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How to Simultaneously Produce Fresh Water and Valuable Minerals from Seawater

Xuanyi Li[1] *

[1]The Affiliated High School of Peking University, Beijing, China
*Corresponding Author: hi-alan@outlook.com

Advisor: Nancy Hua, nancyhua7@gmail.com

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Abstract

Seawater desalination has emerged as a promising solution to meet the increasing demand for freshwater, with reverse osmosis (RO) being the predominant technology due to its energy efficiency. However, challenges such as membrane fouling and brine management persist. Concurrently, seawater harbors a wealth of valuable minerals, with magnesium ions (Mg^{2+}) standing out for its abundance and industrial significance. This study explored the synergistic integration of seawater desalination and mineral extraction technologies to address the global challenges of water scarcity and resource depletion. Through a systematic analysis, this study identified magnesium ions as a prime target for extraction from seawater, considering its concentration and market value. Various extraction techniques, including precipitation, adsorption, nanofiltration, and electrodialysis, were evaluated for their efficiency, cost-effectiveness, and environmental impact. Integration of mineral extraction processes with RO desalination was proposed, either preceding or following freshwater production, to optimize resource utilization and minimize RO scaling challenges. Key considerations such as operating costs and environmental sustainability were emphasized, guiding the selection of extraction technologies. The manuscript underscored the importance of achieving high purity minerals and sustainable extraction practices to support long-term economic viability and environmental responsibility. This manuscript provided a comprehensive framework for the simultaneous production of freshwater and valuable minerals from seawater, while identifying critical areas requiring further investigation.

Keywords: Seawater desalination; Mineral extraction; Economic analysis

1. Introduction

Water resource plays a key role in the development and expansion of various domestic and industrial applications. Water shortage is a pressing issue around the world. Currently, approximately 2.3 billion people live in water-stressed countries, and this number is projected to increase to 3.2 billion by 2050 (Li et al., 2018). The ocean is a huge reservoir of water, accounting for 97% of the total water on earth (Eke et al., 2020). However, the high salt content in seawater prohibits on its direct use for various purposes. Seawater desalination is an effective method to separate salt from water and to extract a steady stream of freshwater from seawater (Zarzo & Prats, 2018). This process has the potential to meet the growing demand for clean and potable water globally (Ayaz et al., 2022).

Among the different desalination techniques, reverse osmosis (RO), electrodialysis (ED) and thermal-driven processes such as multistage flash evaporation (MSF) and mechanical steam compression (MVC) are prominent solutions (Bellona et al., 2008; Curto et al., 2021). Each desalination technology has its own unique advantages but face some specific limitations and challenges in terms of energy consumption, capital cost, and overall performance (Service, 2006). RO, a pressure-driven desalination technology, has become the gold standard in desalination due to its energy efficiency in separating water and salt (Chung et al., 2015). RO uses a highly selective membrane that can achieve near perfect retention toward all salt in seawater. However, RO still faces the challenge of membrane fouling and scaling and brine management issues (Semiat, 2008; Wang et al., 2023).

In addition to serving as an enormous reservoir for water, seawater contains large amount of various mineral resources, including sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), bromine (Br^-), and lithium (Li^+). Mineral extraction from seawater is a potentially low-carbon and cost-effective alternative to conventional ore mining. The challenge is that the concentration of minerals in seawater is relatively low. Additionally, the brine is a mixture of all kinds of minerals that need to be separated from water and each other to obtain high-purity product (Eke et al., 2020).

The simultaneous harvesting of freshwater and valuable minerals from seawater is an emerging research frontier. Ongoing efforts are currently devoted to strengthening the desalination process by increasing freshwater recovery, minimizing brine volume, and continuing technological innovations and improvements to reduce energy consumption. At the same time, integrating mineral extraction procedures into current seawater desalination industries provides promising economic and environmental benefits.

This study explored strategies to couple desalination and mineral extraction technologies. The research first identified the economically profitable mineral species by analyzing the concentration and price of different minerals in seawater. The study then focused on magnesium ions as a valuable components to be extracted. arious technologies for extracting Mg^{2+} from seawater were compared, and their integration into current seawater treatment processes was evaluated. This study provided a systematic analysis of potentially energy-efficient, cost-effective, and environmentally friendly seawater desalination and Mg extraction technologies.

