Zagazig J. Agric. Res., Vol. 51 No. (5) 2024 1001-1019

Soil Science and Agricultural Engineering

Available online at http://zjar.journals.ekb.eg
http:/www.journals.zu.edu.eg/journalDisplay.aspx?Journalld=1&queryType=Master

ENVIRONMENTAL IMPACTS OF SEAWATER DESALINATION TECHNOLOGIES IN THE GULF STATES - A REVIEW

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Received: 10/10/2024; Accepted: 17/10/2024

ABSTRACT: The rapid increase in population growth and subsequent urbanization and industrialization has led to a global water demand. Hence, due to the challenges associated with accessing fresh water, desalination is increasingly being adopted to meet the global water demand. About 61% of the world's desalination capacity is made up of seawater desalination, whilst 30% is made up of brackish water desalination. Half of the world's desalination capacity is accounted for by membrane desalination, which mostly uses reverse osmosis desalination. The remaining half is primarily utilized for thermal desalination, which uses multi-stage flash distillation and multi-effect distillation. Water scarcity poses significant challenges in arid regions like the Gulf Cooperation Council (GCC) countries due to constant population growth, considering the effects of climate change and water management aspects. This paper researches the relationships among water scarcity, energy-intensive desalination, and the development of renewable energy in the Gulf Cooperation Council countries. It examines innovations in solar-powered desalination, considering both solar photovoltaic (PV) and solar thermal technologies, in combination with traditional thermal desalination methods such as multi-effect distillation (MED) and multi-stage flash (MSF). Utilizing bibliometrics, this report provides a comprehensive analysis of scientific literature for the assessment of the research landscape in order to recognize trends in desalination technologies in the Gulf Cooperation Council countries region, providing valuable insights into emerging technologies and research priorities. Despite challenges such as high initial investment costs, technical complexities, and limited funding for research and development, the convergence of water scarcity and renewable energy presents significant opportunities for integrated desalination systems in the Gulf Cooperation Council countries. Summarizing, this paper emphasizes the importance of interdisciplinary approaches and international collaboration by addressing the complex challenges of water scarcity and energy sustainability in the Gulf Cooperation Council countries region.

Key words: GCC, reverse osmosis, water resource, renewable energy, solar energy, water sustainability, solar thermal, high energy consumption, membrane fouling, environmental challenges.

INTRODUCTION

Water, a fundamental resource for human life, constitutes approximately 70% of the Earth's surface. Despite this abundance, just 0.015% exists in rivers and lakes, while 96.5% resides in seas and oceans. The worldwide water demand, currently at 4600 km^3 annually, is projected to surge to 5500–6000 km^3 annually by 2050 because of escalating population growth (**Tashtoush *et al.*, 2023**). However, this demand is met with challenges such as water scarcity, mismanagement, contamination, and over-extraction, resulting in around 3% of the world's freshwater (**CCAOWF, 2024**). Climate change further compounds these issues, leading to extreme weather events that contaminate freshwater resources, disrupt infrastructure, and diminish available water. Approximately 74% of water-related disasters occurred between 2001

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and 2018, a trend expected to intensify with climate change (**Maftouh *et al.*, 2023**).

In the MENA region (including GCC, countries), encompassing a diverse array of countries, water scarcity has already emerged as a pressing issue. The MENA region's unique topography, characterized by deserts, mountains, and coastal regions, contributes to a predominantly arid and semi-arid climate. Annual rainfall in most parts oscillates between 100 and 250 mm, with high variability and low predictability, exacerbating water scarcity (**Mazzoni and Zaccagni, 2019**). Agriculture, the predominant sector consuming water resources, poses a significant challenge to the region‘s water security. Countries like Syria and Yemen utilize up to 90% and 95% of their water for agriculture, respectively, highlighting the strain on water resources. Rapid urbanization and economic expansion further escalate water demands, necessitating strategic interventions to address these challenges (**Maftouh *et al.*, 2023**).

The MENA region primarily relies on limited conventional water resources derived from surface and groundwater. Surface water sources, including rivers and dams, face unreliability and scarcity due to the arid climate. Groundwater, accessed through wells, is crucial for irrigation and drinking water but confronts challenges such as over-exploitation, depletion of aquifers, and increased salinity. This situation is clearly shown in the Gulf Cooperation Council countries, Djibouti, Libya, and Jordan, where both surface and groundwater resources are scarce, as shown in Fig. 1. As the MENA region grapples with these multi-faceted water challenges, addressing issues of scarcity, pollution, and over-extraction becomes imperative for sustainable water management (**FAO, 2018; Zekri, 2020**).

A decision at UNFCCC COP28 urges all parties of the Paris agreement to increase adaptation action and support in order to reach a number of climate-resilience targets. The very first of these targets calls for the significant reduction in climate-induced water scarcity, the implementation of a climate-resilient water supply, and ultimately safe and affordable water for all.

Achieving water sustainability demands a multi-faceted approach, encompassing a reliable water supply, sustainable energy sources, and efficient water utilization across domestic, industrial, and agricultural sectors. An integral aspect of this strategy is water desalination, presenting itself as a potential solution to augment freshwater resources. The process holds promise in addressing water scarcity concerns, especially in regions like the MENA area, which is abundant in brackish water (**Lawal and Qasem, 2020)**. Efforts to enhance water sustainability must not only focus on sourcing additional water but also on optimizing the usage of existing resources to ensure resilience in the face of escalating demands and environmental challenges.

The International Desalination Association (IDA) highlights leading contributors to desalinated water production, including some Arabic Gulf countries and the United States. The MENA region holds a substantial 47.5% of global desalination capacity, with 62.3% allocated to municipal applications and 35% for industrial purposes. Globally, the installed desalination capacity has reached 97.2 million m3 annually from 16,876 plants, contributing to a cumulative capacity of 114.9 million m3 from 20,971 projects (**Jones *et al.*, 2019**).

Desalination, a pivotal process for addressing water scarcity, is energy-intensive, consuming an average of 75 TWh yearly and constituting nearly 0.4% of global electrical energy consumption. This energy intensity leads to significant environmental impacts, producing approximately 76 Mt-CO2 annually, projected to rise to 218 Mt-CO2 annually by 2040 due to the increased desalination capacities. The intricate relationship between water, energy, and the environment nexus underscores the need for sustainable solutions. Renewable energy (RE), especially solar energy, emerges as a viable tool to reduce the environmental footprint of desalination processes by minimizing fossil energy dependency (**Shahzad *et al.*, 2017**).

Desalination processes fall into categories such as thermal, mechanical, electrical, and other processes based on their driving forces and working principles. Thermal processes, like multi-stage flash distillation (MSF), multi-effect distillation (MED), single - effect vapor compression, humidification–dehumidification (HDH) desalination, membrane distillation (MD),

