Innovations

Desalination of Water: Current Status and Future Perspective

Dr. Chandan Adhikari*[a], Souhridya Bhattacharjee[c], Dr. Prabir Kumar Das[b]
Department of Basic Science and Humanities
Institute of Engineering & Management, Kolkata, India
University of Engineering & Management, Kolkata, India

Correspondence Author: **Chandan Adhikari**
orcid.org/0000-0001-6167-4197

Abstract: *As a key technology to solve the global water shortage, seawater and brackish water desalination has attracted more attention. This review will deeply investigate the current status of desalination technologies including advances, challenges and future prospects. The review introduces the traditional methods like Multi-stage Flash Distillation (MSF), Multi-effect distillation (MED) and Reverse Osmosis(RO), presenting their operational principles, efficiency as well as environmental effects. It then discusses new technologies such as forward osmosis (FO), membrane distillation (MD) and capacitive deionization (CDI), focusing on their ability to improve desalination sustainability through additional efficiencies. This adds a perspective to critically evaluate the economic features, energy costs and environment of these technologies should help understand whether they have potential as well as scalability for transportation. The paper also reviews state of the art materials and membrane technologies that have been engineered with a goal to enhance desalination benefits, mitigate fouling issues as well as save energy. Moreover, it talks about the impact of renewable energy sources such as solar and wind power in promoting sustainable desalination approaches. The future outlook towards desalination is the combined discharge of other water treatment technologies, progress in nanotechnology and the concept which centralized membrane distillation can be installed by remote arid zones. The review underscores the necessity of policy support, public-private partnerships and international co-operation to drive the desalination research and development forward. Until today a lot of progress has been achieved in desalination technology, however continuous research and innovation is needed to resolve the current bottleneck issues for supplying clean water at affordable access everywhere on Earth. This review is expected to be an important reference for the desalination researchers, policy makers and industry community that will help in better understanding of where we stand today with incorporation our views on future Desalination.*

Keywords: *Desalination, Seawater Treatment, Reverse Osmosis, Sustainable Technologies, Renewable Energy, Water Scarcity*

Introduction

Desalination: A Brief Overview

As of today, water scarcity has become an existential problem worldwide and is staring at the doors of more than 3 billion people. Freshwater has become increasingly scarce as the human population expands and industrialization grows. The rivers, lakes and groundwater had increased pressure on traditional sources of fresh water, to exceed the needs for drinking by populations in great areas because it does not enough since they also used irrigation of agriculture. The problem is magnified by climate change, which changes the patterns of rainfall on a global scale and means that droughts are likely to become more common, prolonged, and severe. Desalination, in that context, has come a long way for many regions now much needed freshwater help. Desalinationor the removal of salts from brackish water to produce potable water provides a dependable and sustainable solution. Although 3d-printing technology has been around for decades, major strides have also recently emerged more likely driven my efficiency and economic realities. Desalination technologies fall within two main categories - thermal processes and membrane processes. These technologies include Multi-Stage Flash (MSF) distillation, Multi-Effect Distillation (MED), and Vapor Compression Distillation(Med.) Membrane desalination: Reverse Osmosis (RO), Nanofiltration (NF) and Electrodialysis (ED).[1]
Desalination is also a lifeline for inhabitants of the huge arid and semi-arid regions, which are both waters scarce and perpetually thirsty. Regions like the Middle East, North Africa (Dari), some parts of Australia too have invested big way in desalination infrastructure to secure safe potable water for their populace. In addition, on an island where natural freshwater is rare and little-needed for other uses during each day, but large amounts of irrigation water are needed by some species, desalination can be of great help. Desalination also contributes to economic growth by providing water for industrial and agricultural use, both sectors that require abundant water supply on a continuous basis. Desalination additionally has numerous environmental benefits, referring to its function on water shortage. Desalination helps to alleviate any excess pressure on natural ecosystems and take away the threat of over-extraction, at least in some areas. But desalination is not without its own environmental challenges, specifically in the areas of energy usage and brine to be disposedoff, both those need have their careful management so they don't just fast track a way into another serious sustainability issues.[2, 3]