2. Materials and Methods

2.1 Selection of Valuable Minerals.

Seawater contains a diverse array of mineral elements, each varying in concentration and market value. By analyzing the concentration and market price of minerals, the value of each mineral in a given volume of seawater (\$/m³) can be calculated as the product of multiplying the concentration of a mineral species in seawater and its market price:

$$Value = cM$$

where c is the mineral concentration in seawater (ppm) and M is its market price (\$/kg).

2.2 Desalination energy Consumption Calculation.

Desalination of seawater involves the removal of salt and other impurities to produce freshwater suitable for various applications. The process typically relies on the principle of osmosis, where water molecules pass through a semipermeable membrane from a region of lower solute concentration to a region of higher solute concentration. The energy required to overcome osmotic pressure and drive freshwater production is a key parameter in desalination (Amy et al., 2017). In this study, we explore the relationship between water recovery and energy consumption in seawater desalination.

The specific energy consumption (SEC) of a desalination process is a crucial metric indicating the energy required to produce one cubic meter of freshwater. The specific energy consumption (SEC) for desalination was calculated using fundamental thermodynamic principles. For clarity, the analysis process followed these steps:

<u>Basic Osmotic Pressure Calculation</u>

The osmotic pressure (π) exerted by a solution can be calculated using the van't Hoff equation:

$$\pi = iRTc$$

where π is the osmotic pressure (Pa), i is the van't Hoff factor, representing the number of particles into which a solute dissociates (dimensionless), R is the gas constant (8.3145 J/(mol·K)), T is the temperature (K), and c is the molar concentration of the solute (mol/m³).

Applied Pressure Determination:

The applied pressure (P) is determined by the desired excess pressure ratio ($\eta = 0.2$ in this study) and the osmotic pressure (π):

$$P = (1 + \eta)\pi$$

Energy Consumption Calculation:

$$SEC = \frac{P}{1 - WR}$$

where SEC is the specific energy consumption (kWh/m³), P is the applied pressure (Pa), WR is the fraction of water recovered as freshwater (dimensionless).

In seawater desalination, sodium chloride (NaCl) is the predominant solute, with a van't Hoff factor of 2 due to its complete dissociation into Na^+ and Cl^- ions. In seawater, magnesium exists predominantly as Mg^{2+} ions, typically complexed with chloride ($MgCl_2$) or sulfate ($MgSO_4$). MATLAB simulations were conducted to plot the energy consumption as a function of water recovery using the derived equations.

3. Results and discussion

3.1 Identify valuable minerals.

Seawater contains a very large number of mineral elements, but their concentrations vary greatly, spanning more than 10 orders of magnitude. As shown in Figure 1, certain mineral species have relatively high concentrations in seawater, while others have very low concentrations (Sharkh et al., 2022). For example, the most abundant mineral in seawater is sodium chloride (NaCl), which is concentrated enough to support a mature sea salt industry. Magnesium (Mg), as the second most abundant mineral in seawater, is not as concentrated as NaCl, but its absolute content in seawater is still significant, and the current market value of magnesium is high, which makes the extraction of magnesium from seawater a promising field and can promote the effective use of seawater.

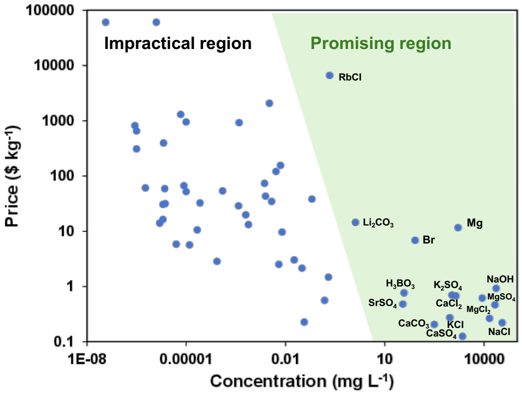

Figure 1. Concentration of different minerals in seawater and their market price. Adapted from reference (Sharkh et al., 2022).

The market value of minerals is largely determined by the traditional and widespread mineral extraction industry, which is characterized by high carbon emissions and high energy consumption. Therefore, the economic viability of extracting minerals from seawater depends not only on the concentration of the mineral, but also on its market price. By analyzing the market price of the mineral and its concentration in seawater, we can calculate the total value of the mineral in a given volume of seawater. The most valuable minerals are those with high concentrations and high prices, as shown in the upper right region of Figure 1. In contrast, minerals with low concentrations and low prices are less economically viable for extraction from seawater.

