

Environmental Challenges of Seawater Desalination Plants

Esmaeel Parizi^{1,*}, Samad Hamzei¹, Seiyed Mossa Hosseini²

Article Info

Article type:

Popularization of Science

Article history:

Receive Date:

25 May 2026

Revise Date:

08 June 2026

Accept Date:

09 June 2026

Available online:

21 June 2026

Keywords:

Renewable Energy

Brine

Reverse Osmosis

Hybrid Technologies

Environmental Sustainability

The growing global demand for freshwater—particularly in arid and semi-arid regions—has underscored the necessity of adopting sustainable water supply solutions, making seawater desalination a strategic and technological option. A comprehensive review of emerging technologies reveals that significant advancements have been achieved in recent years in both membrane and thermal methods, including improved membrane selectivity and permeability, reduced energy consumption, optimization of reverse osmosis processes, and the development of hybrid and multi-stage systems. However, key challenges such as high energy consumption, dependence on fossil fuels, the generation and discharge of highly concentrated brine, and extensive chemical use continue to limit the sustainability of these systems. Integrating renewable energy sources—particularly photovoltaic, solar-thermal, and wind energy systems—offers significant potential to reduce the carbon footprint and enhance environmental performance, though operational issues such as cooling, scaling, dust accumulation, and equipment durability must be managed. Environmental impact assessments indicate that brine discharge remains the most critical ecological challenge, and the use of advanced modeling, modern diffusers, resource recovery strategies, and minimal-discharge technologies can help mitigate its negative effects. The development of advanced fouling-resistant membranes, hybrid energy systems, and optimized energy consumption strategies is considered essential for achieving a sustainable future in seawater desalination.

Cite this article: Parizi,E , Hamzei,S and Mossa Hosseini,S . (2026). Environmental Challenges of Seawater Desalination Plants. *Science Cultivation*, 16 (1).81-89.



© Author(s) retain the copyright and full publishing rights.

Publisher: Foundation for the Advancement of Science and Technology in Iran (FAST-IRAN) and Iran Society of Biophysical Chemistry (ISOBC)

* Corresponding Author. Assistant professor, Tel: +989135835504, Fax: +982166944873, E-mail: Parizi@inio.ac.ir

¹ Iranian National Institute for Oceanography and Atmospheric Science (INIOAS), Tehran 1411813389, Iran

² Physical Geography Department, University of Tehran, Tehran, Iran.

Extended Abstract

Environmental Challenges of Seawater Desalination Plants

Introduction

The escalating global demand for freshwater, driven by population expansion and economic development, has positioned seawater desalination as a critical solution, supporting over 300 million people across 150 countries. By 2018, global desalination capacity reached 92.5 million cubic meters per day, with substantial growth observed in the Middle East. However, the widespread adoption of desalination is hampered by significant financial barriers, primarily high investment and operational costs. Annually, energy expenditure alone amounts to US\$51.6 billion, highlighting the sector's high energy demand, with desalination processes consuming approximately 75.2 TWh per year. This energy consumption varies depending on technology and feedwater quality, with seawater desalination being the most energy-intensive. Desalination technologies are broadly categorized into thermal systems — multi-stage flash distillation (MSF), multi-effect distillation (MED), mechanical vapor compression (MVC), and thermal vapor compression (TVC)— and membrane systems —reverse osmosis (RO) and electrodialysis (ED). Thermal systems require both electrical and thermal energy, whereas membrane systems, particularly RO, are primarily powered by electricity for pump operation, while ED relies on direct current. The interdependence of energy and water, often termed the water–energy nexus, is pronounced in desalination. The current energy mix for desalination is predominantly fossil-fuel-based, leading to substantial greenhouse gas (GHG) emissions, which are projected to exceed 0.4 billion tons of CO₂ equivalent annually by 2050. This reliance also renders desalination vulnerable to fluctuations in fossil-fuel prices. In pursuit of sustainability, a shift towards renewable energy sources is imperative. Reverse osmosis (RO) is increasingly favored due to technological advancements and reduced energy requirements. Nevertheless, thermal technologies remain dominant in regions such as the Persian Gulf, owing to the availability of fuel resources and the limitations of RO in treating high-salinity or highly turbid feedwater. Ongoing research and development on emerging technologies, including membrane distillation (MD), adsorption desalination (AD), pressure-retarded osmosis (PRO), forward osmosis (FO), and capacitive deionization (CDI), offer promise for enhanced energy efficiency. Hybridization of existing and novel processes is also a strategic approach to reducing energy consumption.