Objective and scope of this review

The purpose of this review is to outline the current state, as well as future trends in desalination technologies. Technology has progressed rapidly, and the importance of desalination is continually growing so surveying existing technologies in an application scenario context combined with a provision for future development appears both timely and essential. The review is holistic and encompasses several key facets, each of paramount importance to the role and impact desalination plays in alleviating global water scarcity. The review will first touch on the different desalination technologies that exist today. This provides a thorough discussion of both thermal and membrane separation processes, detailing the principles of their operation as well as discussing advantages & limitations.Emerging technologies including Forward Osmosis (FO), Membrane Distillation (MD) and Capacitive Deionization (CDI) will additionally be discussed to shed light on what hope of direction desalination research and development may hold. Second, the review will evaluate where desalination stands at present in global terms by analyzing global desalination capacity, distribution of plants and key players. It will also include a discussion of the economic and environmental aspects (including cost, energy consumption, etc.) as well as its potential impacts on the environment. The review will then address current progress in desalination technology as a third part. Other topics include membrane innovations, energy recovery systems and the coupling of desalination with renewable energy sources. At the same event, significant progress in pre- and post-treatment processes critical for enhancing desalination operations efficiency and sustainability will be outlined. This will be followed by an examination of the obstacles related to desalination. The technical issues greater than membrane fouling and brine disposal challenge, answer to which is not but advanced might be offered. A clear understanding of these challenges will help us to develop strategies to reduce the impact and ensure more sustainability in the application of desalination as our long-term option for addressing water scarcity.

The review is concluded with a future outlookof desalination. In addition, possible areas of research and development will be proposed, trends in the future development of desalination technologies and forecasting. The review will also examine policies and regulations that facilitate the implementation of desalination projects and their sensitivity to potential climate change scenarios affecting future uncertainties in desalination. The review is intended to be comprehensive and nuanced, encompassing the current scope of desalination as well as offering future perspectives. Through the lenses of Technology, Applications, Challenges and Future Directions in desalination this review aims to add value given ongoing dialogues on sustainable water management thereby envisaging a path how Desalination could emerge as an important solution for global Water scarcity.

Thermal Desalination Processes

Thermal desalination methods are some of the oldest and most solid aspects for accepting fresh water from sea water. They rely on heat to vaporize water, which is then distilled and separated from an aqueous solution of dissolved salts or other impurities. Thermal desalination processes are of three types: Multi-Stage Flash (MSF), Multi-Effect Distillation, and Vapor Compression Desalination. These approaches work in different ways from one another and have their own set of benefits and challenges.

Multi-Stage Flash (MSF)

Among the most common thermal distillation processes, for large scale desalination plants, is Multi-Stage Flash (MSF) technique. This process of MSF involves pressurizing the hot seawater then letting it flash evaporate in multiple stages. Water is boiling then evaporating very rapidly because of working at consecutively reducing pressure per stage. The water cause evaporates away in these chambers, and then cools to condensed into fresh water. The MSF process works by heating seawater in a brine heater to temperatures generally around 90-120°C, and this hot water is passed into the first stage of flash chamber where it enters under a pressure that lower than saturation pressure which creates vaporizing (flashing) steam. The steam condenses on tubes carrying the incoming feed seawater, pre-heating this and substantially enhancing total thermal efficiency. Each stage [typically 20 to 40 in number] further repeats this process at a lower pressure and temperature than the previous, the last one doing so with raw water. As for the main characteristics of MSF: One of its best things is that it has a high capacity to deal with huge volumes and this makes it feasible for large-scale desalination plants. At the same time, MSF plants generally operate for long periods and produce very high-quality water. But the MSF is an energy-hungry procedure, needing relatively large quantities of thermal power and frequently provided from fossil fuels. This results in high process costs as well as environmental issues such as the emissions of greenhouse gases. To alleviate these problems, a few MSF plants are combined with power plants in cogeneration schemes employing waste heat from electricity generation for desalination. This results in better energy savings and lowers the associated costs. Because of their high energy demand, many MSFs still use the same fundamental thermodynamic cycle developed earlier when distillation became central to seawater desalination plans yet they are heralded as a proven and practical technology for regions with abundant resources to produce it.[4, 5]