When businesses estimating the market value, which can be calculated based on the market price and concentration of the mineral, Figure 2 lists the 10 minerals with the highest value extracted from seawater. Although NaCl is the most abundant mineral, it will not be discussed in this study because its mining technology has been very mature. Instead, this study will focus on the extraction of magnesium, which is not only relatively abundant in seawater, but also has high industrial value and a wide range of uses, including its use in aviation, automotive manufacturing, electronics and chemical products. The product results of magnesium concentration and market price in seawater show that its utilization effect and potential are unlimited, and it is worth further research and development. Although the extraction of magnesium has technical and economic potential, the environmental impact and cost-effectiveness of the extraction process need to be considered in practical applications. Future research should focus on developing efficient, low-cost and environmentally friendly magnesium extraction technologies to achieve sustainable extraction of this valuable resource from seawater.

In summary, magnesium from seawater is a potential resource, and its extraction can not only provide raw materials for related industries, but also help promote the process of sustainable resource utilization.

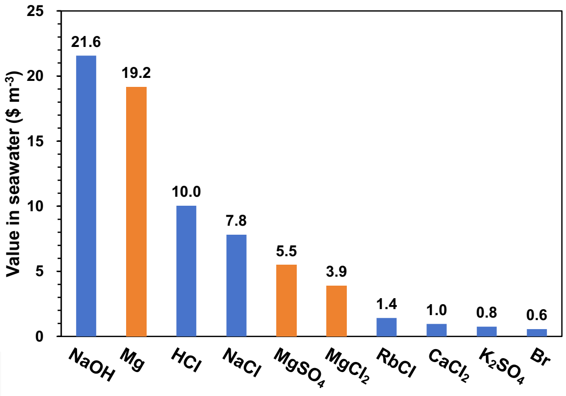

Figure 2. The top 10 minerals with most overall value in seawater.

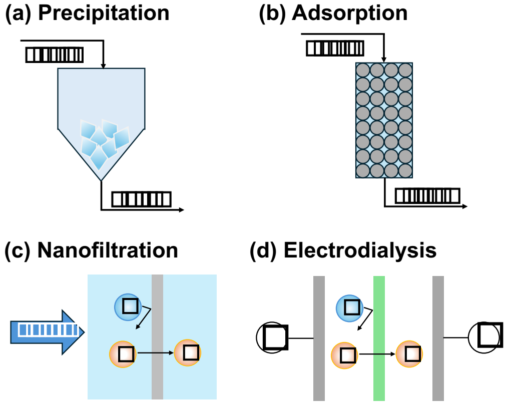

Figure 3. Schematics of different techniques used to extract minerals.

3.2 Evaluate different extraction technology.

Extracting minerals from seawater is a challenging process, but with advances in technology, there are now multiple ways to achieve this goal. These techniques include precipitation, adsorption, nanofiltration, and electrodialysis, each with its own unique advantages and limitations (Figure 3).

Precipitation is a common mineral extraction technique in which magnesium is precipitated or crystallized by the addition of specific anionic species. This method is probably most commonly used in industry, for example the Dow process is a precipitation method used to extract magnesium. The advantages of precipitation are its simplicity and cost effectiveness, but it may produce a large amount of sludge that requires further cleaning and conversion. The adsorption method uses an adsorbent to extract magnesium, which is then transferred to the receiving solution through a desorption step. The advantage of this method is that the magnesium extraction process can be precisely controlled, but it may require regular replacement of the adsorbent, which will increase the cost and economic burden.

Nanofiltration and electrodialysis are two membrane separation techniques that are chemically non-polluting. Nanofiltration is a pressure-driven membrane separation process, similar to reverse osmosis (RO), but using membranes with precise pore size control (Chung et al., 2015). Nanofiltration can separate magnesium ion and sodium ion by size differences. Electrodialysis is a membrane separation process driven by an electric field, which can selectively allow univalent and bivalent ions to pass through a specific electrodialysis membrane. These two methods can improve the purity of the product, but a subsequent crystallization step is usually required to obtain solid magnesium.

3.3 Integrate magnesium extraction with seawater desalination.

Combining magnesium ions extraction with seawater desalination technology can help the world achieve efficient resource use and sustainable environmental development. The mainstream technology for desalination is reverse osmosis (RO), a process through which research hopes to extract both fresh water and minerals.

