ISSN: 2306-8582
eISSN: 2313-2957
DOI: 10.18271/ria.2026.736

Desalination Technologies in the Face of Water Scarcity: Efficiency, Sustainability, and Environmental Consequences

Tecnologías de desalinización ante la escasez hídrica: eficiencia, sostenibilidad y consecuencias ambientales

Edison Rodrigo Castillo[1], Jiovanna Eulalia Rosero Bolaños[2], Natalia Masabanda Paucar[3], Maritza D. Ruiz Medina[4], Elizabeth Velasco Vázquez[5], Marcela Viláñez Obando[6] & Pamela Rodriguez Huera

Abstract

The growing scarcity of freshwater, exacerbated by climate change and population growth, has driven the development and implementation of more efficient and sustainable desalination technologies. This study presents a systematic review of the main processes used to desalinate saltwater, including reverse osmosis, multistage distillation, electrodialysis, and nanofiltration. The technical principles of each method are described, along with their comparative advantages, energy requirements, operational limitations, and associated costs. Additionally, the environmental impacts—particularly brine generation and disposal—are analyzed, as well as current strategies to mitigate these effects. The article contextualizes the global application of these technologies, highlighting regions such as the Middle East, North Africa, and Latin America, where the demand for desalinated water has significantly increased. Emerging solutions that integrate renewable energy sources—such as solar, wind, and geothermal—are also explored, aiming to reduce the energy footprint and enhance economic feasibility. This review provides a comprehensive overview of the current state of desalination, its ecological implications, and the innovative prospects that position it as a strategic alternative to ensure water access in increasingly water-stressed scenarios.

Keywords: desalination, membrane technologies, environmental impact, drinking water, brine.

Resumen

La creciente escasez de agua dulce, agravada por el cambio climático y el aumento poblacional, ha impulsado el desarrollo y la implementación de tecnologías de desalinización más eficientes y sostenibles. Este estudio presenta una revisión sistemática de los principales procesos utilizados para desalinizar el agua salada, incluyendo ósmosis inversa, destilación multietapa, electrodiálisis y nanofiltración. Se describen los fundamentos técnicos de cada método, sus ventajas comparativas, requerimientos energéticos, limitaciones operativas y costos asociados. Asimismo, se analizan los impactos ambientales derivados, especialmente la generación de salmuera y su disposición, así como las estrategias actuales para reducir dichos efectos. El artículo contextualiza la aplicación global de estas tecnologías, destacando regiones como el Medio Oriente, África del Norte y América Latina, donde la demanda de agua desalinizada ha crecido significativamente. También se exploran soluciones emergentes que integran energías renovables, como solar, eólica y geotérmica, con el fin de reducir la huella energética y aumentar la viabilidad económica. Esta revisión proporciona una visión integral sobre el estado actual de la desalinización, sus implicaciones ecológicas, y las perspectivas de innovación que la posicionan como una alternativa estratégica para garantizar el acceso al agua en escenarios de estrés hídrico creciente.

Palabras clave: desalinización, tecnologías de membrana, impacto ambiental, agua potable, salmuera.

Received: 08/07/2025
Accepted: 13/08/2026
Published: 03/09/2026

Section: Review Article

***Corresponding author:** edison.castillo.i@hotmail.com

Introduction

The availability of freshwater on Earth has become a pressing global concern due to a convergence of complex and interrelated factors. Rapid population growth, accelerated urbanization, intensive industrial and agricultural activities, and the overexploitation of natural freshwater sources have placed unprecedented pressure on existing water resources. Additionally, the effects of climate change, including prolonged droughts, irregular precipitation patterns, and the melting of glaciers have intensified water scarcity in numerous regions, further exacerbating the imbalance between water demand and supply. This imbalance is especially critical in arid and semi-arid zones, coastal regions, and countries with seasonal water stress, where the availability of safe drinking water is becoming increasingly uncertain and threatens the well-being of millions in the world.

[1]Posgrado, Universidad Politécnica Estatal del Carchi, Tulca, Carchi, Ecuador.
[2]Ministerio de Educación del Ecuador, Unidad Educativa San Pedro Pascual, Ibarra, Imbabura, Ecuador
[3]Escuela Politécnica Nacional, Ingeniería Química, Departamento de Ciencias Nucleares, Quito, Pichincha, Ecuador
[4]Universidad Politécnica Estatal del Carchi, FIACA, Carrera de Alimentos, Tulcán, Carchi, Ecuador
[5]Universidad de las Fuerzas Armadas ESPE, Departamento de Ciencias Exactas, Sangolquí, Pichincha, Ecuador
[6]Universidad Técnica del Norte, Ibarra, Ecuador
[7]Universidad Politécnica Estatal del Carchi, FIACA, Carrera de Medicina Veterinaria, Tulcán, Carchi, Ecuador

How to cite: Castillo, E. R., Rosero Bolaños, J. E., Masabanda Paucar, N., Ruiz Medina, M. D., Velasco Vazquez, E., Vilañez-Obando, M., & Rodriguez Huera, P. (2026). Desalination of Water and Ecological Consequences. Revista De Investigaciones Altoandinas - Journal of High Andean Research, 28, e28736. https://doi.org/10.18271/ria.2026.736

In response to this global water crisis, seawater desalination has emerged as a promising technological solution. The practice of desalinating water is not new; historical records indicate that civilizations such as the Greeks and Romans experimented with rudimentary methods for salt removal. However, it was not until the twentieth century that industrial-scale desalination technologies began to develop, initially for military and maritime purposes. Today, technological advances have led to the refinement and global deployment of highly efficient desalination processes such as reverse osmosis (RO), multistage flash distillation (MSF), multiple-effect distillation (MED), electrodialysis (ED), and nanofiltration (NF).