Multi- Effect Distillation (MED)

Multi-Effect Distillation (MED) is also a traditional thermal desalination process. MED works based on multi-stage, or "effect," evaporation and condensation of seawater. Again, each of these effects work at a lower temperature and pressure than the last allowing the process to more effectively make use of heat. The seawater is heated and sprayed on to a series of evaporator tubes in the first effect where it results in evaporation at lower pressure in MED process. The steam produced by this effect is then used to heat the incoming seawater in a second boiling tube, causing it to evaporate at lower temperatures and pressures. This is a continuous process run through multiple stages, typically 4-16 effects in all of which water will be introduced and steam being produced from every other stage. The final product is obtained after the last effect, and concentrated brine is rejected. Higher thermal efficiency is one of the key advantages of using MED instead of MSF. MED can save more energy due to the reusing of latent heat of vaporization across multiple effects. This lowers down the specific energy consumption, with MED being more economical and eco-friendlier. In comparison to RO systems, the MED plants also operate at lower temperatures and pressures minimizing scaling and corrosion risks which will translate in less maintenance with a longer life span. MED is also feed flexible and can be designed in a variety of capacities, from small-scale units to large desalination plants. It is fully compatible with renewable sources of electricity such as solar or geothermal, which only enhances its environmental friendliness. The downside is, MED plants use high grade materials and sort of precision engineering to get more efficient heat transfer with minimum losses that can add significantly up on the initial capital costs.[4, 6, 7]

Vapor Compression Distillation (VCD)

Vapor Compression Distillation (VCD) is a variety of thermal desalination processes using either mechanical or thermal compression to enhance the evaporation of water. Conclusion VCD is attractive for small and medium scale desalination applications, such as industrial water production or potable water in remote areas. The VCD process compresses the vapor from evaporation of seawater to heat and pressure it further. This compressed vapor is subsequently employed as a heat source to evaporate additional seawater. Two main types of VCDs are Mechanical Vapor Compression (MVC) and Thermal Vapor Compression (TVC). Mechanical compressor used for vapour compression in MVC. This set of processes begins by evaporating seawater. A mechanical compressor, which increases the temperature and pressure of the generated vapor is used to compress it. At the other end, high-temperature vapor is sent through a heat exchanger where it will condense and release latent heat (the stuff that evaporates more sea water). Fresh water is collected after the vapor has been condensed, and the brine gets discarded. A steam ejector compresses the vapor in a similar way, but there are no moving parts like mechanical compressor in TVC. This process involves a fraction of the vapour outflowing from an evaporator rest or merged point with high pressure steam supplied externally. This combined vapor is then utilized in heating the seawater and for evaporation. TVC systems often are used in conjunction with MED to increase overall desalination efficiency. The most important advantage of VCD is that it has a higher thermal efficiency than the other types of desalination plants. VCD reduces the external energy demand by a significant amount due to recycling of latent heat of vaporization. Turning to VCD, this means that they are especially well-suited for situations in which energy costs are extremely high (e.g., because the network is located near an expensive city), or where renewable electricity from wind and solar power plants can be drawn upon. Furthermore, VCD systems are small, easy to install (modular) and can be efficiently utilized on a decentralized or moveable base. But the VCD systems are complex and require sensitive control systems to regulate their process function, in relation to other energy conservation areas such as the compression and heat exchange steps. Capex is an issue for primary production VCD plant - particularly with mechanical compressor-based systems. Proper maintenance, and operation know how are critical to make sure the equipment gives optimum performance throughout its life.[8, 9]

Thermal desalination processes, including Multi-Stage Flash (MSF), Multi-Effect Distillation (MED) and Vapor Compression Distillation (VCD), thereby are significant for preventing the global water scarcity. All three of these processes offer distinct merits and challenges which will vary by application or scale. Energy wise, although MSF is energy-intensive but due to its capability of managing high volumes of seawater it makes an effective technology for large desalination plants. Its capacity ranges span and it obviously has higher thermal performance rates as well as lower opex which make MED a greener way of going to save environment than flash. With high-energy efficiency and modularity, the VCD2 is perfect for small to medium scale applications as well as decentralized water supply systems. Continuing development of these thermal desalination technologies- and making them more efficient, effective and sustainable - remains a focus at Savannah River National Laboratory. The following integration of these processes with renewable sources can substantially improve their recognition as long-term solutions toward global safe water governance. In the future, as more regions are no longer able to acquire sufficient water from agricultural and ground sources, it may also be economical in those areas of greater salt desalination.[10]

