique in combination with brine treatment processes for the production of $CaCO_3$ (**Yoo *et al*., 2020**).

Few attempts to recover less common ions from brines are also reported: **Le Dirach *et al*. (2005)** identified eight elements (Na, Mg, K, Rb, P, In, Cs, Ge) as being potentially economically and technically viable (**Le Dirach *et al*., 2005; Jeppersen *et al*., 2009**) investigated the economic viability of rubidium and phosphorus extraction and **Peterskov á *et al*. (2012)** extracted the metallic ions Cs(I), Li(I), Rb(I), and U(VI) from a RO concentrate using commercial resins (**Peterskov á *et al*., 2012**). **Naidu *et al.* (2017)** studied the extraction of Rb from seawater brine by an integrated membrane distillation with sorption, and **Chen *et al.* (2020)** recovered Rb and Cs from simulated brines solvent extraction with t-BAMBP. The feasibility of extracting minor components from SWRO brines, considering the advantages related to a minor consumption of primary sources as well as the relevance of the applications of the recovered products, is reported in the work of **Ortiz-Albo *et al.* (2018)**. Recently, some Horizon 2020 projects are dealing with the recovery of materials other than Mg from seawater brines (https://sea4value.eu/the-project/; https:// searcul armine.eu/).

Davis (2006) conducted a laboratory study on the production of NaCl, $Mg(OH)_2$ and Br_2 from seawater RO brine. Figure 3 shows the process flow-sheet. The special ion-exchange membranes in the ED stacks are selectively permeable to Na and Cl ions so that the dilute had a Mg^{2+} concentration 5 times greater than that in seawater. The NaOH addition allowed Mg^{2+} to be precipitated as $Mg(OH)_2$. To prevent Ca from interfering with Mg precipitation, the RO brine is treated with Na_2CO_3. The purity of the obtained Mg $(OH)_2$ is 99% or more.

Drioli *et al*. (2004), in order to limit calcium sulfate precipitation which causes the reduction of SO_4^{2-} content in the solution thus decreasing the recovery of Mg sulfate, proposed a method

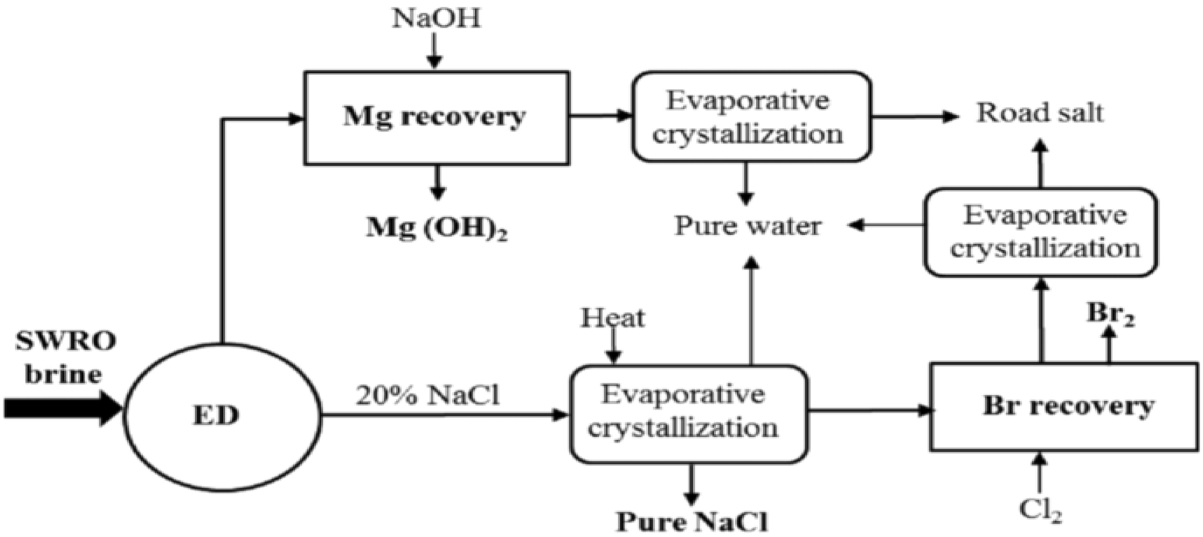

Fig. 3. Schematic illustration of SWRO brine treatment with ED and recovery of NaCl, Br_2 and Mg $(OH)_2$ (Davis, 2006).