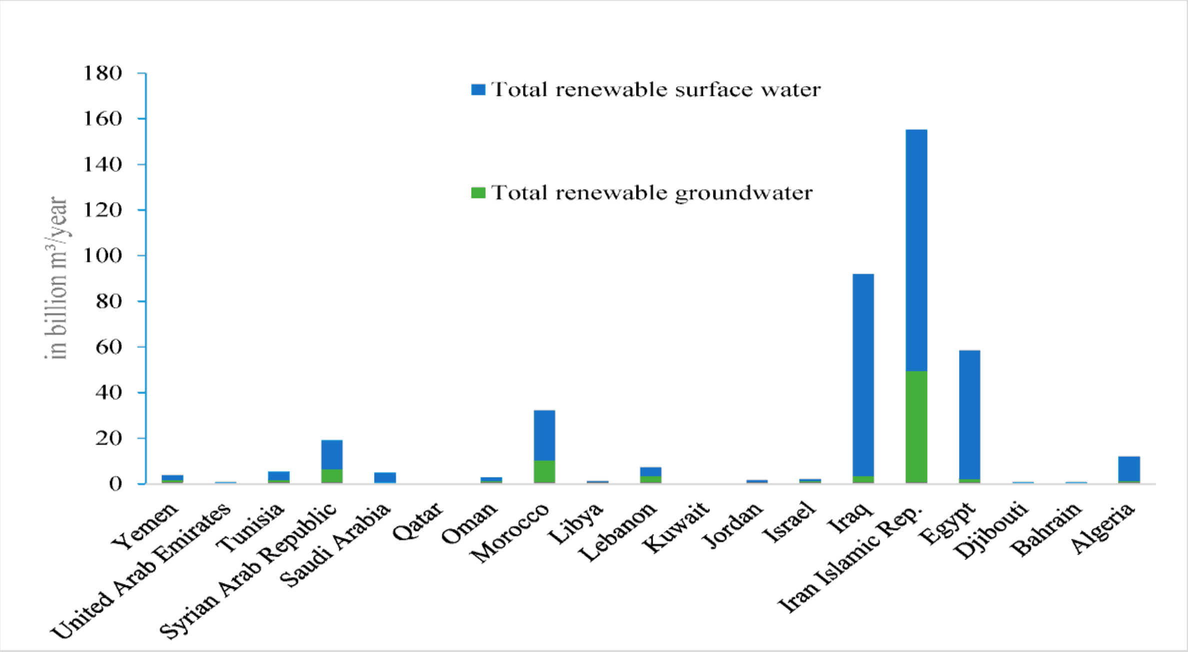

Fig. 1. Groundwater and surface water resources in the Middle East and North Africa (FAO, 2018 and Zekri, 2020)

solar distillation, and freezing use solar thermal energy for evaporation and condensation, mimic the natural water cycle. Mechanically driven processes, such as RO, nanofiltration (NF), and pressure-assisted osmosis (PAO), use pressure and semi-permeable membranes to separate water molecules from ions. Electrically driven processes, like capacitive deionization (CDI) and electrodialysis (ED), focus on ion separation in saline water (**Shalaby *et al*., 2022**). The following Table 1 gives an overview of desalination processes and its driving forces.

Notably, RO dominates both the global and MENA desalination markets, constituting 69% of desalination capacity and 84.5% of the overall plants (**Jones *et al*., 2019**). Fig. 2 illustrates the prevalence of RO technologies, depicting their respective capacities measured in Mm^3/day across various countries in the MENA region. Furthermore, Fig. 3 highlights the trends in desalination technologies, presenting (a) the total number and capacity of desalination units alongside their operational counterparts, and (b) the operational capacity distributed across different desalination technologies (**Jones *et al*., 2019**). Number and capacity of desalination units alongside their operational counterparts, and (b) the operational capacity distributed across different desalination technologies (**Jones *et al*., 2019**).

The MENA region's desalination landscape primarily features RO, MSF, and MED technologies. While thermal processes like MSF and MED are suitable for large capacities, RO plants offer flexibility and modularity (**Sayed *et al*., 2023**). RO, being cost-effective compared to technologies like MSF and multiple-effect evaporation (MEE), has become the preferred choice, constituting 85% of operational desalination plants and 91% of under-construction plants worldwide. The Middle East, representing 39% of global desalination capacity, heavily relies on fossil fuel-based thermal desalination, especially in the Persian Gulf region (**Eke *et al*., 2020**). However, the MENA region's solar and wind energy potential, particularly solar energy, presents opportunities for sustainable water production through solar-assisted desalination (**Maftouh *et al*., 2023**).

Table 1. Desalination processes and driving force (Shalaby *et al*., 2022)

Desalination Process	Driving Force	Working Principle
MSF	Thermal energy	Evaporation and condensation, natural water cycle
MED	Thermal energy	Evaporation and condensation in multiple stages
HDH	Thermal energy	Evaporation and condensation in separate chambers
MD	Thermal energy	Transfer of vapor molecules through a microporous hydrophobic membrane
Solar Distillation	Solar thermal energy	Evaporation and condensation, relying on natural solar radiation
Freezing	Thermal energy	Freezing and separation of water from salt in saline solutions
RO	Mechanical (pressure)	Separation of water molecules from salts through semi-permeable membranes
NF	Mechanical (pressure)	Similar to RO but with slightly larger pore sizes in the membrane for partial salt removal
PAO	Mechanical (pressure difference)	Separation of water from salts across a semi-permeable membrane using osmotic pressure
CDI	Electrical (potential difference)	Attraction and removal of ions from saline water using electrical potential
ED	Electrical (ion-selective membranes)	Separation of ions from saline water using electrical potential gradients

MSF: Multi- Stage
RO: Reverse Osmosis
PAO:
MED: Multi- Effect Distillation
MD: Membrane distillation
CDI: Capacitive Deionization
HDH: Uumidification Dehumidification
NF:
ED: Electrodialysis

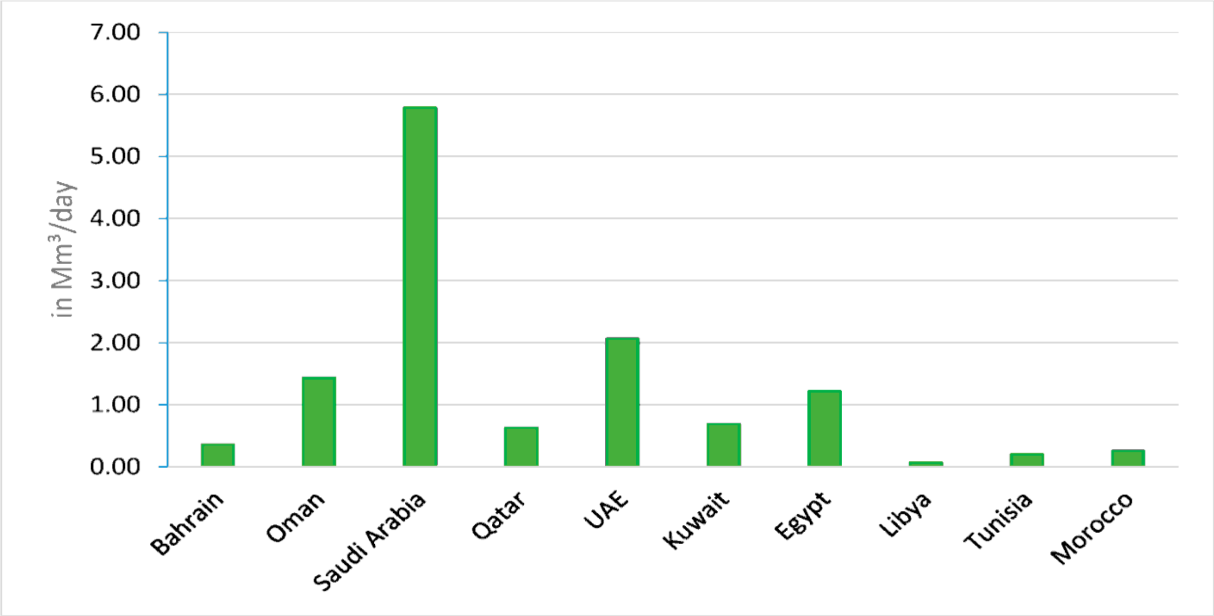

Fig. 2. RO capacity in different countries in the MENA region (Sayed *et al*., 023)