Membranes Desalination Processes

Membrane desalination processes have emerged as important alternatives consuming less energy compared to traditional thermal methods. They use semi-permeable membranes to separate salts and impurities from water. The three main membrane desalination technologies are Reverse Osmosis (RO), Nanofiltration (NF) and Electrodialysis (ED). All of this is based on different principles, and each has its costs and benefits.

Reverse Osmosis (RO)

The most common method of membrane desalination is Reverse Osmosis (RO), which makes up a large fraction of the world-wide installed capacity. RO: The principle of RO is pressurizing seawater or brackish water to pass this through one side a semi-permeable membrane which allows the passage only to water molecules and reject salts as well other impurities. The first step in the RO process is pre-treatment: incoming feedwater is filtered in order to remove particulates, organic matter and other contaminants that may foul or damage both reverse osmosis membranes. Addition of chemical anti-scalants may be employed to inhibit scaling. Most seawater RO systems operate at 55 to 1200 psi depending on the type of feed pump system used. Thispermeation is forced through the RO membrane which pass water molecule only and reject all salts etc.The Salt Rejection Rate of RO is likely 99%, with the performance capable for high quality drinking water. RO systems are modular and scalable to suit any application, from small household units up to large municipal plants. In addition, RO still has much lower energy demands than thermal desalination processes and therefore is more economically competitive. Yet RO has its challenges. They are prone to biofouling, scaling and other particulate fouling which may decrease efficiency and increase operational costs. It requires regular cleaning and membrane changes to keep working properly. Energy consumption is smaller compared to thermal processes, but seawater desalination takes a lot of energy for high pressures. RO Technology & Efficiency The efficiency of RO systems, including post- and pre-treatment processes is constantly being improved with advancements in the membrane materials as well energy recovery devices (ERDs) helping to make them more cost-effective.[11-13]

Nanofiltration (NF)

Nanofiltration (NF) is a membrane desalination process that has larger pores and operates at lower pressures as compared to RO. The sizes of pores in NF membranes range from 1 to10nm, at this size ions which have charges higher than one like divalent cations completely removed and other monovalent anions can pass through everywhere. This selectivity permeability enables NF to be used in desalting or softening applications. NF is frequently used for water softening technology, because it can get rid of hardness causing ions in the feedwater (calcium and magnesium), whilst keeping useful minerals such as sodium or potassium. It is also highly proficient in decolorization and removal of natural organic matter (NOM), as well as micropollutants, making it commonly used for drinking water treatment and industrial purification. In the pre-treatment steps, similar to RO, a variety of techniques are used such as filtration and chemical dosing (i.e. anti-fouling reagents). The feedwater is then pressurized, typically at lower pressures compared to RO, between 4 to 30 bar (60-450 psi), and flows through the NF membrane. Meanwhile the feed streams are divided inpermeate which contains lower levels of divalent ions and organic components and concentrate rich with rejected impurities. The advantages of NF include reduced energy consumption and operational costs, as it operates at lower pressures. Likewise, it generates a reasonable amount of minerals in the water as well that may be good for specific uses. Compared to RO membranes, NF membranes are more resistant to fouling and thus require less maintenance. NF, however, does not entirely desalinate water to the level that RO would require it as it has a few select salts passage through. The NF membranes may vary in selectivity as well and need to be selected and tuned carefully for each individual application. Advances in membrane materials and configurations due to research and development (R&D) are increasing NF efficiency, making this technology available for new applications.[14, 15]

Electrodialysis (ED)