Source: Fontana *et al.* (2022).

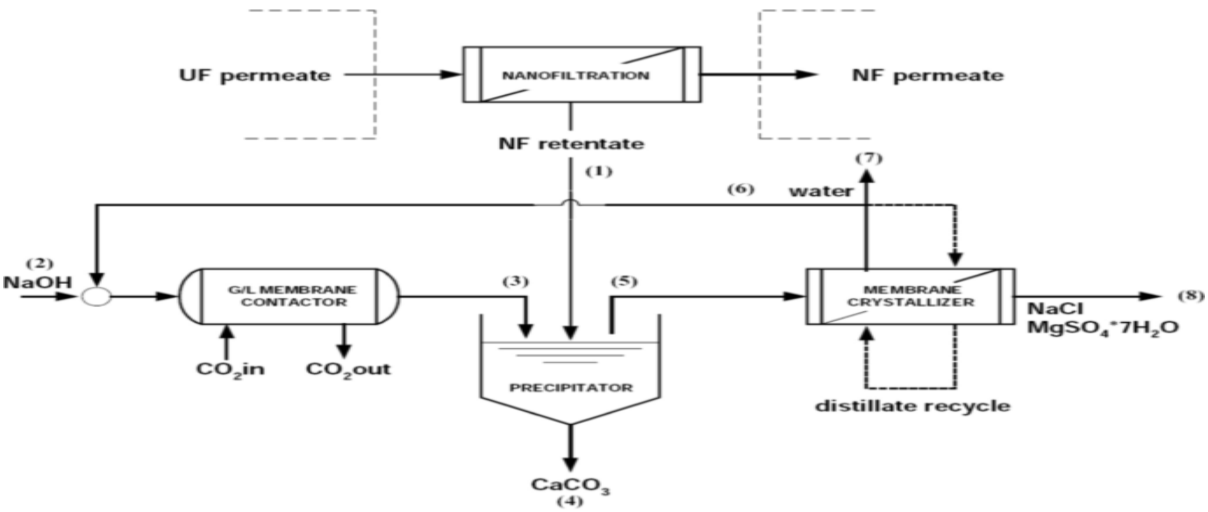

Fig. 4. Flow sheet of the integrated membrane system for the recovery of dissolved salts in NF retentate (Drioli *et al.*, 2004).

Source: Fontana *et al.* (2022).

Ahmed *et al.* (2003) described an integrated process (SAL-PROC process) for the sequential recovery of resources from rejected desalination brines by evaporation, cooling, de-sulfation, crystallization, washing, and finally dewatering. A preliminary feasibility study was conducted using real data resulting from four desalination plants. The obtained products were NaCl, $CaCl_2$, gypsum, $CaCO_3$, $Mg(OH)_2$, and Na_2SO_4. The revenues which can be obtained by processing 405,000 $m^3 y^{-1}$ of SWRO brine are estimated to be about US$ 9,000,000 y^{-1}.

Ohya *et al.* (2001) proposed an integrated approach which combines recovery technologies such as HPRO, ion-exchange, adsorption and NF for the recovery of all valuable materials contained in seawater.

From the analysis of the available literature, it was found that generally batch processes are adopted for Mg recovery, while continuous recovery systems have not been proposed yet, except for few cases (**Sano *et al.*, 2018**).