These technologies have enabled many countries, especially those in the Middle East, North Africa, and island territories, to secure their water supply by treating seawater or brackish water. Nevertheless, despite their growing importance, desalination systems still face significant challenges, including high energy consumption, dependence on fossil fuels, high operational costs, and the environmental risks associated with brine discharge. Consequently, a growing body of research is exploring the integration of renewable energy sources — such as solar, wind, and geothermal power — into desalination systems to improve sustainability and reduce the environmental footprint.

This study seeks to provide a comprehensive review of current desalination technologies from both technical and environmental perspectives. It aims to identify their main applications, operational principles, efficiency levels, environmental impacts, and future development prospects (Bundschuh *et al.*, 2021). The approach adopted is descriptive and exploratory, without formulating hypotheses, as the objective is to consolidate updated and relevant knowledge that can inform further research, policy design, and the adaptation of these technologies to local and regional needs.

Literature Review

Global freshwater scarcity has intensified in recent decades due to multiple interrelated factors: population growth, uncontrolled urbanization, climate change, agricultural expansion, water body pollution, and overexploitation of underground sources. In this context, water desalination emerges as a strategic technological solution to address water stress in arid, semi-arid, coastal, or insular regions (Bundschuh *et al.*, 2021; Saadat *et al.*, 2018)

From a technical perspective, desalination processes are classified into three main groups: thermal, membrane-based, and electrochemical. Among the thermal methods, multistage flash distillation (MSF) and multiple-effect distillation (MED) stand out. In these, saline water undergoes sequential evaporation and condensation stages. Although they offer high reliability, their main drawback is the high energy demand due to external heat requirements (AlMarzooqi *et al.*, 2014; Manjula & Dinesh, 2013).

Among membrane processes, the most widespread is reverse osmosis (RO), which uses a semipermeable membrane to separate dissolved salts from water by applying pressures higher than osmotic pressure. This method involves no phase change and is efficient at large scales, although it demands high pumping energy and presents membrane fouling issues (Saadat *et al.*, 2018)

Electrodialysis (ED), an electrochemical technology, applies electric current to separate ions through selective membranes. It is particularly effective for low-salinity brackish water (<12,000 mg/L) and has lower operational costs compared to RO, though its efficiency decreases for seawater applications (Manjula & Dinesh, 2013). Another promising technology is nanofiltration (NF), positioned between reverse osmosis and ultrafiltration. It shows excellent performance in treating water with high organic matter and emerging pollutants and is effective in removing divalent ions such as calcium, magnesium, and sulfates (Surwade *et al.*, 2015).

One of the main challenges of desalination is its high energy consumption, which affects operating costs and increases the associated carbon footprint. For instance, reverse osmosis requires 3 to 5 kWh/m^3 of potable water, while thermal systems can exceed 10 kWh/m^3 (Nurjanah *et al.*, 2024). To mitigate this, hybrid models powered by renewable energy sources — particularly solar photovoltaic and thermal, geothermal, and wind — have been proposed (Bundschuh *et al.*, 2021). Additionally, emerging technologies such as capacitive deionization (CDI) and microbial desalination cells (MDC) are being developed for small-scale or low-energy applications. These alternatives are still in experimental stages but represent important advances in efficiency and sustainability (Chen *et al.*, 2011; Porada *et al.*, 2012).

Environmentally, the main concern associated with desalination is the management of brine, a concentrated effluent rich in salts, heavy metals, and chemicals. If discharged untreated, it can disrupt marine and coastal ecosystems. Common disposal methods include open sea discharge, dilution in wastewater treatment plants, or evaporation ponds (Bundschuh *et al.*, 2021).

Therefore, adopting zero liquid discharge (ZLD) strategies, valorizing brine subproducts, and developing low-impact technologies are essential to advancing circular water resource management models (Manjula & Dinesh, 2013; Surwade *et al.*, 2015). In the Ecuadorian context, desalination plants are not widely implemented; however, several studies have addressed water treatment and monitoring. Research by León *et al.* documents automated monitoring experiences in natural sources such as the Monjas River and San José de Chaltura, incorporating sensors, IoT platforms, and computational analysis (Castro *et al.*, 2018; León *et al.*, 2018).

Additionally, the work of Ruiz Medina and Ruales proposes sustainable post-harvest conservation solutions using edible coatings and antifungal essential oils applied to fruits like banana Musa paradisiaca (M. D. Ruiz Medina & Ruales, 2025a, 2025b, 2025c) and strawberry Fragaria vesca (M. Ruiz Medina *et al.*, 2016; M. D. Ruiz Medina *et al.*, 2025). These approaches help reduce the use of synthetic fungicides, extend shelf life, and decrease water use in washing and treatment processes, thus positively impacting water consumption in agribusiness.

Recent developments in membrane science and electrochemical processes have further expanded the theoretical and practical framework for desalination. Among these, capacitive deionization (CDI) has gained attention as a low-energy, sustainable option for treating brackish water and removing ionic contaminants. Studies by He *et al.* (2024) highlight the role of activated carbon in enhancing the ion adsorption capacity in CDI systems, improving overall water quality while minimizing energy demand.

Similarly, the development of graphene-based membranes represents a frontier in advanced separation technologies (Zubair *et al.*, 2024). These membranes exhibit superior water flux, high salt rejection rates, and chemical robustness. Dai *et al.* (2022) and Zhang *et al.* (2024) have documented how graphene oxide (GO) and composite nanomaterials significantly outperform traditional polymeric membranes, making them suitable for both seawater desalination and wastewater reclamation.