Electrodialysis (ED) is an electric potential-driven migration of ions through selective ion-exchange membranes, removing them from the water. It works great for brackish water desalination and industrial wastewater treatment as well. It contains a stack of cation and anion exchange membranes separated from each other by two electrodes. Cations migrate to the cathode across cation-exchange membranes, and anions move to the anode through anion-exchange membranes when electric potential is applied between electrodes. Such a movement of ions generates two counter flows (brine-like concentrate and desalinated water) inside the stack. ED is normally used for brackish water desalination, which efficiently decreases salinity to potable levels. It is also used in water recycling and for the recovery of valuable salts from industrial processes. ED can run at lower pressures and hence energy levels compared to traditional RO, making it cost-effective for some applications. One of ED's greatest strengths is its capacity to remove ions selectively and as such it has found use in applications which require removal or concentration of certain ions. This modularity scaffolds to ED systems as well and can conveniently be conjugated with demand. ED can also process a higher salinity of feedwater than NF, making it suitable for various water sources. But ED is constrained by the requirement for electrical energy to power ion migration and raise operating costs. ED membranes are also subject to fouling and scaling, so periodic maintenance activities such as cleaning is necessary. In turn, improvements in ion-exchange membrane materials and stack designs have increased the efficiency of ED systems while decreasing costs.[16, 17]

Membrane desalination processes, including Reverse Osmosis (RO), Nanofiltration (NF) and Electrodialysis (ED), have been an attractive option to address global water scarcity due to high efficiency and relatively low cost to produce fresh water from saline sources. Given the specific strengths and limitations of each, they are all more suitable for one application or scale than another. Due to the high salt rejection and capability of producing good quality potable water RO is one of the most common desalination processes using a membrane. NF requires much less energy than RO and hence is useful for water softening & spot partial desalination applications. ED is particularly effective in brackish water desalination and industrial wastewater treatment where selective removal of ions is desired. Borderline landscapes between different types of water-channel core VACNF membranes, which may amplify or minimize interactions with red blood cells (RBCs). Evolution: many improvements by optimized systems and operations to improve performance or decrease costs exist for both desalinating membrane underscore technologies. By combining such fabrication processes with renewable energy sources and sustainable operational conditions, these technologies could be implemented as permanent solutions for global water-related problems. Given ongoing water scarcity and the growing demand for fresh water, membrane desalination is a key part of global plans to provide future generations with reliable access to safe potable water. Ongoing research and development to improve RO, NF and ED each separately according to their unique strengths can help continue making desalination an important part of the equation in addressing the looming water crisis.[18, 19]

Recent Advances in Desalination Technology

With the global demand for fresh water on the rise, researchers and engineers are pursuing new desalination techniques that render higher efficiency, lower energy consumption, and less environmental side effects. Within these up-and-coming technologies, Forward Osmosis (FO), Membrane Distillation (MD) and Capacitive Deionization (CDI) illustrate particularly high potential. All of these are based on different principles and have their own pros/cons.

Forward Osmosis (FO)

Introduced in the early 21st century, forward osmosis (FO) is a developing desalination process that uses a natural solute concentration difference between two solutions to draw water across a semi-permeable membrane. Whereas Reverse Osmosis (RO) draws on high hydraulic pressure, FO works under much lower pressures by comparison and could thereby reduce energy demand and operational costs. In the Forward Osmosis (FO) process, sea or brackish water (the feed solution) is at a certain side of semipermeable membrane while concentrated draw solution - on another side. The greater osmotic pressure in the draw solution leads to waterflow from the feed side of a membrane module via an acquired membranes into this compartment. This process is able to remove water from dissolved salts and other impurities. Afterwards, the diluted draw solution can be processed to split out the clean water from these ions (draw solutes) which are then circulated back into system. Advantages of FO include reduced energy consumption without high-pressure pumps and lower fouling/scaling membranes bottle. Lower operating pressures lead to less wear and tear on membranes, resulting in lower maintenance costs. Furthermore, FO can process high-salinity and fouling feed solutions well making it versatile for use with different types of water sources such as saline waters or concentrated polluted streams. But FOs are stymied by the limited mechanisms for preparation and recovery of successful draw solutions. This means the drawn solution should have high osmotic pressure differentials and easily be separated from drawn water. Current efforts lie in the discovery of appropriate freak solutions and efficient recapture methods to render FO a practical, mega-scale desalination technology. Nevertheless, FO seems a promising way to perform energy-saving desalination when linked with renewable energies or in coordination with other new desalting processes.[20-22]

