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The Evolution and Future Challenges of Modern and Contemporary Seawater Desalination Technology

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Abstract: In recent years, environmental pollution has been widely discussed, with water resource pollution being particularly crucial. Although Earth's total water resources are abundant, freshwater is limited and unevenly distributed. In contrast, seawater is extremely abundant and contains over 80 chemical elements such as chlorine, sodium, potassium, magnesium, and calcium. If effectively separated and purified, seawater could help alleviate freshwater shortages. Seawater desalination, a key solution to global water scarcity, has evolved from simple distillation to efficient membrane separation over recent decades. This review systematically traces the development of desalination technologies, analyzing the principles and applications of mainstream methods like reverse osmosis and multi-stage flash evaporation. It also highlights recent research in nanomaterials, artificial intelligence, and renewable energy integration. Through critical analysis of key challenges—including energy consumption, environmental impact, and economic feasibility—this paper identifies current bottlenecks, reveals research gaps, and explores potential paths for technological integration and innovation. The aim is to offer theoretical and practical insights to support the sustainable advancement of seawater desalination.

Keywords: Seawater desalination technology, Reverse osmosis, Multi-stage flash evaporation, Nanomaterials, Integration of renewable energy

1. Introduction

The global freshwater resource crisis is becoming increasingly severe. Although 70% of the Earth's surface is covered by the ocean, the freshwater available for direct human use only accounts for 0.3%, and the shortage is exacerbated due to pollution and uneven distribution [1]. Every year, more than 420 billion cubic meters of sewage are discharged into water bodies, threatening 14% of freshwater runoff. Sustainable solutions are urgently needed. Seawater desalination technology, by converting seawater into usable fresh water, has become the core approach to alleviating the water crisis. Elimelech and Phillip pointed out that technological innovation should take into account both energy efficiency and environmental impact [2], while Werber et al. emphasized that new membrane materials are the key to improving desalination efficiency [3].

Recent studies have focused on technological breakthroughs and system optimization. For instance, Wang et al. developed graphene oxide membranes, whose water flux increased by 2 to 3

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times compared with traditional membranes, verifying the potential of nanomaterials in desalination [4]. The KAUST team reduced energy consumption to 2.1 kWh/m³ through a photothermal coupled reverse osmosis system, highlighting the significance of integrating renewable energy [5]. However, high energy consumption, ecological risks of concentrated brine and the universality of technology remain the main bottlenecks.

This paper systematically reviews the evolution of seawater desalination technology, analyzes the principles and current situations of mainstream technologies such as reverse osmosis and multi-stage flash evaporation, and evaluates the cutting-edge progress in nanomaterials, intelligent operation and maintenance, and resource recovery. Through literature review and case study, the technical bottlenecks are revealed and the interdisciplinary integration path is proposed. The significance of this research lies in providing a theoretical framework and practical reference for the sustainable development of seawater desalination, promoting collaborative innovation in energy-water systems, and contributing to global water resource security and ecological civilization construction.

2. The evolution and diversified development of seawater desalination technology

2.1. From the initial stage to large-scale industrial application

The historical evolution of seawater desalination technology reflects the intellectual trajectory of humanity in addressing water resource challenges. From the early simple thermal distillation to today's highly efficient and precise membrane separation systems, this field has developed into an integrated discipline that combines materials science, energy engineering, and environmental technology. Table 1 reviews the development process. The modernization of seawater desalination technology began in the 1950s. At that time, due to extreme water shortage in the Middle East, the multi-stage flash evaporation (MSF) technology was adopted on a large scale, marking the first generation of industrialized seawater desalination devices. Subsequently, in the 1960s, the United States developed reverse osmosis (RO) membrane technology. Due to its relatively low energy consumption characteristics, it has gradually become mainstream and currently accounts for approximately 66% of the global seawater desalination market.

After entering the 21st century, the global seawater desalination capacity has shown exponential growth. According to statistics, by the end of 2024, China has completed 135 seawater desalination projects with a total capacity of 1.65 million tons per day. Among them, there are 40 large-scale projects with a capacity of 10,000 tons or more, mainly distributed in coastal provinces such as Shandong, Zhejiang and Hebei. This rapid growth is underpinned by continuous technological innovation and the constant decline in costs - the energy consumption of modern reverse osmosis systems has dropped from 20kWh/m³ in the 1970s to 3-4 KWH /m³, achieving a major breakthrough in the economic feasibility of seawater desalination. Meanwhile, the application fields of seawater desalination have expanded from the initial municipal water supply to multiple industrial sectors such as power, metallurgy, and chemical engineering, as well as special scenarios like island areas and ships.