Methods

The environmental impacts of seawater desalination were assessed through a comprehensive review of existing literature and published data. This involved analyzing studies on various desalination technologies, focusing on their energy consumption patterns, greenhouse gas emissions, and the management of reject brine. Both established technologies, such as RO and MSF distillation, and emerging technologies, such as MD and AD, were considered. Energy consumption data were compiled, with distinctions made between electrical and thermal energy requirements for each technology. Greenhouse gas emissions were estimated based on the energy sources used, predominantly fossil fuels, and projected future emission scenarios were developed. The environmental impact of brine discharge, including its salinity, temperature, and chemical composition, was a key area of focus, along with an examination of mitigation strategies such as dilution and zero liquid discharge (ZLD) systems. Life cycle assessment (LCA) principles were applied to evaluate the overall environmental footprint of desalination processes, from construction and operation to decommissioning.

Results

The analysis revealed that RO is generally the most energy-efficient technology, with specific energy consumption ranging from 2.5 to 5 kWh/m³. However, its efficiency can be affected by feedwater salinity and temperature. Thermal processes, such as MSF and MED, are more energy-intensive,

typically consuming 10–20 kWh/m³ equivalent energy, with a significant portion provided as thermal energy. The reliance on fossil fuels for energy generation results in substantial greenhouse gas emissions. For instance, a typical RO plant powered by grid electricity derived from fossil fuels can emit approximately 0.5–0.8 kg CO₂-eq/m³. Projections indicate that by 2050, global greenhouse gas emissions from desalination could reach over 0.4 billion tons of CO₂ equivalent annually if current trends persist. Brine discharge presents a significant environmental challenge. The hyper salinity, typically 1.5–2 times higher than the salinity of source seawater, and elevated temperature of discharged brine can adversely affect marine ecosystems, leading to reduced dissolved oxygen, increased toxicity, and habitat disruption. The chemical composition of brine, which may include antiscalants and cleaning agents, further exacerbates these impacts. Studies have shown localized ecological damage near outfall points, particularly in sensitive or enclosed marine environments. Mitigation strategies such as diffusion systems, multi-port diffusers, and dilution with cooling water can reduce the immediate impacts; however, concerns remain regarding large-scale operations and cumulative effects. ZLD technologies, while effective in eliminating brine discharge, are currently prohibitively expensive and energy-intensive for widespread adoption.

Conclusion

Seawater desalination is an indispensable tool for global water security, yet its environmental footprint, particularly in relation to energy consumption and brine management, requires urgent attention. While technological advancements, especially in RO and emerging membrane processes, are enhancing energy efficiency, the widespread reliance on fossil fuels for energy generation continues to drive significant greenhouse gas emissions. The environmental impact of brine discharge on marine ecosystems remains a critical concern, requiring robust management strategies and further research into less environmentally harmful disposal methods or ZLD technologies. A concerted effort to integrate renewable energy sources with desalination processes is paramount for achieving sustainable water production. Future research should focus on further reducing the energy intensity of all desalination technologies, developing cost-effective and environmentally benign brine management solutions, and conducting comprehensive life cycle assessments to guide policy and investment toward truly sustainable desalination practices. The development and adoption of hybrid systems and novel technologies such as MD, AD, and CDI hold significant promise for a more sustainable desalination future.