Membrane Distillation (MD)

Membrane distillation (MD) is not beyond them which simply a thermally driven desalination process involving separation of water vapor from saline water using hydrophobic membrane. This would provide potential energy savings and operational simplicity compared to conventional thermal desalination methods that work at higher temperatures and pressures. Heated seawater is fed on to one side of a hydrophobic membrane in the MD process. Water vapor moves through a vapor pressure gradient created by the difference in temperature of the feed solution and cooler permeate side but salts, scaling ions, trajectory minerals or contaminants with high boiling points will not. The water vapor is condensed on the permeating side to create fresh drinking water. MD has these configurations: Direct contact membrane distillation (DCMD) Air-gap membrane distillation (AGMD) Vacuum driven membrane distillation (VD-MD), Sweeping gas-driven vacuum-aided drinking water production, etc. Each of these configurations has its own benefits and places they are used. DCMD meanwhile combines simplicity and high-water flux, AGMD/VMD together offer higher energy efficiency and reduced heat loss. In fluid dynamics, a system with MD offers many of the benefits including high salt rejection and low operating temperatures, all while being able to use waste heat from industrial processes or even renewable energy sources. Finally, the stuff described above make MDs suitable for applications in remote areas or special industries with existing waste heat. As a bonus, MD systems suffer less from fouling and scaling compared to alternate membrane processes allowing for far fewer maintenance requirements of the membranes. Yet, there are many energy efficiency and scalability challenges for MD. It operates by feedingthrough a continuous heat source and can consume excessive amounts of energy unless tied to waste heat or renewable energy sources. Current research is intense about improving the membrane materials, heat, and mass transfer or at using hybrid systems that conjugate MD with other desalination technologies to save energy consumption as well as reducing cost. Nevertheless, it has a good potential for sustainable desalination with MD especially in specific cases and hybrid systems.[23-26]

Capacitive Deionization (CDI)

Capacitive Deionization (CDI) is a new electrochemical desalination technology based on applying an electrical potential across two electrodes serving as electrically active surfaces, which results in the electromigration and electrosorption of ions from saline water. The low voltage operation of CDI and its benefits in terms of energy efficiency are particularly interesting for brackish water desalination or applications needing partial purification. In the process called CDI, saline water flows between two porous carbon electrodes. Cations and anions are attracted to the oppositely charged electrodes, respectively, as a voltage is applied across the electrodes. It takes all the ions out of this water that makes it salty and makes desalinated water. The electrodes are saturated by the ions, and then we reverse (or just annul) that voltage to let out those specialized for this waste stream. In addition to the ability of CDI to remove ions selectively, it is also highly energy-efficient compared with traditional technologies, especially in cases involving Low-salinity feedwater. The latter is not necessary as the process (which works at ambient pressure and temperature) simplifies operations. Decentralized Context: CDI systems Flexible and scalable Item 1 for the treatment of water in-situ together with renewable energies Challenges associated with electrode materials and fouling, however, remain for CDI. CDI performance relies upon the properties of both electrode materials including surface area, conductivity, and ion adsorption capability. Research is concerned with the production of novel electrode materials like carbon aerogels, graphene and nanocomposites to improve a low-energy and long-lasting performance for CDI systems. Fouling and scaling of electrodes may also adversely affect performance, thus effective pre-treatment and maintenance strategies are necessary. Albeit cumbersome, CDI reflects a promising horizon in sustainable desalination especially where selective ion removal even partial desalination is highly desirable. The technology is ideal for brackish water, industrial wastewater & remote off-grid application where energy efficiency and simplicity are critical.[27-30]