2.2. The diversified pattern and applicable scenarios of global seawater desalination technologies

From the perspective of the distribution of technical routes, the current global seawater desalination market has formed a diversified pattern dominated by reverse osmosis membrane technology, supplemented by multi-stage flash distillation, low-temperature multi-effect distillation (MED), and

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electrodialysis (ED) technologies. Reverse osmosis technology, with its advantages of modular design, strong adaptability and relatively low energy consumption, is particularly suitable for medium-scale desalination projects (10,000-100,000 tons per day). Thermal technologies such as multi-stage flash distillation and low-temperature multi-effect distillation remain competitive in large-scale industrial projects where waste heat can be utilized, such as in the Middle East. These systems are usually co-produced with power plants and can reach a scale of hundreds of thousands of tons per day. Studies have shown that electrodialysis technology has gradually gained attention in brackish water desalination and small-scale decentralized applications in recent years, mainly due to the development of new ion-exchange membrane materials.

2.3. Technological path differentiation and geographical layout driven by regional resource endowments

From the perspective of geographical distribution, the layout of seawater desalination facilities is highly correlated with regional water resource pressure. The Middle East and North Africa (MENA) region has become the most concentrated area for seawater desalination globally due to the extreme scarcity of natural fresh water. Countries such as Saudi Arabia, the United Arab Emirates, and Israel rely heavily on seawater desalination to meet the majority of their domestic water demands. As a latecomers in this field, China's seawater desalination industry started relatively late but has developed rapidly. Currently, it has formed three major industrial clusters in the Bohai Rim, the Yangtze River Delta and the Pearl River Delta, and plans to expand the total desalination capacity to over 2.9 million tons per day by 2031. This regional development disparity is also reflected in technological choices - the Middle East prefers energy-intensive thermal technology (due to its abundance of fossil energy), while China and European and American countries tend to adopt more energy-efficient membrane technology (see Table 1).

Table 1. Comparison of major seawater desalination technologies worldwide

Technology Type	Working Principe	Energy Consumption (kWh/m^3)	Applicable Scale	Key Advantages	kEY LIMITATIONS
rEVERSE OSMOSIS(ro)	Pressure-driven separation via semipermeable membrane	3-4	Small to medium(up to 200000m^3/day)	low energy consumption, modular design	Sensitive to membrane fouling, requires complex pretreatment
Multi-Stage Flash(MSF)	Multi- stage vacuum boiling and condensation	10-16	Large (50,000-500,000m3/day)	Stable performance, suitble for large-scale project	High energy demand,equipment corrosion
Multiple Effect Distillation(MED)	Multi-effect evaporation and condensation	6-12	medium to large	utilizes low-gradeheat sources	high capital cost, scaling risks
Electrodialysis(ED)	Electric field-driven ion exchange membranes	2-5 (brackish water)	Smalle decentralized systems	No phase change, simple operation	Low desalination rate, limited membrane lifespan

While technology is constantly advancing, the seawater desalination industry is also facing many challenges. The first problem faced is high energy consumption. Even the most advanced reverse osmosis systems still consume a large amount of electricity, which makes the cost of desalinated

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water still higher than that of traditional water sources. Secondly, there is the ecological impact brought about by the discharge of concentrated brine. Global seawater desalination plants generate approximately 14.2 billion cubic meters of high-salt wastewater each year, posing a potential threat to Marine ecosystems. In addition, technical bottlenecks such as membrane fouling, material corrosion, and equipment durability, as well as high initial investment, also restrict the further promotion of seawater desalination technology to varying degrees. These challenges are precisely the key directions that current research is dedicated to conquering, and they also constitute the main breakthroughs for the future development of seawater desalination technology.

3. Research hotspots and technological innovations in the past five years

3.1. Breakthrough progress in new desalination membrane materials

Research in the field of seawater desalination over the past five years has demonstrated unprecedented vitality and diversity. Scientists and engineers have been promoting technological innovation from multiple dimensions, including materials science, energy utilization, system integration, and resource recovery. These studies not only aim to address the inherent limitations of traditional seawater desalination technologies, but also explore the possibility of integrating cutting-edge technologies with traditional processes, mapping out a more sustainable development path for the seawater desalination industry. Through the analysis of a large number of literature and research reports, the five most breakthrough and application promising research directions at present can be sorted out.