In addition to laboratory results, bibliometric reviews by researchers such as Zubair *et al.* (2024) and analytical studies in journals like Polymers and ACS Environmental Science Au reinforce the growing global interest in GO–polysulfone membranes and their applications in real-world desalination plants (Zhang *et al.*, 2024). The literature also reflects increased emphasis on integration with renewable energy and hybrid membrane systems for sustainable water treatment solutions.

Moreover, the evolution of zero liquid discharge (ZLD) systems is closely tied to these advancements. Enhanced membrane technologies now allow partial mineral recovery from brine and increased water recovery efficiency. High-performance polyimide membranes embedded with graphene are a promising example, contributing to circular water economies and environmental resilience.

These technological pathways, supported by extensive literature and real-world validation, underscore the shift towards intelligent, decentralized, and energy-conscious desalination systems aligned with global water sustainability goals.

Methodology

This study was conducted using a qualitative approach of descriptive and exploratory nature, with the aim of analyzing the main desalination technologies from both technical and environmental perspectives. The methodology was based on a systematic literature review, which enabled the consolidation of the current state of the art regarding widely adopted processes for obtaining freshwater from saline and seawater sources, as well as their ecological, energetic, and operational implications.

The search strategy was structured using relevant keywords in both English and Spanish, including desalination, reverse osmosis, membrane technologies, brine management, renewable energy, desalinization, osmosis inverse, and impact Ambiental. Scientific databases of high international recognition were consulted, such as Scopus, ScienceDirect, SpringerLink, Taylor & Francis Online, and Google Scholar, prioritizing primary sources, peer-reviewed articles, and specialized technical literature.

The inclusion criteria considered:

- Publications in English or Spanish,
- Indexed in high-impact scientific journals,
- Focused on specific desalination technologies (reverse osmosis, multistage distillation, electrodialysis, nanofiltration),
- Providing empirical data or technical analysis on energy efficiency, operational costs, environmental impact, and scalability.

A thematic analysis matrix was developed to categorize the selected studies according to the type of technology, operational principles, application level (pilot or industrial), energy consumption, integration with renewable energy sources, ecological implications (such as brine management), and implementation regions. This framework facilitated the identification of patterns, knowledge gaps, emerging trends, and critical challenges.

Given the documentary nature of the research, no field data collection or quantitative instruments were used. Content analysis was applied as the main technique, complemented by theoretical triangulation to validate the internal coherence of the findings. This methodological design enabled the construction of a rigorous, up-to-date synthesis that may guide future applied research and support strategic decision-making in the sustainable management of water resources at both regional and global scales.

Sample: This study adopted a qualitative documentary approach based on a systematic review of recent and high-impact scientific literature. The sample consisted of 48 peer-reviewed articles and international reports published primarily between 2013 and 2024, selected from databases such as Scopus, ScienceDirect, SpringerLink, and Google Scholar.

The selected documents focused on core desalination technologies—reverse osmosis, electrodialysis, multistage distillation, nanofiltration, and capacitive deionization (CDI)—and addressed variables such as energy consumption, environmental impacts, renewable energy integration, and brine management. Additionally, a regional emphasis was placed on Latin America, especially case studies or technological assessments related to Ecuador and other countries with water stress conditions.

Data collection instruments: A qualitative content analysis was carried out through authors, years, and keywords such as desalination, reverse osmosis, electrodialysis, brine management, renewable energy, membrane fouling, and zero liquid discharge. The instruments ensured data consistency and relevance to the study's objectives.

Statistical analysis: Given the qualitative nature of this research, no statistical modeling or numerical instruments were applied. Instead, a descriptive content analysis was conducted, identifying recurring patterns, technological trends, and research gaps in desalination studies.

Results and Discussion

Salt water or also known as sea water, is a very important and valuable resource that provides a wide variety of products such as water, salt, algae, krill, fish, substances of great value for medicines and cosmetic products, among others (Flores & Bernabe Calle, 2015).

Throughout history, various discoveries and applications have been made that have allowed the study of the properties and components of seawater, with significant results for human health. It has developed several applications, from the bottling of seawater as a nutritional supplement, to its use in pharmacotherapy and cosmetics, among many others (Bundschuh *et al.*, 2021; Surwade *et al.*, 2015).

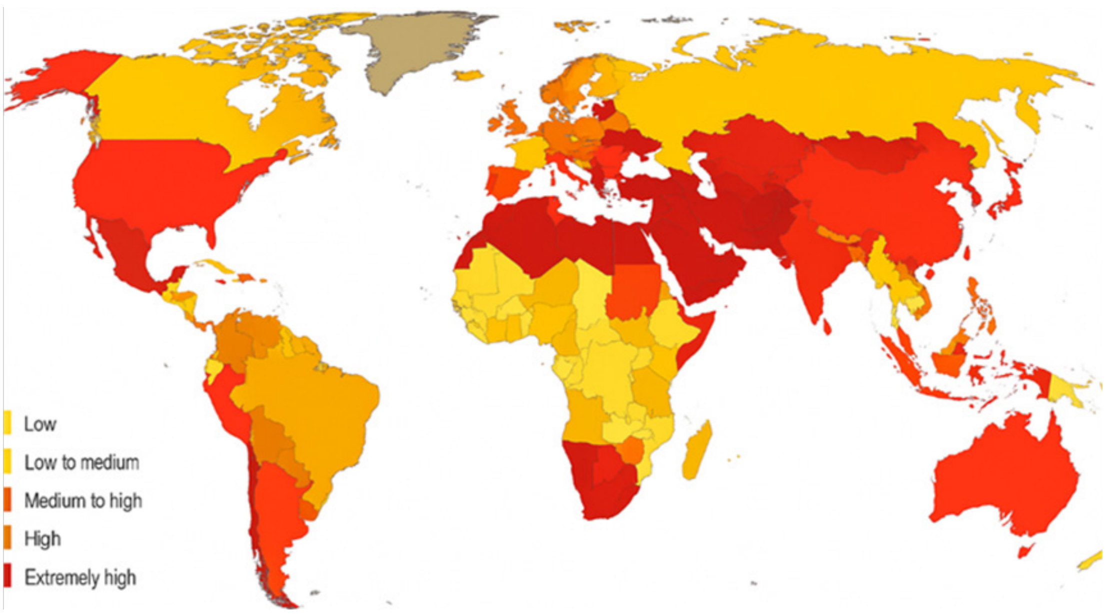
This work builds upon a previously established research line developed by the author, focusing on water treatment and monitoring in both urban and rural areas of Ecuador. Previous studies addressed quality control systems in natural water sources such as the Monjas River and San José de Chaltura (Castro *et al.*, 2018; León *et al.*, 2018).