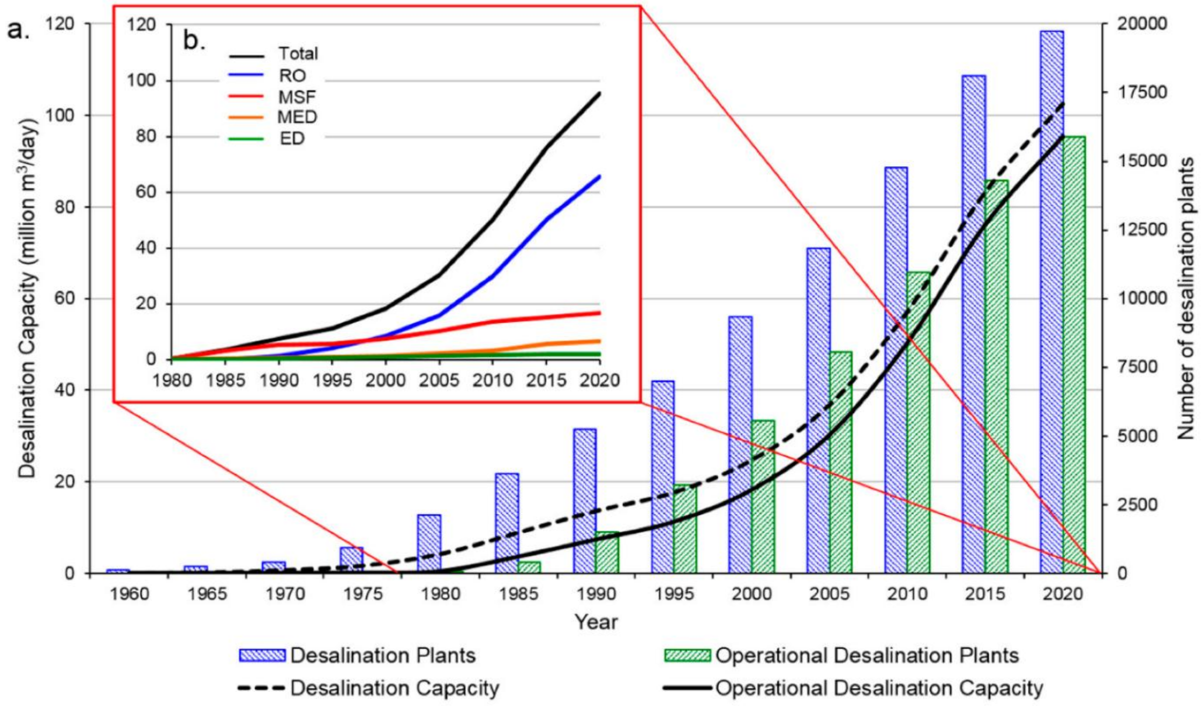

Fig. 3. Global desalination trends: analysis of facility numbers, capacities, and technology operationalities: (a) the total number and capacity of desalination units alongside their operational counterparts, and (b) the operational capacity distributed across different desalination technologies (Jones *et al*., 2019)

The MENA region's desalination landscape primarily features RO, MSF, and MED technologies. While thermal processes like MSF and MED are suitable for large capacities, RO plants offer flexibility and modularity (**Sayed *et al*., 2023**). RO, being cost-effective compared to technologies like MSF and multiple-effect evaporation (MEE), has become the preferred choice, constituting 85% of operational desalination plants and 91% of under-construction plants worldwide. The Middle East, representing 39% of global desalination capacity, heavily relies on fossil fuel-based thermal desalination, especially in the Persian Gulf region (**Eke *et al*., 2020**). However, the MENA region's solar and wind energy potential, particularly solar energy, presents opportunities for sustainable water production through solar-assisted desalination (**Maftouh *et al*., 2023**).

Integrating solar energy into desalination processes offers a promising solution to address both water scarcity and environmental concerns. Direct and indirect solar desalination methods, utilizing PV and concentrated solar power (CSP), emerge as attractive energy sources. PV-solar-based desalination, which provides electricity for membrane-based desalination processes, is suitable for treating brackish water. In contrast, CSP, offering backup energy and extended working hours, is connected with RO systems. While PV has no limitations and is suitable for densely populated areas, CSP's ability to operate after sunset makes it an advantageous choice (**Maftouh *et al*., 2023**).

Traditional desalination methods such as RO, MED, and MSF require significant amounts of energy, mostly from fossil fuels. This reliance results in higher operating costs and increased environmental impact due to carbon emissions. For instance, desalinating seawater using RO consumes about 2.5 to 4 kWh/m^3 of energy, with production costs ranging from 0.5 to 3 USD/ m^3 (**Alawad *et al*., 2023**). In comparison, MSF and MED methods have even higher energy consumption, with MSF varying from 13.5 to 25.5 kWh/m^3 and MED from 6.5 to 28 kWh/m^3, with associated costs ranging from 0.84 to 1.56 USD/m^3. Incorporating solar power into desalination technologies offers the benefit of reducing reliance on fossil fuels and minimizing greenhouse gas emissions, leading to a smaller environmental impact. Solar-powered desalination processes also tend to have lower operational costs due to minimal energy input requirements once the solar infrastructure is installed.

However, the initial capital investment for solar panels and related equipment can be substantial, and the efficiency of solar-powered systems can be influenced by geographical and climatic conditions. For example, when using PVRO for seawater desalination, the energy demand ranges between 2.5 and 6.6 kWh/m^3, with costs ranging from 0.89 to 1.8 USD/m^3 (**Al-Obaidi *et al.*, 2022**). Therefore, the choice between solar-powered desalination and traditional methods depends on various factors, including the specific regional energy landscape, environmental priorities, and economic considerations.

With the MENA region hosting approximately half of the global desalination capacity, the adoption of solar-powered desalination technologies is gaining traction, particularly in countries like Saudi Arabia, the UAE, and Qatar. Investments in solar desalination, despite higher initial costs, indicate a shift toward sustainable practices. For example, the construction of the world's largest PV-RO plant in Saudi Arabia and plans for a significant PV-RO project in the UAE underscore the region's commitment to solar-powered desalination (**Ahmed *et al*., 2019; Rahimi *et al*., 2021**).

Although challenges such as brine disposal and high upfront costs persist, advancements in solar-driven desalination technologies and the increasing demand for water in the MENA region suggest a promising future for sustainable desalination practices. Ongoing research aims to optimize reverse osmosis plants, coupled with renewable energy sources, to improve the efficiency and economic viability of these processes. The integration of solar energy into RO desalination not only addresses water scarcity but also aligns with global efforts to transition toward sustainable and eco-friendly solutions. This paper delves into the feasibility and potential of implementing solar-driven reverse osmosis (RO) desalination plants within the MENA region. It offers a comprehensive examination of the reverse osmosis membrane process, detailing the fundamental processes within RO plants, while also addressing the challenges inherent to RO technology. These challenges encompass high energy consumption, membrane fouling, environmental challenges, and boron removal. Furthermore, the paper delves into the realm of renewable energies, particularly focusing on solar photovoltaics and solar thermal energy, and their abundant presence within the MENA region. By highlighting the solar energy potential in this region, the discussion extends to advancements in the deployment of solar energy-driven RO technology. Both solar photovoltaic-powered and solar thermal-powered RO systems are explored, showcasing the strides made in integrating renewable energy sources into desalination processes. Through a comprehensive review, this paper sheds light on the current landscape of solar-powered RO desalination, emphasizing the ongoing endeavors aimed at surmounting technical barriers and commercializing these sustainable technologies. Ultimately, the overarching aim is to foster the development of economically viable and ecologically sound RO desalination systems, capable of mitigating the escalating water scarcity challenges prevalent in the MENA region (**Al-Addous *et al*., 2024)**.

This research was conducted to provide comprehensive information on environmental impacts of seawater desalination technologies in the Gulf States. We have reviewed the current global water demand and production capacity of desalination. The EIs of desalination applications are also discussed. Thus, this research contains important information on various desalination technologies in terms of their capacity to provide a sustainable water supply in an environmentally friendly manner under Golf countries conditions.