Precipitation/crystallization is the most occurring recovery technique; the process is often carried out at room temperature and it allows high recovery rates (95–100%). The recovered Mg can be utilized as a source for valuable Mg products and has potential to generate economic, social and environmental benefits (**Zhang *et al*., 2021**). For example, $Mg(OH)_2$ can be used in medication and water/ wastewater treatment as well as fire retardant, while MgO—produced by calcination of $Mg(OH)_2$—can be used in applications such as food, cosmetics, pharmaceutical and construction industries (**Dong *et al*., 2018; Zhang *et al*., 2021**). The obtained $Mg(OH)_2$ has purity grade ranging from 93.5 to 98.8% in most cases; these purity grade values are mainly due to co-precipitation of Ca ions, which concentration in the brine is about one third of Mg. It was also observed that when Mg recovery is integrated in a broader process flow-sheet, information about the efficiency and purity of the obtained Mg products is not exhaustive, since most of the reported results refer to NaCl and $CaCO_3$. To accelerate the development of salt recovery technologies toward commercialization, a potential research direction should be then in the field of applied separation and purification technologies: the ultimate goal is optimizing and improving such separation steps in a cost-effective way, thus obtaining a product with purity grade levels able to meet market requirements.

Further studies are necessary to evaluate the costs of the proposed technologies, with the aim of verifying the possibility to commercially exploit the recovered Mg. **Shahmansouri *et al.* (2015)** performed an economic analysis to evaluate the feasibility of extracting MgO from brines. The Authors found out that changes in magnesia price and operation and maintenance costs greatly affect the profitability of the extraction and that magnesia mining can be considered profitable at a price above 420 $ t^{-1}, assuming an interest rate of 6%; in particular, when the price is 540 $ mt^{-1}, the estimated net worth for its production would be 18.9 million $, with a payback period of 8 years. **Kim (2011)** performed an economic analysis of concentrate utilization compared to disposal and found out that MSF and ED as well as the Dow chemical process are relatively expensive methods for producing salts compared to NF and MCr, evaporation and ion exchange. **Davis (2006)** performed a preliminary analysis of the economic feasibility of the proposed ZLD process by using a mathematical model based on material and energy balances. The Authors found out that NaCl salt is the most profitable product and its value offsets the cost of its recovery; Mg and Br recovery appear to be economical as well and could support the added cost of the required equipment.

Chemical Resources Recovery

Seawater contains a large number of chemicals which could potentially be extracted to add to the chemical resources on the land. It has drawn the world's attention to recover and reuse these chemical resources for the sake of sustainable development of natural resources. In conventional desalination process, especially SWRO, rejected brine containing the majority of chemicals was supposed to discharge into the ground or sea. Thus, it is essential to improve the recovery of chemical resources from the brine to alleviate the discharge environmental compact. Various strategies have been proposed, including solar ponds, membrane distillation/ crystallization, electrodialysis and reverse electrodialysis, chemical precipitation, adsorption/ desorption, eutectic freezing and crystallization, pressure infiltration and microbial desalination ponds (**Mohammad *et al*., 2019**). Apart from salt, the main chemical resources produced from brine include bromine, potassium chloride, magnesium chloride, magnesium sulfate, and potassium sulfate, etc. In China, most of such enterprises are located in Tianjin, Hebei, Shandong, Fujian, and Hainan. The Chinese government offers great financial supports for research programs on chemical resource recovery from brine, promoting advances in unique chemical extraction technologies, high efficiency equipment and industrial-level energy-saving demonstration. ISDMU has achieved progress in the research of continuous hydrothermal preparation of high purity magnesium hydroxide as well as in the construction of a pilot line for the macro process. Still, there are some challenges in these areas such as high costs, large energy consumption, relatively deficient equipment, and low efficiency. In 2019, Tianjin Changlu

Hangu Saltern Co., Ltd. (Tianjin, China) successfully implemented the equipment remodeling for bromine recovery from highly concentrated seawater, enabling the construction of thousand-ton demonstration installation. As a result, the energy consumption was reduced by nearly 10% and the recovery rate increased by 8%, providing excellent demonstration for further applications of this technology in Shandong and other places (unpublished work).