Forward Osmosis (FO), Membrane Distillation (MD) and Capacitive Deionization Extraction of freshwater from seawater contains many novel desalination technologies such as FO, MD and CDI. These technologies each have their strengths and weaknesses which make them ideal depending on the use case or scale of operation. Osmotic pressure is harnessed to drive water through membranes, with the force maintained over time, leading potentially to lower energy requirements and reduced fouling. Nevertheless, the problem of drawing yet effective solutions through development and then finding a roadmap to recovery is still one of challenges ahead. Our MD system is energy efficient because it operates at relatively low temperatures and pressures, we can use waste heat or renewable energy will work well with MDBR systems but requires continuous heating (such as solar) long life membrane materials are still needed for this type of technology. While using electrochemical principles to strip ions from water, CDI units promise low energy use and modularity but struggle with electrode materials and fouling. Membrane technology (type of membrane materials and module design), process configuration, system arrangement, and operation practices are changing to improve performance for lower costs. 4-6 Where the implementation of these practices is incorporated with renewable energy sources and improve its viable in future water disparities on a global scale. These new desalination technologies are poised to become an increasingly critical component of ensuring a safe and sustainable water supply as the demand for fresh water continues to soar. Through the advantages FO, MD and CDI bring to different dimensions of desalination as well as continued research and development that tackle challenges faced by each technology, we will be able to improve how much better water provision for those in need can get.[31, 32]

Current Status of Desalination

Desalination is an important part of the global strategy to reduce water scarcity and meet future increased demand for fresh, rechargeable water in regions with low natural renewable freshwater resources. Considering all the above, desalination today is in a good place with very high advancement levels and growing global capacities along with numerous industry frontrunners and mega plants. Nevertheless, economic and environmental considerations, including cost analysis, energy consumption and foot printing etc., continue to dominate the discussion when it comes to discussions on desalination sustainability/feasibility.[33, 34]

Global Desalination Capacity and Distribution

In response to growing needs for fresh water, there has been a rapid growth in the global desalination capacity. Worldwide, as of 2023 the total global desalination capacity surpassed over million cubic meters per day (m^3/day), for more than people worldwide. The capacity is distributed amongst about 18,000 desalination plants in more than 150 nations. Indeed, the Middle East and North Africa (MENA) region is home to over half of global desalination capacity as well. Saudi Arabia, the United Arab Emirates, and Kuwait rely heavily on desalination to convert seawater into drinking water. Large plants like the one in Ras AL Khair and Jubail, make up a substantive portion of this capacity – just Saudi Arabia by itself provides over 9 million m^3/day. Besides the MENA region, other key desalination markets include the United States and Spain as well as Australia. The USA has a desalination capacity of around 4 million m^3/day, located almost entirely in California, Florida and Texas Its 3 million m^3/d desalination capacity makes Spain the largest European market, primarily supported by requirements of water for their arid coast areas and in Canary Islands. Desalination is another Australian success story, and the country has already spent countless millions of dollars in answering to persistent water shortages especially In cities like Perth arid Melbourne.[35, 36]

Major Desalination Plants and Key Players

There are a few large multinational corporations and some smaller specialized desalination companies that play a dominant role in the global market of PDOs. The other is in the development of advanced desalination technologies with its goal to design, construct, and operate some sea water plants. Veolia Water Technologies, Suez Water Technologies & Solutions and Acciona Agua are one of the key companies in the desalination industry. Veolia has constructed several large-scale desalination plants globally, including Australia's Sydney Desalination Plant and the Al Dur plant in Bahrain. Desalination pioneer Suez operates major plants such as the Ashkelon plant in Israel and the Perth Seawater Desalination Plant in Australia. This is a company that has worked on major projects, including the Al Jubail 3A desalination plant in Saudi Arabia and the Cartagena health care facility in Spain. Examples of the biggest and most advanced desalination plants in the world include Ras Al-Khair plant, Saudi Arabia; Sorek Plant, Israel; Carlsbad Desalination Plant, California. The Ras Al-Khair plant comprises multi-stage flash (MSF) distillation and reverse osmosis (RO), making it the world's largest hybrid desalination facility at >1,000? Sorek's production capacity is about 624,000 m^3/day and it holds the title for one of the world largest RO desalination plants operating with innovative energy recovery systems. The Carlsbad plant, the largest desalination plant in the Western Hemisphere and producing about 190,000 m^3/day of potable water for San Diego County.[37-39]