Methodology

The planning stage began by defining the objective of the literature review, focusing on themes like water scarcity, seawater availability, desalination challenges, and potential solutions. After establishing the primary research objective, we formulated sub-topics for qualitative reviews.

A search and evaluation procedure for information was then created to ensure article quality, selecting content from peer-reviewed journals indexed by DHET and Scopus (**Valdés *et al*., 2021**). The literature search in the selected databases initiated the implementation phase. Duplicate articles identified during the review were consolidated and analyzed. Each article was assessed as relevant or irrelevant based on its abstract and title. Following this, the "Quality assessment" was completed for the relevant articles. The authors then chose the publications most closely related to the topic after a careful review of the literature. Relevant data were cross-checked, as per the previous phase (**Krippendorff, 2018**).

The analytical process began with "data extraction", which involved gathering information relevant to the study's objectives. Methodological guidelines were adhered to while systematically identifying and evaluating the data and evidence from the articles. Evidence was collected, coded and assessed through comparisons to establish linkages between the articles, ultimately providing conclusive support for the proposed issues and emerging answers (**Pellicer *et al*., 2012**).

The reporting stage commenced with the integration of the study findings, which were methodically presented through qualitative summaries, figures, and tables. The analyzed data were then published.

Water Scarcity in GCC

The availability of water resources, population expansion, climate change, pollution, poor resource management, the speed of water consumption and water withdrawal globally are some of the variables that contribute to water scarcity. Additionally, the unequal distribution of water resources both geographically and socially can also contribute to water scarcity. Furthermore, the ever-growing demand for water due to urbanization, industrialization, and (increased) agricultural activities puts pressure on already scarce water resources. Water scarcity will remain a major problem impacting countries and communities globally in the absence of effective water management and conservation initiatives. **Azevedo (2014**) observed that local needs, which vary globally based on location, are connected to water scarcity. According to **Ceribasi *et al*. (2018**), approximately 80% of people globally may be exposed to water scarcity. **Karagiannis and Soldatos (2008**) have estimate that roughly 25% of the world's population is experiencing severe water scarcity, which is predicted to leave many people without access to potable water. Drought, desertification, and global warming are predicted to exacerbate the issue to the point where even nations without current water shortages may face them in the near future. **Pangarkar *et al*. (2011**) claim that the gap between the world's demand and supply of water has grown to the point where, in some regions, it poses a serious threat to human survival. Also, they found that the issue of fresh water scarcity is becoming more and more of a global concern because so little of the water on Earth is fit for human use and this percentage comes from non-saline sources. Similarly, **Greenlee *et al*. (2009)** have reported findings from a geological survey conducted in the United States, which revealed that approximately 96.5% of the world's (potential) water resources exist in the oceans and seas. Only around 1.7% of the global water supply consists of ice.

The remaining percentage consists of groundwater located in salty aquifers, as well as brackish water and weakly saline water. This distribution of water resources highlights the dominance of oceans and seas as the primary repositories of Earth's water, with a relatively small portion held in ice and other sources. **Ceribasi *et al*. (2018**) have concluded that saltwater desalination has become increasingly popular since saline water makes up more than 97% of the world's water, found in oceans, seas, and other saline water sources. This process has attracted significant recognition as a practical alternative water supply, especially in countries where freshwater resources are depleted or misused. Being one of the most important issues facing the world, the urgent demand for freshwater supplies has been elevated to the top priority of the international agenda. Water withdrawal is the quantity of water extracted for any purpose from a river, lake, or aquifer, whereas water consumption is the portion of the extracted water that evaporates as a result of vaporization, absorption, chemical conversion, or transmission, or is rendered unavailable for further use as a result of human use or consumption (**Azevedo, 2014**). Recent statistics have shown that agricultural sector activities account for approximately 70% of freshwater withdrawals worldwide. This staggering figure highlights the heavy reliance of the agricultural sector on water resources. In comparison, commercial activities utilize around 20% of potable water, while the domestic sector accounts for the remaining 10% (**UN, 2012**). Over 90% of freshwater withdrawals in less-developed countries are attributed to agriculture, whereas in wealthier nations, industry accounts for a considerably higher share of freshwater withdrawals. The majority of freshwater extraction and consumption figures are based on estimates rather than on accurate calculations. The OECD predicts that the increase in domestic consumption (130%), industrial demand (400%), and thermal electricity generation (140%) will result in a 55% increase in worldwide water withdrawals (**UN, 2012**). Approximately 2.8 billion people on Earth currently live in regions vulnerable to water scarcity and of this number, 1.2 billion live in locations where water scarcity is already a problem, and half a billion people are rapidly approaching this status.

Commercial water scarcity affects the remaining 1.1 billion individuals who experience water scarcity. This population resides in regions of the world where water is readily supplied by nature, but their access to it is restricted due to institutional, financial, or distribution infrastructure problems, even though the amount of water that is available is adequate to cater for their needs. This is the situation in the sub-Saharan region of Africa. Shortage of water in the physical sense is when a community lacks an adequate water supply to satisfy its needs. This kind of scarcity is prevalent in arid areas (including GCC). Shortage in other regions experiencing artificially induced water shortage is triggered by excessive water withdrawal, resulting in environmental damage to groundwater tables and river systems.

Environmental Challenges

Although SWRO desalination is an effective solution to water scarcity in coastal areas, it also poses several environmental challenges. The process of desalination has significant interactions with various environmental subsystems, which include the water (hydrosphere), land (geosphere), living organisms (biosphere), air (atmosphere), and human-made processes (technosphere) (**Elsaid *et al.*, 2020**). The desalination process requires substantial energy consumption, which is often generated from fossil fuels and results in air pollution and greenhouse gas emissions that contribute to climate change. The extraction and processing of materials for desalination infrastructure can also worsen environmental degradation. The extensive land footprint of desalination plants may impact local ecosystems and land use patterns.

Additionally, the intake of seawater and discharge of concentrated brine can disrupt coastal habitats and affect the biodiversity of marine life within the biosphere. Brine disposal, a concentrated saline by-product generated during desalination processes, poses significant challenges and environmental concerns. One of the most critical environmental issues associated with desalination is the intake of seawater and the discharge of concentrated brine, which can disrupt coastal habitats and affect the biodiversity of marine life within the biosphere. Intake systems can cause marine species such as fish, plankton, algae, and seagrass to become trapped against suction racks, resulting in injury or death (**Panagopoulos and Haralambous, 2020)**. The harmful effects of brine on the environment are attributed to its salinity, turbidity, temperature, and chemical composition. The salinity of brine is 1.6–2 times higher than that of seawater, and its temperature depends on the desalination process employed. Various chemicals employed in pre-treatment and membrane cleaning, including copper, ferrous, nickel, molybdenum, and chromium further contribute to the potential environmental impact (**Panagopoulos *et al.*, 2019**). Studies have shown that even a slight increase in salinity can disrupt the osmotic balance of marine species, leading to irreversible dehydration of their cells and potential extinction in the long term. While brine from a single desalination plant may not cause significant harm, the cumulative effects of brine from multiple plants operating in the same area over an extended period could adversely affect marine life (**Cambridge *et al.*, 2017**).