Boron Removal

Seawater contains varied content of boron in different geographical locations. Typical, the boron content is in the range of 4–6 mg/L in most seawater resources whilst about 4.6 mg/L in standard seawater (Boubakri et al., 2015). The existence of residual borides from desalination has become a major concern among people, as minute boron would be detrimental to human health and plant growth. The limit level of boron content in drinking water was established in different countries to guarantee safe drinking, for example, the World Health Organization (WHO, 2.4 mg/L, 2011), Japan (1.0 mg/L, 2015), European Commission (1.0 mg/L, 1998), and China (0.5 mg/L, 2006) (**Güler *et al.*, 2015**). As the majority of the boron compounds in seawater is in the form of small molecules of H_3BO_3 and the remaining being $H_2BO_3^-$, it is difficult to get rid of boron residues to meet such criterion via traditional desalination (**Güler *et al.*, 2015**). In fact, the removal of boron can be sensitive to the temperature, salinity and pH of the feed water in the thermal desalination processes (**Alpatova *et al.*, 2018**). Whilst, in SWRO, the boron removal level is closely related to the pH value, which affects the dissociation of boric acid and surface charge negativity of the RO membrane (**Rahmawati *et al.*, 2012**). Moreover, two-pass system or integrated technologies have been adopted in SWRO to realize the higher boron removal in desalination (**Ban *et al.*, 2019**).

Novel Technologies

ISDMU has undertaken a lot of research based on desalination technologies beyond traditional SWRO process, including but not limited to MD, FO and CDI **(Xu *et al.*, 2020)** for example, **Xu *et al.*(2020)** reported a novel electrospun nanofibril membrane derived from Coca Cola bottles , which was successfully used in the MD process (**Xu *et al.*, 2020**). In another ongoing work, the performance of the membrane was improved by enhancing the hydrophobicity of the membrane surface through hierarchical inorganic nanostructure design. This configuration was designed to promote thermal energy efficiency by reusing latent evaporation heat. It should be noted that FO, MD, or CDI is not standalone and always combined with other technologies (i.e., hybrid configuration) when being used in desalination (**Ghaffour *et al.*, 2019**). For example, FO-NF, FO-RO, and FO-MD hybrid systems were designed for wastewater reuse (**Giagnorio *et al.*, 2019**). A FO-RO hybrid system was used to improve the antifouling and antiscaling properties of desalination. A RO-MD-PRO hybrid system was used to increase the energy efficiency of desalination. In China, FO and MD have been applied in high-concentration water treatment whilst CDI is only for lab-scale study, an FO-MD hybrid system was designed exhibiting a capacity of 12.5 m^3/d. FO, as a spontaneous osmotic-driven process, was coupled with MD to recover water from draw solutions while the MD process was used to concentrate the draw solution from FO to obtain the maximum energy utilization. Furthermore, as an emerging novel desalination technology, FO has undergone significant development during the past decades, due to its high energy efficiency and favorable separation performances.

Abbreviations

BWRO: Brackish water reverse osmosis,

CCU: Carbon capture and utilization,

CDI: Capacitive deionization,

CrIEM: Ion exchange membrane crystallizer,

CSTR: Continuous-flow stirred-tank reactor,

DiaNF: DiaNanoFiltration,

EC: Electrical conductivity,

ED: Electrochemical potential-driven,

EDBM: Electro dialysis with bipolar membranes,

EDR: Electro dialysis reversal,

EFC: Eutectic freezing crystallization,

EMP: Environmental monitoring plans,

EoL: End of life,

EU: European Union,

GHG: Greenhouse gases,

HPRO: High pressure reverse osmosis,

IG: Interessen-Gemeinschaft,

LCA: Life cycle assessment,

MCr: Membrane crystallization,

MD: Membrane distillation,

MED: Multi effect distillation,

MLD: Minimal liquid discharge,

MPLC:, Mineral Processing Licensing Corporation,

MSF: Multistage flash,

NF: Nano filtration,

OECD: Organization for Economic Co-operation and Development,

Ppm: Parts per million,

PRO: Pressure retarded osmosis,

QMC: Queensland Metals Corporation,

RED: Reverse electro dialysis,

RO: Reverse osmosis,

SWRO: Seawater reverse osmosis,

*t-BAMBP:*4-Tert-butyl-2-(α-methyl benzyl) phenol,

TDS: Total dissolved solids,

VC: Vapor compression,

ZLD: Zero liquid discharge.