The population growth of the planet has resulted in the excessive use of freshwater resources in comparison with their renewability, in addition to the constant deterioration that occurs in the quality of groundwater and surface water. Climate change in recent years has resulted in limited access to quality drinking water, even in new areas where water supply was not a critical problem (AlMarzooqi *et al.*, 2014).

At present, the water desalination process has been considered a very important solution to this problem, which can provide adequate water quality for crop irrigation and industry, as well as for domestic purposes (Saadat *et al.*, 2018).

Figure 1

Projected water stress in the world for 2040



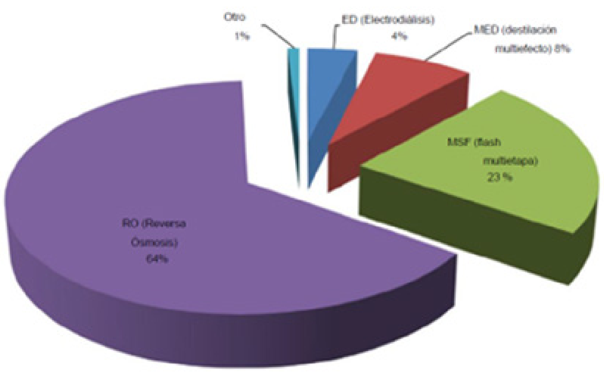
Several countries, mainly in the Middle East and North Africa, experience structural and periodic water shortages. The scarcity of fresh water is also felt in central and western European countries as well as in Latin America (Fig. 1) (Bundschuh *et al.*, 2021), in addition to the critical situation that aggravates the problem due to toxic pollutants of geogenic and anthropogenic origin, such as arsenic, boron , fluoride, chromium, uranium, etc. in shallow flowing waters.

Due to all these problems and the significant increase in the population, it has caused the amount of water per capita to fall well below 1500 m^3 /year, that is, the level determined by the United Nations as the minimum existence (Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

Desalination is the removal of sales and other minerals from saltwater or seawater to make it fit for human consumption. There are three types of desalination processes: Thermal processes including multi- stage flash distillation (MSF), multi -effect distillation (MED) and mechanical vapor compression, membrane processes including reverse osmosis (RO) and electrodialysis (ED) as shown in Fig. 2 (AlMarzooqi *et al.*, 2014), process that acts on chemical bonds such as ionic exchange (Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

Figure 2.

Methods used for desalination of water.



Currently, desalination and water treatment processes cover an important part of the demand for high quality water, providing a solution that is, in a certain sense, economically viable and technologically feasible. Some 15,906 desalination plants are operating in 177 countries, with a total desalination capacity of about 95.35 million m3 /day (34.810 million m3 /year), and this figure will increase very rapidly due to the installation of mega plants around the world (Manjula & Dinesh, 2013).

Currently, the capacity of the desalination plants that were contracted worldwide at the beginning of 2019 was about 4 million m^3 / day. In addition , a large number of desalination facilities are located in the Middle East and North Africa (4,826 plants, 47.5% of world desalination capacity), East Asia and the Pacific (3,505 plants, 18.4% of world capacity), North America (2,341 plants, 11.9% global capacity), Western Europe (2,337 plants, 9.2% global capacity), Latin America and the Caribbean (1,373 plants, 5.7% global capacity) , South Asia (655 plants, 3.1% of global capacity), Eastern Europe and Central Asia (566 plants, 2.4% of global capacity) and Sub-Saharan Africa (303 plants, 1.9% of global capacity).

In addition, it can be noted that countries such as Israel, the United Arab Emirates, and the Kingdom of Saudi Arabia cover more than 50% of their demand with desalinated water, which is used both for industrial and domestic purposes, but also for energy, irrigation, military, and others uses (Youssefa *et al.*, 2014).

Desalination processes

Due to the increase in the world demand for fresh water, which has become the bottleneck for the development of the population, caused by the increase in the population, the increase in the standard of living, environmental pollution and the expansion of agriculture and industrialization are driving the development of new, energy-efficient water desalination technologies (Porada *et al.*, 2012).

For the treatment of saltwater, which typically contains relatively few ions, there is significant potential to achieve high energy efficiency using technologies that specifically remove ions to desalinate the water, rather than the reverse approach where excess ion molecules are removed. water from saline solution as in state-of-the-art distillation technologies (Bundschuh *et al.*, 2021; Chen *et al.*, 2011; Saadat *et al.*, 2018).

Generally considering the large seawater and saltwater capacities, desalination is considered an important approach to produce the necessary fresh water. The main desalination technologies that have been commercialized include electrodialysis, reverse osmosis (RO), and distillation (Saadat *et al.*, 2018; Surwade *et al.*, 2015). For the above approaches, the main concerns are relatively intensive power consumption in the form of heat or electricity.