Therefore, careful management practices and innovative solutions are essential to minimize the environmental impacts of brine disposal. Besides ongoing research to limit the environmental effects of brine discharge, full scale plants implemented various process optimizations in new installations. Careful engineering of mixing and diffusion in brine discharge locations helps to limit the local effect of salinity. Alternative pre-treatments like ultrafiltration (UF) (**Kim *et al*., 2020**) lower the amount of chemicals added in the process. And effective heat recovery in thermal desalination systems limits the temperature change in receiving waters while it improves the overall and economic efficiency of the system. The increasing public awareness of the adverse environmental impacts of brine disposal has led to the development of stricter regulations, potentially limiting conventional disposal methods. In response to these challenges, minimal and zero-liquid discharge (MLD and ZLD) has gained attention. MLD/ZLD systems aim to recover high-quality freshwater with the near complete elimination of liquid waste from desalination plants, achieving water recovery rates of more than 95%. The compressed solid waste generated can be disposed of in an eco-friendly manner or repurposed as high-value-added compounds (**Xiong and Wei, 2017**). ZLD/MLD systems comprise a pre-concentration stage (membrane-based technologies) and successive evaporation and crystallization stages (thermal-based technologies), exhibiting variations in design, arrangement, and operation. As shown in Fig. 4, membrane-based technologies encompass reverse osmosis (RO), high-pressure reverse osmosis (HPRO), forward osmosis (FO), osmotically assisted reverse osmosis (OARO), nanofiltration (NF), membrane distillation (MD), membrane crystallization (MCr), electrodialysis (ED) and electrodialysis reversal (EDR), and electrodialysis metathesis (EDM). In contrast, thermal-based technologies include multi-stage flash distillation (MSF) and multi-effect distillation (MED), brine concentration (BC), crystallizer (BCr), spray drying (SD), eutectic freeze crystallization (EFC), and wind-aided intensified evaporation (WAIV) (**Cui *et al*., 2018**). Recently, numerous studies have addressed the challenge of managing brines from SWRO with innovative methods aimed at reducing environmental impacts and enhancing resource recovery. **Morgante *et al*. (2024)** have proposed a novel MLD system that includes a nanofiltration (NF), crystallizer, and MED hybrid process.

Their findings demonstrate that this MLD system not only helps alleviate environmental concerns but also produces high-purity minerals and salts at lower costs compared to current market prices. Similarly, **Zuo *et al*. (2022**) have focused on treating real SWRO brines using a hybrid BC and MD process. They achieved a water recovery rate exceeding 95% and generated salt slurries with around 10–20% moisture from the crystallizer. This approach highlights the potential of the proposed system to achieve ZLD, providing an eco-friendly solution to brine management by maximizing water recovery and generating economically valuable salt by-products.

Desalination Technologies

Various methods of desalinating seawater are being identified and investigated to increase the amount of available potable water. The desalination process is classified into two based on the process's physical characteristics (**Zhao, 2006**). The two categories are membrane technology and thermal technology. Thermal technology uses the concept of vaporization/ evaporation to separate salinity from water, whereas membrane technology uses a filtering device to produce potable water from saltwater. Thermal technology is subdivided into multistage flash distillation, freeze separation techniques, multiple effect distillation, solar still distillation, and vapor compression. Membrane technology is divided into reverse osmosis (RO) and electro dialysis procedures (Fig. 5).

A new desalination method, known as forward osmosis desalination, is poised to transform the concept of generating freshwater from brackish water or saltwater. This innovative method enhances desalination's cost-effectiveness and energy efficiency by extracting water from dissolved salts through a semi-permeable membrane. By harnessing osmotic pressure differences, forward osmosis desalination can revolutionize water treatment and provide sustainable solutions to resolve

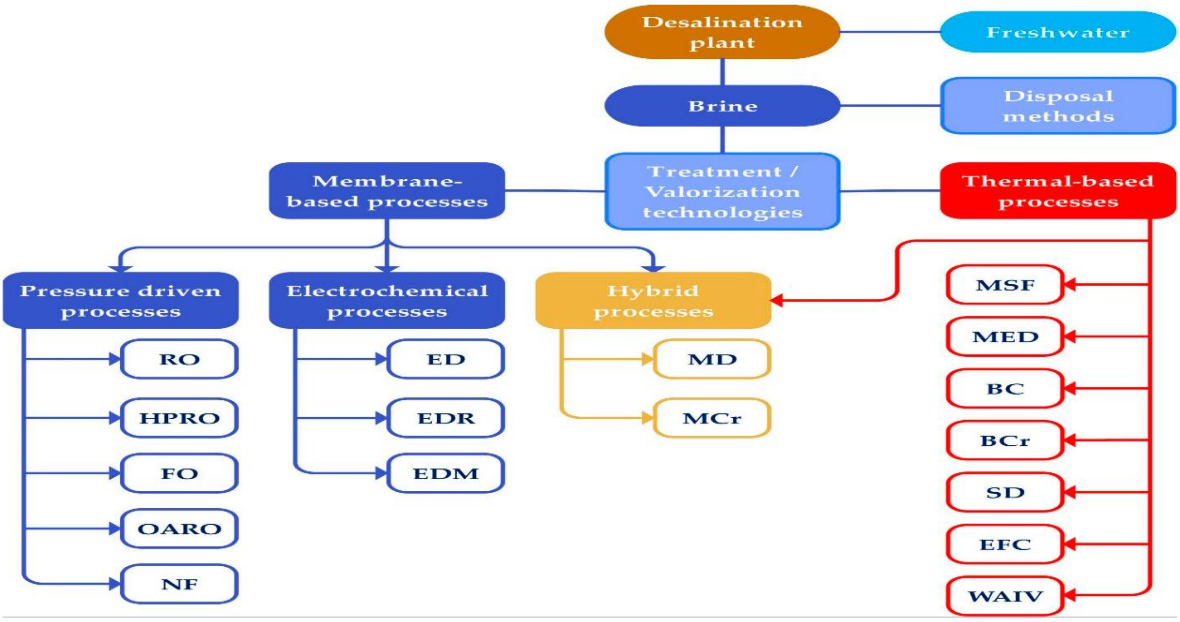

Fig. 4. Main technologies used for the treatment and valorization of desalination brine (Al-Addous *et al.*, 2024)

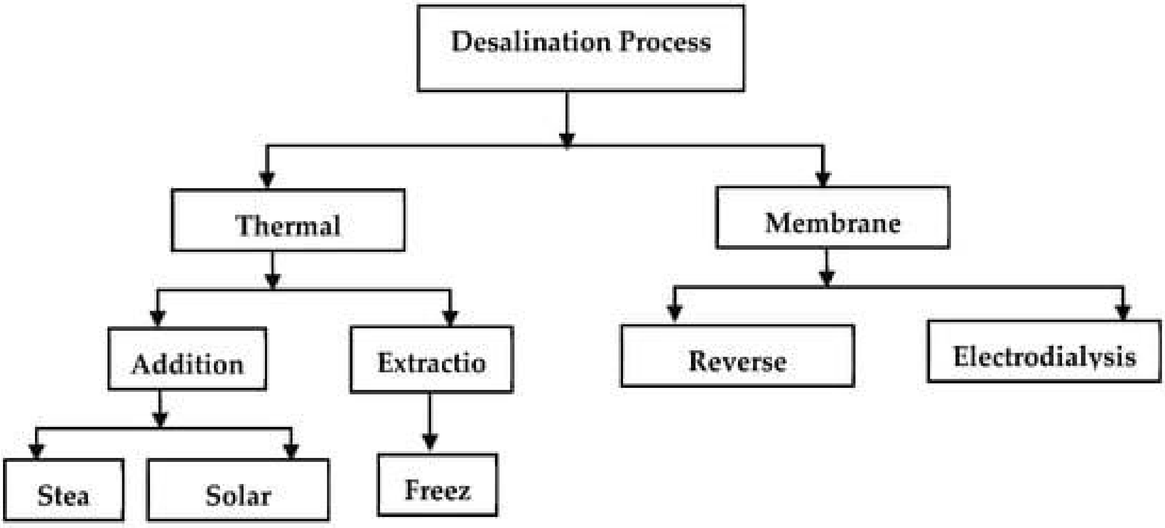

Fig. 5. Desalination technology (Olufisayo and Inambao, 2021)

freshwater scarcity worldwide (**Ceribasi *et al.*, 2018**). It will take the development of dependable new forward osmosis membranes and the extraction of solutes for this technology to progress from the laboratory to practical applications. Flux behavior across a variety of osmotic membranes is presently being studied.