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المـــــــردود البيئـــي لعمليـــات تحليـــة ميـــاه البحـــر فـــي الصـــين – دراســـة مرجـعية

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الهدف من هذا الاستعراض هو تقرير ومناقشة الدراسات السابقة ذات الصلة بالتأثير البيئي لتحلية مياه البحر في الصين. تواجه الصين، ولا سيما المقاطعات الساحلية ، نقصًا خطيرًا في موارد المياه العذبة وقضية تلوث المياه ، مما يقيد المزيد من التنمية. لمعالجة الخلل الخطير بين العرض والطلب على الموارد المائية، بالإضافة إلى الاستخدام الفعال للموارد المائية العادية، سعت الصين جاهدة لتطوير موارد مائية بديلة لمواجهة أزمة المياه، ومن بينها تحلية مياه البحر التي تلعب دورًا مهمًا. استعرضت هذه الدراسة الوضع الحالي لاستخدام مياه البحر المحلاة في الصين، بما في ذلك النقاط الموضحة أدناه. من أجل تقليل الآثار الضارة لتقنيات تحلية المياه على البيئة وجعلها مستدامة، من الأهمية بمكان تطوير مناهج "دائرية" تهدف إلى تثمين التيارات المركزة التي تتطلب التخلص منها، مع الهدف النهائي المتمثل في عدم تصريف السوائل. قد يكون دمج مخطط الاستخراج في محطة تحلية مياه البحر بهذا المعنى نهجًا مثيرًا للاهتمام للتغلب على بعض الحواجز. على المدى الطويل، من الأهمية بمكان تطوير تقنيات تحلية المياه لمواجهة تحديات أزمة المياه العالمية. على وجه التحديد، يجب التركيز على الجوانب التالية على النحو التالي: (1) الابتكار التكنولوجي: زيادة تحسين أداء محطات التناضح العكسي للمياه والصرف الصحي على نطاق واسع. وتشمل الجهود توسيع سعة وحدة واحدة ، وتقليل استهلاك الطاقة، وتحسين تكامل النظام، واستقرار التشغيل والموثوقية، وتكلفة تحلية المياه. يجب بذل مزيد من الجهود نحو المعالجة المسبقة وأجهزة النظام، وأغشية التناضح العكسي عالية الأداء، ومضخات الضغط العالي وأجهزة استعادة الطاقة، إلخ. (2) استخدام الموارد الكيميائية من مياه البحر: يجب استكشاف تقنيات أفضل لاستعادة المواد الكيميائية وتقليل التكلفة المحتملة. ويعد استخراج الليثيوم واليورانيوم أكثر صعوبة ويحتاج إلى تقنيات أفضل. (3) طرق المعالجة الخضراء؛ يجب تطوير المعالجات الخضراء التي تشتمل على عوامل مضادة للتكلس الخضراء وطرق بيولوجية خالية من العوامل. وفحص التخثير الكهربي وتقنيات تعويم الهواء المذاب. (4) تقنيات التحلية الناشئة: بصرف النظر عن تقنيات تحلية المياه التقليدية بتقنية SWRO، تتطلب التقنيات الناشئة بما في ذلك عمليات تحلية المياه MD و CDI و ED مزيدًا من الجهود البحثية، من استغلال مواد الأغشية الجديدة إلى تصنيع المكونات والمعدات الأساسية. بشكل عام، مع البحث والتطوير المستمر لتحلية المياه، يُعتقد أن الصين تلعب دورًا أكثر أهمية في سوق تحلية المياه الدولية بانفتاح وشمولية ملحوظة، حيث توفر أحدث تقنيات التحلية والمرافق والخدمات، مما يستفيد منه البلدان والمناطق المجهدة بالمياه في العالم.

المحكمـــــون:

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