For example, current reverse osmosis systems typically cost between 3 and 5 KWh /m^3 of electrical energy to produce potable water. 2.5 In order to reduce traditional energy consumption, renewable energies such as solar and wind power are being investigated to drive the desalination process (Almetwally *et al.*, 2025). However, the costs of these technologies, even higher than conventional ones, prevent their use on a large scale (Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

Multistage flash distillation

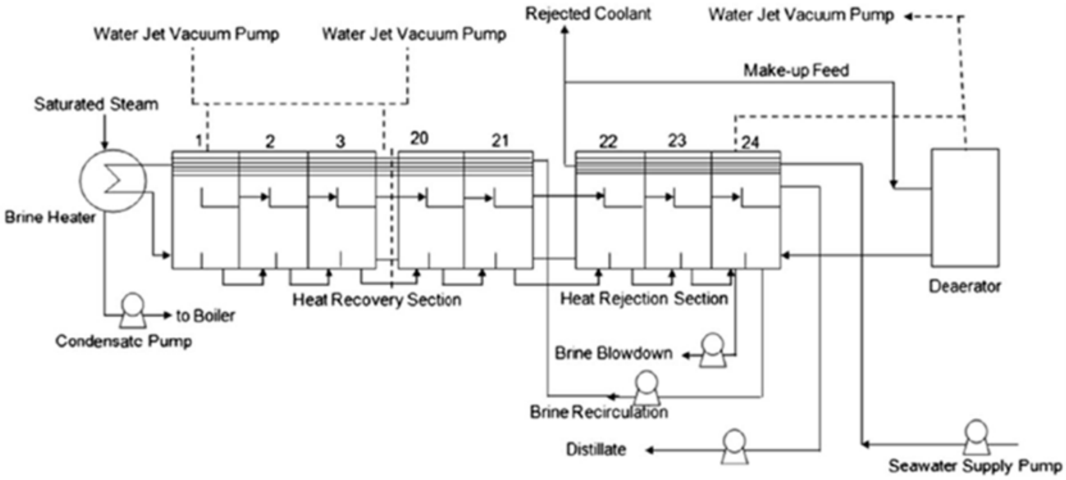
The principle of this method or process is to distill seawater and condense the steam obtained, recovering the latent heat to heat more seawater that will subsequently evaporate. This means that seawater must be brought to a boil in several stages in a closed container under pressure.

If the process were ideal, that is to say, if the heat transmission occurred with an infinite area and an infinite number of stages and there were no losses, once the process started, no more heat would have to be supplied and the process would be self-maintaining, but as this it is thermodynamically impossible, it is necessary to have an external source of energy, which provides the increase in temperature that is missing to start the cycle (Saadat *et al.*, 2018).

In this process there are three sections, the heat input section, heat recovery section and heat rejection section.

Figure 3

Multistage flash distillation



The multi–stage flash desalination unit is a desalination unit that begins by heating water and ends by condensing water, with a total of 40 stages.

The condenser, known as the heat rejection section, consists of two or three stages. Cold seawater flows through the tubes of the heat rejection section heat exchanger, starting with the last stage, which has the lowest absolute temperature. The steam that condenses on the outer surface of the heat exchanger tubes gives up its latent heat to the seawater flowing through the tubes. The temperature of seawater increases as it flows from one stage to the other.

Seawater leaves the heat reject section and is split into a make-up feed stream and a reject stream. The make-up stream is sprayed with chemicals and enters the last stage of evaporation. A part of the brine is also mixed with the feed water. As the feed water flows through the stages in the heat recovery section, it is heated by the latent heat of the steam that is constantly condensing. Finally, the feed water is heated in the brine heater using externally supplied steam.

This raises the feed water to its highest temperature called "upper brine temperature" (TBT) which ranges from 90 to 110°C. Then it goes through the different stages where the flashing takes place. The steam generated by flashing is converted to fresh water by condensing on the tubular heat exchangers that pass through each stage. Pure water vapor is drawn by vacuum through defrosters that remove brine droplets.

The water vapor encounters cold condenser tubes and condenses to form pure water that is collected in trays. The vacuum is increased through successive stages so that the water boils at lower temperatures. Water salinization processes at each stage, the brine concentration increases due to the vaporization of water. The concentrated brine that remains at the end of the process is rejected as purge (Figure 3) (Bundschuh *et al.*, 2021; Saadat *et al.*, 2018).

Distillation multistage (MED)

It is the oldest desalination process and was popular until the 1960s, when multistage flash distillation began to win the desalination market. This process resembles MSF distillation, the multi- stage distillation taking place in a series of vessels (effects) at reduced ambient pressure in the various effects. Feedwater is sprayed onto the evaporator surface (usually tubes) in thin films to promote rapid boiling and evaporation. The surfaces in the first effect are heated by steam from power plant turbines or a boiler.

The surfaces of all other effects are heated by the steam produced in each previous effect. The steam produced in the final effect is condensed in a separate heat exchanger called the final condenser, which is cooled by the incoming seawater, preheating the feedwater. The number of effects ranges from 4 to 14 and the yield ratio is around 10 to 18. Multistage distillation consumes less energy than MSF and has a better yield ratio (Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

Generally, the distillation multistage can be used in small to medium-sized plants, which operate at a maximum temperature of 70°C, reducing the scaling problem. But this increases the need for additional heat transfer areas and increases the size of the plant.