The first method is the extraction of bivalent magnesium and then reverse osmosis treatment of seawater. During the RO process, as the water is recovered, the remaining brine becomes increasingly concentrated, which can eventually lead to mineral crystallization, membrane scaling and fouling, reducing the performance of the whole system (Saji et al., 2020). A key advantage of pre-extraction of magnesium is that scaling and fouling of RO membranes can be mitigated by reducing insoluble magnesium.

The second route is to first extract fresh water using RO technology and then extract magnesium from the saline water produced by RO (Van der Bruggen & Vandecasteele, 2002). Since the current RO water recovery rate (i.e. the ratio of fresh water to total water intake) in seawater is about 50%, the magnesium concentration in salt water has tripled. The amount of salt water to be treated is reduced by 50%, making magnesium extraction more efficient. Both pathways propose magnesium extraction methods and, depending on the magnesium extraction technique to be used, both pathways can be integrated to extract fresh water and minerals simultaneously.

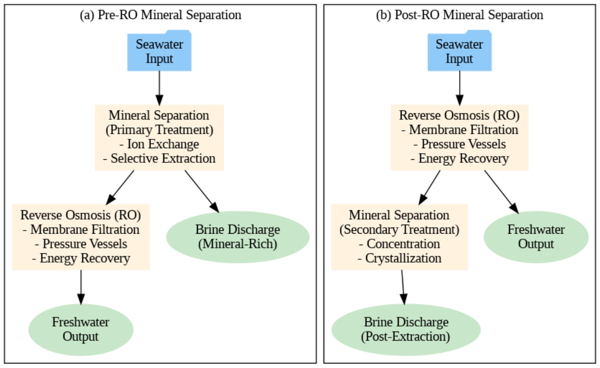

Figure 4. Integrated seawater desalination and mineral extraction process.

According to the combining the integrated desalination and mineral extraction processes shown in Figure 4, we can see that whether magnesium extraction or freshwater extraction is carried out first, the dual use of resources can be achieved in the end. By optimizing the process flow and selecting the appropriate magnesium extraction technology, not only can freshwater production be increased, but valuable minerals, especially key industrial raw materials such as magnesium, can be effectively recovered from seawater.

3.4 Evaluate economic benefit of integrating magnesium extraction with seawater desalination.

When investigating the various technologies for extracting magnesium ions from seawater, we need to consider the capital cost, operating cost and environmental impact of each technology. Operating energy consumption for desalination range from about 1-5 kWh/m3 (Figure 5), depending on the salinity of the feed, water recovery rates and local energy costs. There a trade-off between water recovery and energy consumption, with higher water recovery leading to increased energy requirements due to the higher osmotic pressure. The optimal water recovery is around 50% with an energy consumption of around 2 kWh/m3. Depending on the regional electricity price, the cost for producing fresh water from seawater ranges 0.5-2 USD/m3.

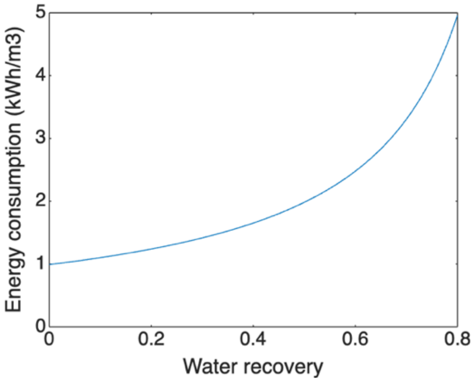

Figure 5. Tradeoff between seawater desalination water recovery and energy consumption.

The estimated operating cost of Mg extraction is 2-4 USD/kg and this cost is critical in deciding which technology to use (Figure 6). Overall, the extraction of magnesium is profitable in the long term. However, this profitability must be achieved by selecting the most cost-effective extraction technology. In terms of environmental impact, all four technologies are more environmentally friendly than traditional ore mining. Though precipitation and adsorption are more cost-effective than membrane-based processes, membrane-based separation is greener. Precipitation uses some anions to precipitate magnesium and is generally considered an environmentally friendly method. Adsorption may use some sorbents that are at risk of leaking into the environment, and desorption involves the use of enhanced chemicals. Nanofiltration and electrodialysis are processes without chemical additives, but they do not produce magnesium salt crystals directly and usually need to be integrated with other processes.