There is also research being carried out on novel draw solutes that can readily regenerate and do not require energy for water recovery. The study conducted by **Kamble and Pitale (2015)** investigated various solar-powered desalination systems, including but not limited to MSF, MED, humidification–dehumidification, electrodialysis, solar still, and adsorption systems. It concluded that, of all the desalination methods previously discussed, solar-powered RO desalination systems based on solar photovoltaic technology are the most widely utilized and embraced since the RO and the PV are readily available and adaptable. The global saltwater desalination plants installed and categorized by technology are roughly 49% for thermal processes and 35% for membrane systems (**Pangarkar *et al.*, 2011**). According to **Ceribasi *et al.* (2018**), the principles of membrane separation, thermal vaporization, electro-dialysis, etc. have served as the foundation for the development of desalination technologies. The authors proceeded to further classify desalination processes into two main groups: membrane and thermal desalination technologies. The least expensive and most practical method of desalination is the solar still (**Aybar and Aybar, 2007**). A solar still is a compact device that utilizes solar energy to extract potable water from contaminated water. It operates on the basic principle that water vaporized from an exposed container in an open space will recondense into water on a chilled surface.

Thermal Desalination Process

The thermal desalination process involves heating seawater as a source of saline water or other saline sources to create steam, which will require cooling to generate condensed water with less salt (**Ceribasi *et al.*, 2018**). In thermal desalination, pressure is lowered to reduce the amount of heat needed for the saline water to evaporate. According to **Research and Clayton (2015**), thermal desalination systems can reduce saline water's salt concentration to as little as 10 mg/L or even less for TDS, between 60,000 and 70,000 mg/L.

Membrane Desalination Process

The most common method for desalinating seawater is membrane desalination (**Ceribasi *et al.*, 2018**). There are diverse applications for membrane technology when brackish water and seawater desalination challenges are encountered. Seawater desalination technology can be classified according to the range of involved components and the prime mover input used. The membrane desalination process relies on the semi-permeable membrane's ability to selectively allow water molecules to pass through. Forward and Reverse Osmosis are the two fundamental desalination techniques used in membrane-type desalination, and they can be used to categorize the membrane desalination process. According to **Lattemann *et al.* (2010**), Forward and Reverse Osmosis were concepting that scientist discovered many years ago. However, the concept of utilizing RO in the desalination process is somewhat novel. Osmosis is the movement of water from a low-concentration solution to a high-concentration solution across a semi-permeable membrane. The reverse osmosis process happens when external pressure to the membrane's higher-concentration side is applied causing the higher-concentration solution to diffuse into the lower-concentration solution.

According to **Ceribasi *et al.* (2018)**, RO desalination is the process by means of which a semi-permeable membrane rejects salt and only permits pure water to flow through. When the feed water is pushed to one side of a semi-permeable membrane, the hydrodynamic pressure needs to be high enough to surpass the osmotic pressure in order to produce a reverse water flow. This is shown in **Figure 6**. **Fikana and Raafi'u (2023)** reiterated that RO has been established to be the most widely accepted desalination method worldwide. Investigated the continuous mobility of industrial RO processes, where the use of a high-pressure pump is necessary to apply external force to the systems. This process involves delivering the salt water at high pressure before it is dispensed for membrane separation. When dealing with seawater, the input feed pressure must be increased to between 40 and 82 bars (600 and 1200 psi), and when dealing with brackish water, it must be increased to between 2 and 17 bars (30 and 250 psi).

Reverse Osmosis Process

Primarily, any floating materials that can give the membrane a foul smell are eliminated from the flow of the sea water or brackish water sources using a hydraulic strainer. Depending on the salinity level, the remaining flow is elevated to the functional pressure of the system before being sent to the desalination unit. During the desalination process, water permeates through the membrane and accumulates as a permeate flux downstream of the membrane. The standard water treatment methodology will be used during the after-treatment phase to treat the permeate flux to the WHO-safe water standard. **Strohwald (1992**) reported that RO systems

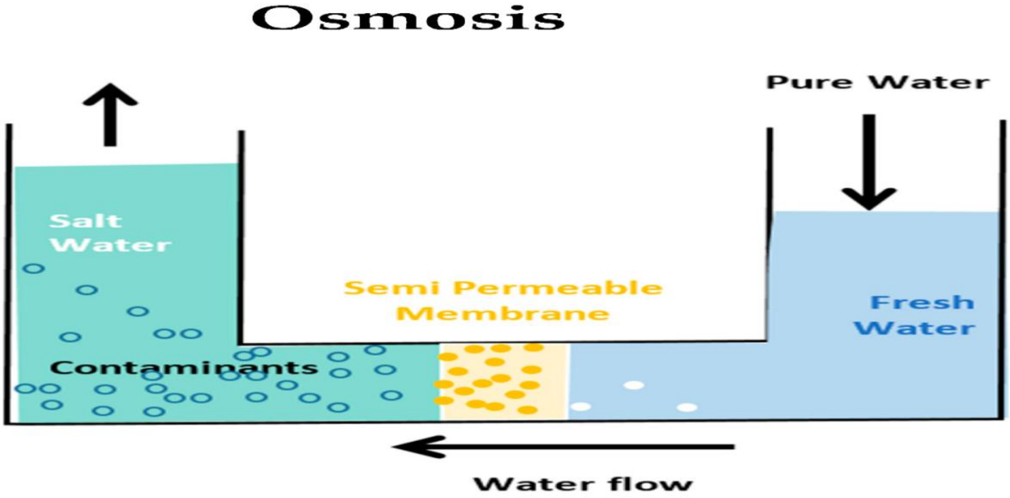

Fig. 6. Reverse osmosis (Olufisayo and Inambao, 2021; Ceribasi *et al*., 2018)

have been investigated and shown to be successful in desalinating seawater. Choosing an efficient pre-treatment system was stressed in one of the studies. Despite the low quality of the raw water source, the use of a low-cost tubular ultra-filtration system in conjunction with a double media and cartridge filtration resulted in extremely good RO residual water of exceptional quality. Even in situations where ultra-filtration membrane fouling is evident, sponge balls can aid in restoring flow. Using a scale inhibitor allows for reverse osmosis reclamations of 40% without damaging the membranes. The single-stage RO unit's residual water quality is often well within the approved SABS limits for home supply and free of RO membrane fouling.

Energy and Rate of Water Desalination

Conventional sources and renewable sources are the two primary types of energy sources used in desalination systems **(Karagiannis and Soldato, 2008)**. Renewable-powered desalination is the solution to sustainability, reducing energy usage and CO_2 emissions while also having a positive climate impact. Renewable-sourced energy can be in three forms for desalination systems. Wind, solar (photovoltaics or solar collectors), and geothermal energy are the three renewable energy sources. Renewable energy systems can also be adapted to a conventional energy source (e.g., local power grid) as a backup. The most commonly used membrane technique is RO. When it comes to effectively desalinating saline seawater, thermal methods appear to be more efficient than the membrane approach. However, critical research has revealed that thermal methods are costlier since an enormous quantity of fuel is needed to cause the saline water to evaporate. The use of membrane techniques, namely RO, has replaced thermal technologies in favor of a more cost-effective way to desalinate brackish water. However, membrane technologies are not commonly utilized for desalination due to the exorbitant price of replacing the membranes. **Nthunya *et al*. (2022)** have reaffirmed that advancements in technology have contributed to a reduction in the overall cost of desalination by optimizing energy efficiency (via hybrid systems or multi-flash distillation), enhancing energy recycling through cogeneration, and enhancing transfer procedures.