Developments in the MED process include the coupling of thermal vapor compression with MED and the use of aluminum for heat transfer tubes leading to reduced unit costs of water. MED can even be used for the harsh waters of the Gulf. Each consists of six effects. The process combines MED thermal vapor compression with falling film evaporation (AlMarzooqi *et al.*, 2014; Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

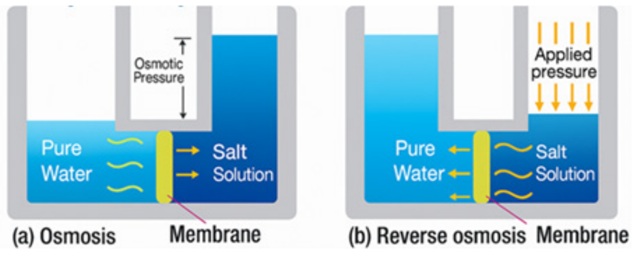
Inverse osmosis

It is a membrane-based process and does not involve a phase change. This process is physical and uses the phenomenon of osmosis. Osmosis occurs when a semi-permeable membrane (which allows the passage of water, not solute) separates two aqueous solutions of different concentrations.

At the same pressure and temperature on both sides of the membrane, water will diffuse through the membrane resulting in a net flux from the dilute to the concentrated side until the concentrations on both sides of the membrane reach equilibrium. This process will also take place if the pressures on both sides are different, if the pressure difference between the concentrated and diluted side is not more than a certain value which depends on the difference of the respective concentrations and is the osmotic pressure.

When the pressure difference is greater than the osmotic pressure, the flow direction is reversed and the water flows from the concentrated side to the dilute side. This process is called reverse osmosis, and a pressure greater than the osmotic pressure is applied to the salt water to force the fresh water through a semi-permeable membrane to overcome the concentration difference (Fig. 4) (AlMarzooqi *et al.*, 2014; Bundschuh *et al.*, 2021; Saadat *et al.*, 2018).

Figure 4
Reverse osmosis processes



The applied pressure depends on the Total Dissolved Solids (TDS) of the feed water. Pressure is generated by pumps, so feedwater TDS influences energy use and the corresponding cost of produced water. Pressure ranges from 10 to 28 bar (145 to 400 psi) for brackish water and 54 to 83 bar (800 to 1,200 psi) for seawater (Bundschuh *et al.*, 2021; Manjula & Dinesh, 2013; Saadat *et al.*, 2018).

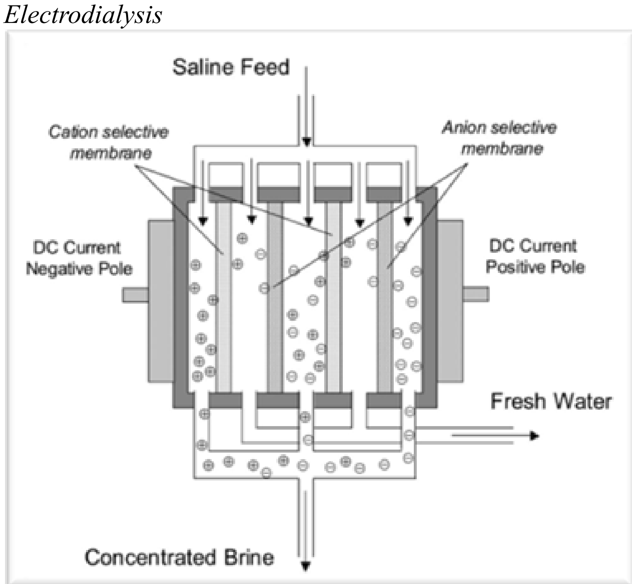
Electrodialysis

This process is suitable for the desalination of brackish water with a salinity of up to 12,000 mg/L. The saltwater passes through a series of stacked cationic and anionic membranes and electrical potential are applied. Most of the dissolved salts in water, being ionic, migrate towards the electrode with the opposite electrical charge. The cationic and anionic membranes are arranged alternately, and a spacer sheet is placed between each pair of membranes. As the electrodes charge, anions in the water are attracted to the positive electrode. They cross the anion selective membrane but are blocked by the selective membrane.

Similarly, cations move across the cation-selective membrane to the concentrated channel on the other side, where they are trapped because the next membrane is an anion-selective. By this arrangement, concentrated and dilute solutions are created in the spaces between the alternating membranes. These spaces, bounded by the two types of membranes, are called cells.

A basic electrodialysis unit is made of several hundred pairs of cells attached with electrodes on the outside and is known as a membrane stack (Manjula & Dinesh, 2013; Saadat *et al.*, 2018). A development of this method is the reverse electrodialysis technique. This process involves a reversal of the water flow to break up and remove scale, slime, and other encrustations deposited in the cells. This flushing also allows the unit to run with fewer pretreatment chemicals (Poirier *et al.*, 2023), which minimizes costs (Fig. 5) (AlMarzooqi *et al.*, 2014; Manjula & Dinesh, 2013).

Figure 5
Electrodialysis



Nanofiltration

Nanofiltration Membranes are made of polypiperazinamide , polysulfone sulfonated and CA. The molecular weight limit is between 300 and 1,000. conditions such as algae blooms. Using this process, SDI values less than 2.5 can be obtained (Manjula & Dinesh, 2013; Saadat *et al*., 2018; Surwade *et al*., 2015).

Power consumption is comparatively low, and it effectively removes pollutants. NF membranes have properties between reverse osmosis and ultrafiltration and provide higher water flow at lower operating pressure. Furthermore, they have a very high rejection of divalent ions, while the rejection of monovalent ions is limited. Sulfate rejection is around 99% while Ca, Mg rejection is 98 and 92% respectively. Additionally, NF is used to soften, disinfect, and remove organic materials and metals.

Due to their ability to effectively remove dissolved organic compounds and bivalent ions, NF membranes are of great interest from the point of view of meeting water quality standards (Manjula & Dinesh, 2013; Saadat *et al*., 2018; Surwade *et al*., 2015).

The adoption of Integrated Membrane Systems (IMS) such as UF/RO, MF/RO, or NF/RO helps improve desalination operations and meets the increasing demand for pure water (Manjula & Dinesh, 2013; Saadat *et al*., 2018). The integration of power generation with MSF is one of the main technology options prevailing in the United Arab Emirates.