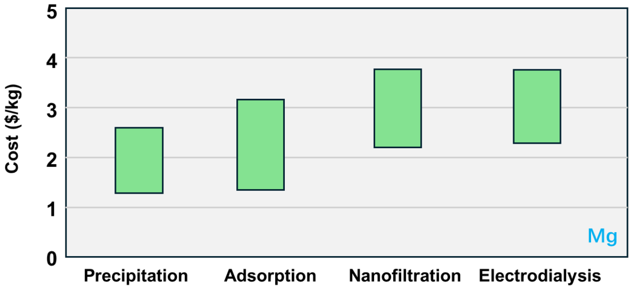

Figure 6. Energy consumption of seawater desalination and cost of extracting magnesium from seawater using different technologies.

3.5 Case studies and practical viability of different technologies

The feasibility and scalability of integrated desalination and mineral extraction hinge on proven industrial implementations and lessons from pilot studies, as seen in the Dow Process, Singapore Water Technology Center, and Israeli Dead Sea Works. These examples highlight the technical and economic viability while uncovering critical operational challenges.

The Dow Process for magnesium extraction from seawater, historically operated in Freeport, Texas, was a pioneering demonstration of commercial-scale magnesium production from seawater. The process involved precipitating magnesium hydroxide using lime (calcium hydroxide), followed by conversion to magnesium chloride and then electrolysis to produce metallic magnesium. Key operational aspects included careful control of seawater pre-treatment and pH levels to optimize precipitation. While the process proved the technical feasibility of seawater magnesium extraction, it faced challenges with energy consumption and byproduct management, particularly the handling of calcium chloride waste.

Regarding membrane-based magnesium extraction technologies, several facilities have explored combining reverse osmosis (RO) with electrodialysis. The Singapore Water Technology Center pilot study highlights the integration of reverse osmosis (RO) with electrodialysis for magnesium removal. This approach aims to address membrane scaling issues that commonly affect RO systems processing magnesium-rich waters. The integration of pre-treatment steps helps extend membrane lifespan, though significant challenges remain in terms of electrode longevity and energy efficiency. Optimization of membrane selectivity and operational parameters continues to be an active area of research.

The Dead Sea has been a significant source of magnesium production due to its naturally high magnesium concentration (Almousa et al., 2024). Operations there have focused on developing efficient processes for extracting magnesium from high-salinity brines. Key considerations include the use of corrosion-resistant materials due to the aggressive nature of concentrated brines, and the implementation of energy recovery systems to improve overall process efficiency. Environmental considerations have led to increased focus on minimizing liquid discharge and improving sustainability of the extraction processes.

Scaling these processes demands robust equipment design, advanced process control systems, and comprehensive operator training. Managing feed water variability, optimizing energy consumption, and adhering to environmental regulations are essential for economic viability. These case studies underscore the potential for integrated systems but highlight the need for continued research to address technical and economic challenges for broader implementation.

3.5 Limitations and future directions

Current challenges in integrated systems include technological limitations in achieving high magnesium recovery rates and economic constraints that hinder large-scale implementation. Environmental impact assessments remain underexplored, and knowledge gaps persist in understanding long-term membrane performance under operational conditions. To address these challenges, future research should prioritize developing fouling-resistant membranes to enhance system reliability and longevity. Process optimization is essential to reduce energy consumption, making the systems more economically viable. Additionally, conducting life cycle assessments will provide a holistic understanding of environmental impacts. Exploring novel pre-treatment strategies will further improve performance, enabling more sustainable and scalable solutions for integrated desalination processes.

4. Conclusion

The price of minerals is heavily influenced by their purity, which means we need very good separation or extraction techniques. When choosing a magnesium extraction technology, it is important to consider not only cost, but also environmental sustainability. The environmentally friendly properties of precipitation and nanofiltration/electrodialysis make them attractive options, although additional steps may be required to obtain a high purity magnesium product (Ghaffour et al., 2015). While adsorption may be more economical in some cases, adsorbents and chemical desorbents must be handled with care to avoid adverse environmental effects.

In summary, the choice of technology for extracting magnesium from seawater should be based on a comprehensive assessment of cost, efficiency, and environmental impact (Meerganz von Medeazza, 2005). Future research and development should aim to optimize these technologies, reduce costs, improve magnesium purity, and reduce environmental impact (Birnhack et al., 2008). Through such efforts, we can ensure that magnesium extraction is not only economically viable, but also environmentally responsible, thus supporting the goal of sustainable development.

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