Seawater Reverse Osmosis

Large volumes of standard potable water can be produced using desalination system technologies at a cost that is competitively low, but the system's high energy consumption is still a significant drawback (**Pangarkar *et al*., 2011**). The most current advancements in membrane technology, such as Reverse Osmosis (RO), Nano-Filtration (NF), and Electro-Dialysis (ED), have garnered recognition recently due to their dependable capabilities for separation. Since RO membrane technology is appropriate for applications involving both seawater and brackish water, it has been largely regarded as the best option for desalination systems. Higher permeate flux, lower salt rejection and lower osmotic pressure are common characteristics of brackish water desalination (RO) membranes. This desalination process also requires lower operational pressures **(M'nif *et al*., 2007)**. However, this approach is usually identified to have inherent challenges as a result of polarization films and byproducts, which can lead to the growth of bacteria and pollutants. According to **Pangarkar *et al*. (2011)**, problems like this are addressed by employing alternative membrane technology like membrane distillation for desalination of subsurface water. Typically, RO membrane desalination methods are tailored to adopt either pressure or traditional electrical-driven technologies. There are four groups under which the pressure-driven membrane process can be classified: Reverse Osmosis (RO), Ultra-Filtration (UF), Micro-Filtration (MF), and Nano-Filtration (NF). Nano-filtration processes are recognized for their effectiveness in salt desalination. Four main sub-systems make up a typical RO system, according to **Poullikkas (2001)**: the membrane module, the high-pressure pump, the pre-treatment system, and the post-treatment system. When a high-pressure pump is activated, the pre-treated feed water is directed to pass through the surface of the membrane. For brackish water, the working pressure of RO ranges from 17 to 27 bars, while for seawater, it varies from 55 to 82 bars. According to **Strohwald (1992),** seawater desalination has been a commercial application for RO membranes ever since Loeb and Sourirajan developed asymmetric cellulose acetate membranes in the early 1960s. According to the paper, the majority of prominent membrane manufacturers, such as DuPont (USA), Filmtec (USA), and Toyobo (Japan), developed membranes using synthetic polymers designed especially for seawater desalination. In the middle of the 1970s, desalination plants began to appear all over the world as the RO method of producing water from seawater became increasingly popular. The author notes that because there is no phase shift involved, RO desalination has lower running costs than MSF evaporation. Due to economic factors, excessive energy usage and advancement in RO technology, the market share of MSF evaporation plummeted from 67% in the early 1980s to 3% in 1989, and in the same timeframe, RO increased from 23% to 85% (**Ghafoor *et al*., 2020**). The desalination of seawater and brackish water is receiving increased attention due to the rapid depletion of water resources (Raju and Ravinder, 2018). Nowadays, desalination requires a substantial amount of energy, which makes it less economical. According to **Tzen and Morris (2003**), the most popular and cost-effective way to desalinate brackish water is by using RO. Other approaches do exist; however, they are not that common. However, one instance may be found on the Greek island of Kimolos, where the MED process uses the island's plentiful geothermal energy to produce 80 m3/day of potable water at a rate of 2.00 h/m3. The total dissolved solids (TDS) in brackish water impacts the daily cost of potable water production, which ranges from 2000 ppm to 10,000 ppm.

Raju and Ravinder (2018) compared the expenses linked to brackish water desalination. The desalination plant for 230 ppm brackish water in Jordan costs a low 0.26 USD/m^3, whereas the plant for 5000 ppm brackish water in Florida costs a low 0.27 USD/m^3. Their study revealed that comparable systems employing varying total dissolved solids (TDS) levels generally exhibit notable cost variations. According to **Tzen and Morris (2003)**, desalinating 10,000 parts per million brackish water with conventional energy sources costs 0.43 USD/m^3, but in a similar scenario, employing renewable energy sources can cost as much as 10.32 USD/m^3. At the initial stage, the desalination cost using traditional energy sources like gas, oil, or electricity is initially cheaper than using renewable energy. However, renewable energy proves to be more cost-effective in the long run. The RO desalination process, as seen in Fig. 7, has gained popularity in recent years due to the decreasing cost of membranes. RO was mostly employed for brackish water desalination a few years ago but because of its reduced energy requirements, it has recently emerged as the most widely used technique for desalinating varied types of water. Consequently, larger facilities that can produce in excess of 320,000 m3 per day are now using RO technology.

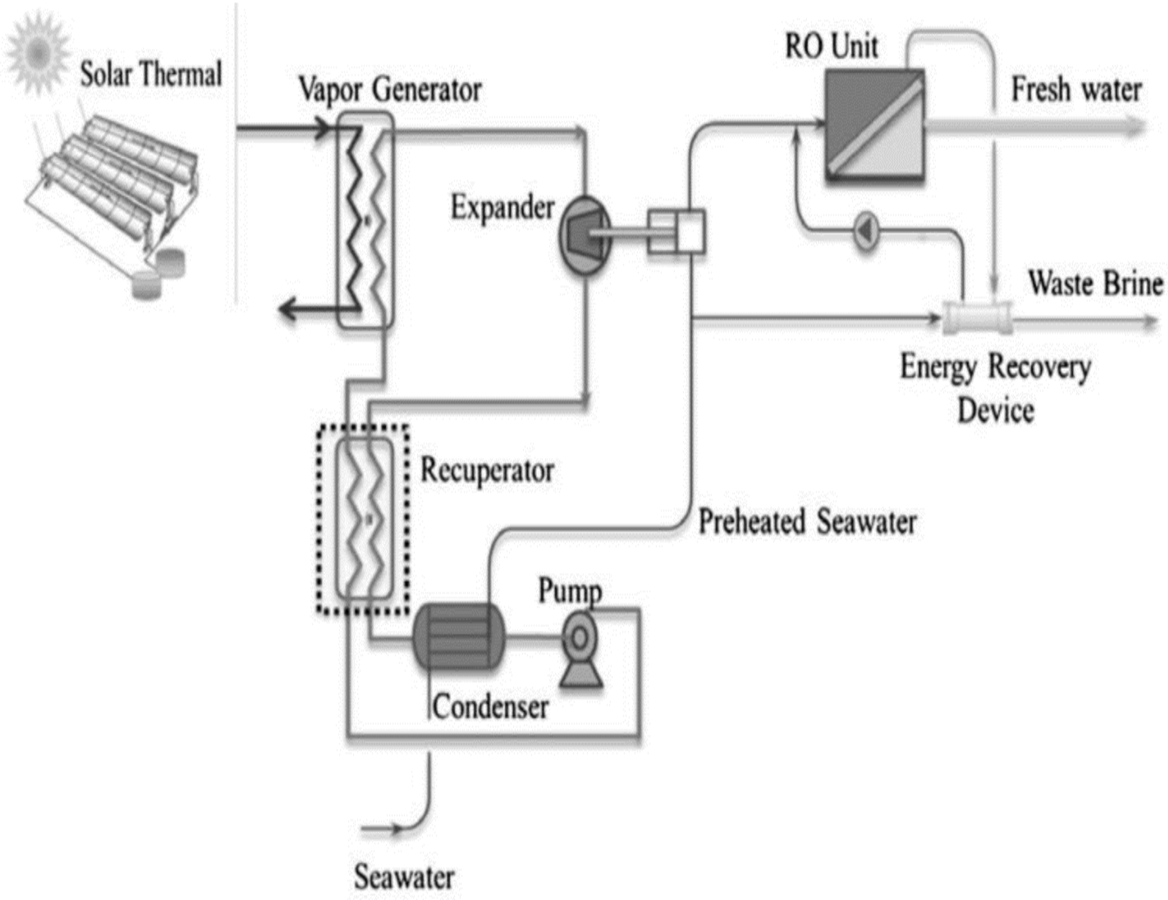

Fig. 7. Reverse Osmosis (Olufisayo and Inambao, 2021)

According to **Maalouf (2014**), high-salt rejection membranes are commonly used in RO plants. These membranes are designed to have a lifespan of about seven years with proper pretreatment. Factors such as target recovery, temperature, salinity, and cleaning methods can affect the membrane's efficiency for salt passage.