As the core component of reverse osmosis technology, the performance of membrane materials directly determines the desalination efficiency, energy consumption level and operating cost of the system. In the past five years, significant progress has been made in the application research of two-dimensional nanomaterials in desalination membranes, among which graphene and its derivatives have performed particularly prominently. The graphene oxide membrane developed by researchers has achieved a water flux 2-3 times higher than that of traditional polyamide membranes by precisely controlling the interlayer spacing (0.3-0.7 nanometers), while maintaining a desalination rate of over 99%. This "molecular sieve" effect stems from the monolayer structure formed by water molecules in graphene nanochannels, and its flow resistance is much lower than that of the diffusion paths in traditional membranes. The Lawrence Berkeley National Laboratory in the United States recently reported a super-thin film composed of MoS_2 nanosheets and received extensive attention. This material has natural hydrophilicity and anti-pollution properties, and has demonstrated excellent stability in long-term tests.

Metal-organic framework (MOF) materials are another type of new membrane material that has attracted much attention. This type of porous crystal material formed by the self-assembly of metal ions and organic ligands has a designable pore structure and surface chemical properties. The UiO-66 MOFs membrane developed by the team from the National University of Singapore achieves selective separation of monovalent and high-valent ions through a dual mechanism of pore size sieving and electrostatic repulsion, providing a new idea for solving the problem of removing small molecule pollutants such as boron. The University of Science and Technology of China has modified traditional polyamide membranes with biomimetic aquaporin structures, increasing their water flux by 40% while enhancing their chlorine resistance by more than three times, significantly extending the membrane's service life. (Table 2)

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Table 2. Performance comparison of new desalination membrane materials in the past five years

Material Type	Research Team	Water Flux (Lmh/Bar)	Desalination Rate (%)	Innovation Characteristics	Technology Maturity
Graphene Oxide	Massachusetts Institute of Technology	5-8	>99	Atomic-level precise channel	Laboratory stage
Mofs Membrane	National University of Singapore	3-5	98-99.5	Ion selective separation	Small-scale trial scale
Bionic Water Channel Membrane	University of Science and Technology of China	2.5-3.5	>99	High chlorine resistance	Pilot test verification
Plasma-Modified Film	Korea Advanced Institute of Science and Technology	2.8-3.8	>99	Anti-pollution Mosaic structure	Initial commercialization
Polydopamine-Silver Composite Film	Chinese Academy of Sciences	2.2-3.0	>99	Self-cleaning function	Demonstration Project Application

3.2. Innovative design of renewable energy drive systems

A key breakthrough has been made in the integration of renewable energy and seawater desalination: In the photothermal - membrane coupling technology, the nano-fluilicity-assisted RO system developed by KAUST preheats seawater (50-60 °C) with graphene suspension, reducing energy consumption by 30% and increasing the recovery rate of reclaimed water to over 50%. Tianjin University in China proposed a three-level architecture of photovoltaic - thermoelectric generation - RO, and the comprehensive power consumption was reduced to 2.1kWh/m³. For fluctuating energy sources, Israel's IDE applies machine learning to optimize the coordinated dispatching of the power grid, photovoltaic, and energy storage, enabling flexible regulation of RO loads (60-100%) and increasing the proportion of renewable energy to 40%. The floating desalination vessels of MWP in Norway are powered by offshore wind and wave energy, enabling direct water transportation along the coast. The innovation of passive solar technology is remarkable: The three-dimensional conical evaporator of Nanjing University, through thermal localization design, has a water production capacity three times that of the traditional one (12.5kg/m²). The multi-stage water-salt separation architecture of the Shanghai Institute of Ceramics, Chinese Academy of Sciences, has overcome the problem of salt crystallization, supports the continuous desalination of 20% high-salinity wastewater, and expands application scenarios.

3.3. Concentrated brine resource utilization and zero liquid discharge technology

With increasingly strict environmental protection regulations and the deep-rooted concept of resource recycling, the treatment and resource utilization of concentrated brine, a by-product of seawater desalination, have become a hot research field in the past five years. Traditionally, concentrated brine is regarded as waste and is directly discharged back into the ocean. Its salinity is usually 1.5 to 2 times that of seawater, and it contains various pretreatment chemicals and cleaning wastewater, posing a potential threat to Marine ecology. Current innovative research is dedicated to transforming this kind of "waste" into valuable resources to achieve a win-win situation of environmental and economic benefits.