Since MSF is an energy-intensive process, recovering waste heat from large-scale power plants helps reduce the cost of thermal desalination. RO processes have also been integrated with MSF/CHP systems. When RO and MSF operate in parallel, capital savings result from the use of common input and output facilities (AlMarzooqi *et al*., 2014; Manjula & Dinesh, 2013; Saadat *et al*., 2018).

Ecological Consequences of Desalination

Generally, almost all desalination, capacitive deionization and membrane technologies suffer from the more generic environmental problem of brine solution disposal (He *et al*., 2024a). However, solutions for the treatment of the brine solution and the reduction of its environmental effect have been proposed and implemented and the simplest method is using evaporation ponds (Prado de Nicolás *et al*., 2022). Since capacitive and membrane deionization are relatively low energy intensive technologies, the other environmental impacts would be in the manufacturing process of electrodes and ion exchange membranes and their elimination strategy (AlMarzooqi *et al*., 2014)

Regarding disposal, the expected lifespan for electrodes and ion exchange membranes is reported to be 10 years and 10 to 15 years, respectively. However, the closest match to the environmental assessment of capacitive deionization technology was the long-term stability of the electrodes, addressing the oxidation of the positive electrode that leads to a significant reduction in desalination capacity (He *et al*., 2024b).

However, it sets the steppingstones for further investigation into both the long-term stability and reliability of the technology and offers a basis for future environmental evaluations (Saadat *et al*., 2018). To reduce the impact of desalination on the environment, research is ongoing to integrate membrane processes such as reverse osmosis and nanofiltration with crystallization methods to achieve zero liquid discharge. The desalination industry continues to advance technologies that reduce energy requirements, improve sustainability, and address environmental responsibility (Manjula & Dinesh, 2013).

The analysis of results confirms that desalination has emerged as a strategic alternative in response to the growing global scarcity of freshwater, particularly in arid, semi-arid, and coastal regions. Technologies such as reverse osmosis (RO) lead global implementation due to their efficiency and adaptability to different water sources; however, they still face critical challenges, including high energy consumption, membrane fouling, and complex pretreatment requirements (Saadat *et al*., 2018).

Comparative analysis shows that thermal processes such as multistage flash (MSF) and multiple-effect distillation (MED), while reliable, are less energy-efficient and more expensive to operate. In contrast, emerging technologies like electrodialysis (ED) and nanofiltration (NF) have shown benefits in ionic selectivity and efficiency when treating brackish water, although their large-scale deployment is still under development (Manjula & Dinesh, 2013). A trend is the integration of renewable energy sources into desalination systems. Recent studies highlight the potential of solar, wind, and geothermal energy to reduce the carbon footprint and improve the economic viability of desalination plants (Bundschuh *et al*., 2021).

Additionally, low-energy technologies such as capacitive deionization (CDI) are gaining momentum, particularly for decentralized applications in rural communities (He *et al*., 2024a, 2024b).

The development of advanced membranes, especially those based on graphene oxide (GO), represents a significant technological breakthrough. Research by Dai *et al.* (2022) and Zhang *et al.* (2024) demonstrates that GO-based membranes exhibit high permeability, excellent salt rejection, and strong chemical resistance, making them promising candidates for next-generation desalination systems.

From an environmental perspective, brine management remains the most pressing ecological concern. Untreated brine discharge can severely impact marine and coastal ecosystems. Consequently, strategies such as zero liquid discharge (ZLD) systems and brine valorization for mineral recovery are gaining attention, contributing to circular water economies and pollution reduction (Manjula & Dinesh, 2013).

Desalination, far from being a stand-alone solution, must be integrated into a broader framework of intelligent and sustainable water resource management, especially in the face of climate change and increasing pressure on conventional water systems.

Conclusions

Desalination has emerged as a viable and strategic response to the global freshwater crisis, offering a reliable means of securing water supply in regions experiencing acute water stress. Technologies such as reverse osmosis provide high efficiency and operational flexibility; however, the sector continues to face critical challenges, particularly related to high energy demands and the environmentally sensitive disposal of concentrated brine. In this context, the integration of renewable energy sources — such as solar, wind, and geothermal — represents a promising path toward minimizing environmental impact, lowering operational costs, and improving the long-term sustainability and resilience of desalination systems. Continued innovation, policy support, and region-specific adaptation will be positioning desalination as a cornerstone of sustainable water management.

Author Contributions

All authors contributed equally to all aspects of this work, including conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing of the original draft, and review and editing of the final manuscript.

References

AlMarzooqi, F. A., Al Ghaferi, A. A., Saadat, I., & Hilal, N. (2014). Application of Capacitive Deionisation in water desalination: A review. Desalination, 342, 3-15.

Almetwally, E. M., Elazab, M. A., Kabeel, A. E., Yasser, Y., & Elgebaly, A. (2025). Solar powered reverse osmosis desalination: A systematic review of technologies, integration strategies and challenges. *Desalination*. https://doi.org/10.1016/j.desal.2025.119228

Bundschuh, J., Kaczmarczyk, M., Ghaffour, N., & Tomaszewska, B. (2021). State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. Desalination, 508, 115035. https://doi.org/10.1016/j.desal.2021.115035

Castro, M., Ruiz Medina, M. D., Guarda, T., Montalvan, R., Arguello, L., & Tapia, A. (2018). Analysis of the Water Quality of the Monjas River: Monitoring and Control System. En Advances inm Intelligent Systems and Computing (pp. 363-374). https://doi.org/10.1007/978-3-319-77700-9_36

Chen, X., Xia, X., Liang, P., Cao, X., Sun, H., & Huang, X. (2011). Stacked Microbial Desalination Cells to Enhance Water Desalination Efficiency. Environmental Science & Technology, 45(6), 2465-2670.