To convert seawater into potable water (as shown in Table 2, it is necessary to reduce TDS levels. This can be achieved through various desalination methods including traditional techniques or more advanced ones such as electro deionization (EDI), multi-effect distillation (MED), electrodialysis (ED), and multi-stage flash (MSF) distillation. In some instances, a hybrid configuration combining multiple desalination approaches can yield optimal outcomes while saving energy.

Properties of Saline and Product Water Produced with Brine

Physicochemical properties

The quality and volume of RO waste brine are influenced by the feed water quality, pre-treatment approach, desalination process, water recovery rate, and waste disposal method (**Panagopoulos *et al*., 2019**). **Omerspahic, *et al*. (2022**) reported in their study that during the feedwater pretreatment phase of membrane desalination, chemicals such as acids, biocides, antiscalants, antifoams, and corrosion inhibitors are commonly used, impacting the physicochemical composition of the resulting brine. Additionally, environmental factors like temperature, pH, and ionic strength can influence the concentration of pollutants in desalination brine. The quality of the brine is

Table 2. Potable water organoleptic properties (WHO, 2003)

Concentration (mg/L)	Classification
TDS ≤ 300	Excellent
300 ≤ TDS ≤ 600	Good
600 ≤ TDS ≤ 900	Fair
900 ≤ TDS ≤ 1200	Poor
TDS > 1200	Unacceptable

also affected by the membrane pore size used in the process. According to **Jones *et al.* (2019)**, the desalination plant's capacity and the water recovery rate, which is the proportion of freshwater generated relative to the total volume of feed water used, determine the quantity of brine produced. Better quality feed water leads to a greater recovery rate, as higher salinity levels in the feed water will result in more concentrated brine if the water recovery rate stays the same. As the water recovery rate increases, the amount of brine produced is reduced and is more concentrated. Even though RO is dependent on hydraulic pressure and does not alter the temperature of the seawater it processes, it requires a number of extremely intricate pre-treatment steps, such as the addition of coagulants and antiscalants, which have the potential to alter the pH of the water and produce brine with a salinity that is significantly higher than ambient water. According to the **WHO-Geneva (2007)** the allowable salt content in water is 500 ppm and 1000 ppm in special cases, but most water available on earth has a maximum salt content of 10,000 ppm. Seawater usually contains salts (about 35,000 ppm to 45,000 ppm of total dissolved salts). Extreme brackishness will lead to taste and stomach problems. Desalination systems are designed to solve these problems by purifying seawater or brackish water and providing clean water with allowable limits of 500 ppm or less (**Kalogirou, 2005)**. The density of freshwater is 1.00 (grams/mL or kg/L), which can be increased by adding salt. The saltier the water is, the higher its density. Water will expand and become less dense when it becomes hot. The colder the water, the higher the density. **Table 3** shows the salt ion content of different seawater sources.

Shomar and Hawari (**2017)** have highlighted the differences between natural and desalinated waters, noting that natural waters exhibit a wide range of physical, chemical, and biological characteristics influenced by climatic and biogeochemical factors, while desalinated water has a controlled chemical profile. The study also indicated that the quality and appearance of desalinated water depend on the chemicals and materials used in the desalination process. Although groundwater is sometimes mixed with desalinated water to reduce corrosion and stabilize quality, post-treatment procedures often result in inconsistent quality (**Cotruvo *et al.*, 2010**). Water with a Total Dissolved Solids (TDS) level of 25–50 mg/L is reported to be less thirst-quenching and may have undesirable flavors (tasteless, metallic) (**WHO, 2005**).

Table 3. Ion composition of Seawater (WHO, 2007)

Constituent	Normal Seawater	Eastern Mediterranean	Arabian Gulf at Kuwait	Red Sea at Jeddah
Chloride ($C1$−1C1−1)	18,890	21,200	23,000	22,219
Sodium (Na+1Na+1)	10,556	11,800	15,850	14,225
Sulfate (SO4−2SO4−2)	2649	2950	3200	3078
Magnesium (Mg+2Mg+2)	1262	1403	1765	742
Calcium (Ca+2Ca+2)	400	423	500	225
Potassium (K+1K+1)	380	463	460	210
Bicarbonate (HCO3−1HCO3−1)	140	-	142	146
Strontium (Sr+2Sr+2)	13	-	-	-
Bromide (Br−1)Br−1)	65	155	80	72
Boric Acid (H3BO3H3BO3)	26	72	-	-
Flouride (F−1)F−1)	1	-	-	-
Silicate (SiO3−2)SiO3−2)	1	-	1.5	-
Iodidie (I−1I−1)	<1	2	-	-
Other	1	-	-	-
Total dissolves solids	34,483	38,600	45,000	41,000

Source: Olufisayo and Olanrewaju (2024).

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التأثيرات البيئية لتقنيات تحليـــة مياه البحر في دول الخليج – دراســـة مرجعية

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لقد أدى الارتفاع السريع في النمو السكاني والتحضر والتصنيع اللاحق إلى زيادة الطلب العالمي على المياه. وبالتالي، نظرًا للتحديات المرتبطة بالوصول إلى المياه العذبة، يتم اعتماد تحلية المياه بشكل متزايد لتلبية الطلب العالمي على المياه. يتكون حوالي 61% من قدرة تحلية المياه في العالم من تحلية مياه البحر، في حين يتكون 30% من تحلية المياه المالحة. يتم احتساب نصف قدرة تحلية المياه في العالم من تحلية الأغشية، والتي تستخدم في الغالب تحلية التناضح العكسي. يتم استخدام النصف المتبقي في المقام الأول لتحلية المياه الحرارية، والتي تستخدم التقطير الفوري متعدد المراحل والتقطير متعدد التأثيرات. يفرض ندرة المياه تحديات كبيرة في المناطق القاحلة مثل دول مجلس التعاون الخليجي بسبب النمو السكاني المستمر، مع مراعاة آثار تغير المناخ وجوانب إدارة المياه. تبحث هذه البحث في العلاقات بين ندرة المياه وتحلية المياه كثيفة الطاقة وتطوير الطاقة المتجددة في دول مجلس التعاون الخليجي. يتناول هذا التقرير الابتكارات في مجال تحلية المياه بالطاقة الشمسية، مع الأخذ في الاعتبار كل من تقنيات الطاقة الشمسية الكهروضوئية والطاقة الشمسية الحرارية، جنبًا إلى جنب مع طرق تحلية المياه الحرارية التقليدية مثل التقطير متعدد التأثيرات والتبخير متعدد المراحل. وباستخدام القياسات الببليومترية، يقدم هذا التقرير تحليلاً شاملاً للأدبيات العلمية لتقييم المشهد البحثي من أجل التعرف على الاتجاهات في تقنيات تحلية المياه في منطقة دول مجلس التعاون الخليجي، مما يوفر رؤى قيمة حول التقنيات الناشئة وأولويات البحث. وعلى الرغم من التحديات مثل ارتفاع تكاليف الاستثمار الأولية والتعقيدات الفنية والتمويل المحدود للبحث والتطوير، فإن التقارب بين ندرة المياه والطاقة المتجددة يقدم فرصًا كبيرة لأنظمة تحلية المياه المتكاملة في دول مجلس التعاون الخليجي. وبإيجاز، تؤكد هذه الدراسة على أهمية النهج متعدد التخصصات والتعاون الدولي من خلال معالجة التحديات المعقدة المتمثلة في ندرة المياه واستدامة الطاقة في منطقة دول مجلس التعاون الخليجي.

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