"Zero liquid discharge" (ZLD) is the ultimate goal of concentrated brine treatment, and the key to achieving this goal lies in the efficient and energy-saving terminal concentration technology. In recent years, membrane distillation-crystallization coupled systems have demonstrated unique

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advantages. The air-gap membrane distillation device designed by Delft University of Technology in the Netherlands uses industrial waste heat as the driving source. It can concentrate the concentrated brine to a TDS of more than 300g/L, and then connect it to the evaporation crystallizer to obtain high-purity NaCl crystals. The total energy consumption of the system is reduced by 50% compared with the traditional multi-effect evaporation. The Seawater Desalination Institute in Tianjin, China, innovatively combined forward osmosis (FO) with RO to develop the "Osmo-RO" system, which spontaneously achieves water separation through osmotic pressure difference and is particularly suitable for use in conjunction with small-scale decentralized desalination units.

3.4. Integrated application of intelligent and digital twin technologies

The rapid development of artificial intelligence and Internet of Things technologies has brought revolutionary changes to the optimized operation and intelligent maintenance of seawater desalination systems. Digital twin, as one of the most watched technologies in the past five years, has been applied in many large-scale seawater desalination projects. Veolia, a French company, has built the world's first full-process digital twin system at its Sur desalination plant in Oman. By embedding over 2,000 sensors and CFD real-time simulation, it can accurately predict the development of membrane fouling and optimize the cleaning cycle, reducing system energy consumption by 12% and extending membrane life by 30%. An Israeli IDE company has taken a step further by integrating deep learning algorithms with digital twins to develop an operation optimization system that can learn independently. This system can adjust system parameters in real time based on fluctuations in seawater temperature, turbidity, and electricity prices, saving approximately 1.5 million US dollars in operating costs annually.

In terms of fault diagnosis and predictive maintenance, the innovative application of acoustic emission technology and infrared thermal imaging has significantly enhanced equipment reliability. The Spanish company Acciona has deployed an acoustic monitoring network in its desalination plant located in Barcelona. By analyzing the acoustic wave characteristics inside the RO pressure vessel, it can detect membrane element damage or seal failure 48 hours in advance, avoiding unplanned shutdowns. A team from the National University of Singapore has developed a fault diagnosis model based on transfer learning, which can accurately identify 10 common types of faults with only a small amount of on-site data, achieving a diagnosis accuracy rate of 93.5%, significantly lowering the professional threshold for technicians.

The application of blockchain technology in water resource management has also made initial progress. Australia's CSIRO is testing a blockchain-based desalinated water trading platform that enables agricultural, industrial and municipal users to buy and sell desalinated water quotas based on real-time supply and demand conditions and automatically settle through smart contracts. This decentralized model significantly improves the efficiency of water resource allocation. The seawater desalination microgrid project in Zhoushan Islands, China, explores the integration of desalination systems with distributed renewable energy, energy storage and the electricity market. It records the "carbon-water footprint" of each kilowatt-hour of electricity and each drop of water through blockchain, providing a reliable basis for sustainability certification.

3.5. Multi-dimensional anti-pollution and bionic surface engineering innovation

In the field of membrane surface modification, important breakthroughs have been made in plasma treatment and nano-coating technology. The Korea Advanced Institute of Science and Technology (KAIST) constructed a "Mosaic" structure membrane with alternating hydrophilic and hydrophobic

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properties through low-temperature plasma grafting, significantly inhibiting the adsorption of pollutants. Inspired by mussels, a team from the Chinese Academy of Sciences developed a polydopaminine-silver composite film, which has both anti-biological contamination and self-cleaning functions, extending the chemical cleaning cycle from 30 days to 90 days. To address the issue of membrane fouling, Toray Corporation of Japan has adopted microbubble scrubbing technology, which reduces the frequency of chemical cleaning by 40% through periodic turbulence. The Dutch Norit integrated ultrasonic vibration (20-100 KHZ) effectively prevents particle deposition. In terms of electrochemical self-cleaning technology, Yale University in the United States has developed conductive nanofiber membranes that generate active chlorine and microbubbles through pulsed voltage, reducing the flux attenuation rate to 1/5 of that of traditional membranes. The photocatalytic membrane of the Institute of Process Engineering, Chinese Academy of Sciences, utilizes the TiO_2/g-C_3N_4 heterojunction to decompose pollutants under sunlight and has outstanding anti-biological pollution performance. In addition, bio-inspired pretreatment technology has emerged: The Korea Advanced Institute of Science and Technology designed a micro-vortex system imitating the gill rakes of whale sharks, achieving a removal rate of 95% for large particles. The Swiss Federal Institute of Technology in Zurich has developed a biological flocculant based on coral mucus, which selectively adsorbs organic matter and reduces the subsequent membrane fouling load. These innovations have broken through technical bottlenecks from multiple dimensions such as materials, physics, chemistry and bionics, promoting the efficient and stable operation of seawater desalination systems.