Dai, Y., Liu, M., Li, J., Kang, N., Ahmed, A., Zong, Y., Tu, J., Chen, Y., Zhang, P., & Liu, X. (2022). Graphene-Based Membranes for Water Desalination: A Literature Review and Content Analysis. Polymers, 14(19), 4246. https://doi.org/10.3390/polym14194246

Flores, D. A., & Bernabe Calle, B. V. (2015). El agua de mar en la alimentación y en la terapia. Boletín de la Sociedad Española de Hidrología Médica, 30(1), 37-55.

He, S., Zhu, T., Wang, Y., Xiong, W., Gao, X., & Zhang, E. (2024a). Application of capacitive deionization technology in water treatment and coupling technology: A review. Environmental Science: Water Research & Technology, 10, 2313-2340. https://doi.org/10.1039/D4EW00413B

He, S., Zhu, T., Wang, Y., Xiong, W., Gao, X., & Zhang, E. (2024b). Enhancing capacitive deionization for water desalination: The role of activated carbon in contaminant removal. Environmental Science: Water Research & Technology, 10, 1034-1060. https://doi.org/10.1039/D4EW00026A

León, M., Ruiz, M., Haz, L., Montalvan, R., & Medrano, V. P. (2018). Water Treatment Monitoring System at San Jose de Chaltura, Imbabura – Ecuador. Computational Science and Its Applications – ICCSA 2018, 610-624. https://doi.org/10.1007/978-3-319-95171-3_48

Manjula, N., & Dinesh, K. (2013). Water desalination and challenges: The Middle East. Desalination and Water Treatment, 51, 2030-2040.

Nurjanah, I., Chang, T.-T., You, S.-J., Huang, C.-Y., & Sean, W.-Y. (2024). Reverse osmosis integrated with renewable energy as sustainable technology: A review. *Desalination, 581*, 117590. https://doi.org/10.1016/j.desal.2024.117590

Poirier, K., Lotfi, M., Garg, K., Patchigolla, K., Anthony, E. J., Faisal, N. H., Mulgundmath, V., Sahith, J. K., Jadhawar, P., Koh, L., Morosuk, T., & Al Mhanna, N. (2023). A comprehensive review of pre- and post-treatment approaches to achieve sustainable desalination for different water streams. *Desalination, 566*, 116944. https://doi.org/10.1016/j.desal.2023.116944

Porada, S., Sales, B. C., Hamelers, H. V., & Biesheuvel, P. M. (2012). Water Desalination with Wires. The Journal of Physical Chemistry Letters, 3(12), 1613-1618.

Prado de Nicolás, A., Molina-García, A., García-Bermejo, J. T., & Vera-García, F. (2022). Reject brine management: Denitrification and zero liquid discharge (ZLD)—Current status, challenges and future prospects. *Journal of Cleaner Production, 381*, 135124. https://doi.org/10.1016/j.jclepro.2022.135124

Ruiz Medina, M., Ávila, J., & Ruales, J. (2016). DISEÑO DE UN RECUBRIMIENTO COMESTIBLE BIOACTIVO PARA APLICARLO EN LA FRUTILLA (Fragaria vesca) COMO PROCESO DE POSTCOSECHA. Revista Iberoamericana de Tecnología Postcosecha, 17(2), 276-287.

Ruiz Medina, M. D., & Ruales, J. (2025a). Essential Oils as an Antifungal Alternative for the Control of Various Species of Fungi Isolated from Musa paradisiaca: Part I (No. 2025051213). Preprints. https://doi.org/10.20944/preprints202505.1213.v1

Ruiz Medina, M. D., & Ruales, J. (2025b). Essential Oils as an Antifungal Alternative to Control Several Species of Fungi Isolated of Musa paradisiaca: Part II (No. 2025011894). Preprints. https://doi.org/10.20944/preprints202501.1894.v1

Ruiz Medina, M. D., & Ruales, J. (2025c). Essential Oils as an Antifungal Alternative to Control Several Species of Fungi Isolated of Musa paradisiaca: Part III (No. 2025012025). Preprints. https://doi.org/10.20944/preprints202501.2025.v1

Ruiz Medina, M. D., Yupangui, Y. Q., & Ruales, J. (2025). Effect of a Designed Coating on the Physicochemical Properties of Banana Musa paradisiaca During Storage. https://doi.org/10.20944/preprints202504.1754.v1

Saadat, A. H., Islam, M. S., Islam, M. S., Parvin, F., & Sultana, A. (2018). Desalination Technologies for Developing Countries: A Review. Journal of Scientific Research, 10(1), 77-97.

Surwade, S. P., Smirnov, S. N., Vlassiouk, I. V., Unocic, R. R., Veith, G. M., Dai, S., & Mahurin, S. M. (2015). Water desalination using nanoporous single-layer graphene. Nature Nanotechnology, 10(5), 459-464.

Youssefa, P. G., AL-Dadaha, R. K., & Mahmouda, S. M. (2014). Comparative Analysis of Desalination Technologies. Energy Procedia, 61, 2604-2607.

Zhang, Y., Zhang, S., Gao, J., & Chung, T.-S. (2024). Graphene oxide-based membranes for water desalination and wastewater treatment under realistic conditions. npj 2D Materials and Applications. https://doi.org/10.1038/s41699-024-00462-z

Zubair, M., Farooq, S., Hussain, A., Riaz, S., & Ullah, A. (2024). A review of current developments in graphene oxide–polysulfone derived membranes for water remediation. Environmental Science: Water Research & Technology. https://doi.org/10.1039/D4VA00058G