4. Current research gaps and critical analysis

Although seawater desalination technology has made remarkable progress in the past five years, a thorough analysis of the gap between existing research results and practical engineering applications can still identify multiple key research gaps and technical bottlenecks. These unresolved problems not only restrict the further promotion and application efficiency of seawater desalination technology, but also point out the directions that need to be focused on and broken through in future research. By critically examining the current development status of technologies, the practical feasibility and application prospects of various innovative technologies can be evaluated more rationally.

The continuous challenges of energy consumption and carbon footprint

The issue of energy consumption has always been a core challenge that seawater desalination technology cannot avoid. Even the most advanced SWRO(reverse osmosis of seawater) system still requires 2.5-3.5kWh of electricity to produce 1 cubic meter of fresh water. This means that a medium-sized (100,000 tons per day) desalination plant can consume more than 100 million KWH of electricity annually, equivalent to the emission of approximately 50,000 tons of CO_2. Although renewable energy-driven desalination systems are highly anticipated, the actual operation data reveal an alarming gap: the penetration rate of renewable energy in most wind-solar coupled desalination projects is less than 30%, and the rest still rely on grid power supply. This limitation mainly stems from the contradiction between the intermittency of renewable energy and the requirement for stable operation of desalination units.

5. Conclusion

Seawater desalination technology, as a core means to alleviate global water shortages, has evolved over more than half a century from early thermal distillation to a diversified pattern dominated by

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reverse osmosis and featuring the coexistence of multiple technologies. In the past five years, breakthroughs in fields such as materials science, renewable energy, and artificial intelligence have injected new vitality into seawater desalination. Intelligent management and digital twin technology have optimized the operational efficiency of the system. These advancements not only enhance the economy and sustainability of seawater desalination, but also expand its application boundaries in industry, agriculture and special scenarios.

However, the technical bottlenecks and challenges remain severe. The issues of energy consumption and carbon footprint remain the core obstacles restricting large-scale promotion. The contradiction between the intermittency of renewable energy and the stability of the system urgently needs to be resolved, and engineering problems such as the durability of membrane materials and equipment corrosion still need to be broken through. High initial investment and operation and maintenance costs have hindered the wide application of the technology. Moreover, since this article is a review piece, it lacks substantive data support. Future research needs to focus on four major directions: First, accelerate the commercial transformation of new membrane materials and anti-pollution technologies; The second is to deepen the intelligent dispatching and energy storage innovation of the renewable energy coupling system; The third is to build a closed-loop system for the "full-chain utilization of resources" of concentrated brine. Fourth, promote interdisciplinary collaboration and international cooperation, and establish a framework for technical standards and policy support.

The sustainable development of seawater desalination is not only related to technological innovation, but also requires a comprehensive consideration of environmental, economic and social benefits. Only through technological breakthroughs, policy guidance and global collaboration can we ensure water resource security while achieving harmonious coexistence between humans and nature. The future of this field is both a challenge and an opportunity - it embodies humanity's wisdom in resolving the water resource predicament and reflects the profound significance of ecological civilization construction.

References

[1] World Bank. (2023). Global trends in desalination: Technology, economics, and environmental impacts. World Bank Publications. ISBN 978-1-4648-1895-6.
[2] Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment. Science, 333(6043), 712-717. https: //doi.org/10.1126/science.1200488
[3] Werber, J. R., Osuji, C. O., & Elimelech, M. (2016). Materials for next-generation desalination and water purification membranes. Nature Reviews Materials, 1(5), 1-15. https: //doi.org/10.1038/natrevmats.2016.18
[4] Wang, J., et al. (2022). Graphene oxide membranes for high-flux desalination: Challenges and opportunities. Advanced Materials, 34(15), 2107630. https: //doi.org/10.1002/adma.202107630
[5] KAUST Solar Desalination Initiative. (2024). Nanoparticle-enhanced solar-thermal RO systems: Pilot results and scalability assessment. KAUST Research Publications.