Economic and environmental considerations

In the past, desalination has been too expensive to be economically viable on any large scale, but it is much less of a concern now with newer technology and larger plants. RO is still likely to be the most cost competitive and widely used due to their lower energy demand as compared with thermal processes. Energy recovery devices, membrane technology and system design have made inroads into lowering the cost of desalination to where desalinated water has been priced competitively with traditional sources off bulk water throughout many regions. As such the initial capital investment remains high, in addition to substantial operational costs including energy consumption and membrane maintenance, respectively. The combination of desalination with renewable energy sources such as solar and wind power is becoming an attractive opportunity to lower price differences and make the process more sustainable. The environmental concerns related to desalination are in large part connected with the energy used and brine disposed. Energy-intensive desalination processes and mostly thermal methods in operation emit greenhouse gases inducing climate change. Thus, this is an area of concern requiring actions targeting increased energy efficiency and renewable resources. Another, profoundly genuine issue is brine disposal: a highly saline byproduct that can be harmful to the marine environment in case of improper discharge. These include measures like the dilution of brine, novel methods for discharge as well recovering valuable minerals from brine to mitigate environmental impacts. Desalination is one important technology for water shortage, so keeping the economy and sustainability in desalination-process can be crucial to maintain its practical/plausible position. To do so more sustainably and to address the challenges of desalination, it is important to investigate these issues further and broaden our understanding with ongoing research-to-innovation processes.[40-42]

Cost Analysis

The cost of desalinated water can vary depending on the technology, size of plant and location, as well as local energy costs. The cost of desalination is typically around \$0.50 to \$3.00 per cubic meter (m^3). Reverse Osmosis (RO): The aqueduct desalination technology with the lowest unit cost, typically between \$0.50 to \$1.50 per m^3 This type of process such as multi-stage flash (MSF) distillation and the cheaper version are thermal desalination methods and costs about $1.50 to $3.00 per m³ The cost of desalination depends on several factors, including: 1) capital expenditure (CAPEX) - all the costs to construct an infrastructure such as a plant, or pipes/lines; 2) operational expenditure (OPEX), which includes energy and maintenance needs for technologies that need these. Whereas OPX includes energy, which can make up to half of the total cost. In recent times, RO desalination costs have been brought down by advances in technology such as better membrane materials and energy recovery devices. External financial support by governments and international organizations is key to the viability of desalination projects. In a number of regions, these can provide significant support through subsidies and concessions on financing conditions at the consumer level which enable desalinated water sale prices to be brought closer in line with conventional sources. Private companies also are investing in desalination infrastructure through public-private partnerships (PPPs), where financial risks and responsibilities are shared between the private sector and a government.[43-45]

Energy Consumption

The energy inputs in desalination are necessary consideration, as this is one of the biggest contributors to its economic and environmental impacts. Conventional thermal desalination techniques like MSF and MED, you need a ton of heat to evaporate the water. While RO desalination is less energy-intensive, than MSF and MED processes, it still requires a considerable amount of electricity in order to produce the high pressures necessary for forcing water through membranes RO desalination has seen a reduction in the energy consumption over many years due to better technology. In comparison, a few decades ago RO plants consumed roughly 6–8 kilowatt-hours (kWh) per cubic meter of desalinated water. These reductions have been thanks in part to energy recovery devices-wheelie pots and isobaric turbines that capture and reuse pressure-induced kinetic retrogression from high-pressure brine streams. Renewable energy sources combined with desalination processes are an exciting area of research and development. High-tech methods to harness solar, wind and geothermal energy could cut the carbon footprint of desalination considerably and make it more sustainable. For example, solar-powered desalination has gained significant attraction in areas with high-quality solar resources like the Middle East and North Africa. Nonetheless, the sporadic availability of these abundant types and high upfront costs still present intrinsic issues for grid-scale deployment.[46-48]

Environmental Impact

In desalination, it is esp. problematic because of energy intensity and the negative effects associated with brine discharge & waste generation on marine systems The energy-intensive process of desalination, which is mostly powered by fossil fuels, releases a considerable amount of carbon dioxide into the atmosphere and adds to global warming. These impacts can be reduced by saving energy, adding renewable sources of power and pollutant emission control measures such as carbon capture and storage (CCS), among other things. Another significant environmental consideration that accompanies desalination is the issue of brine disposal. The highly concentrated brine from the desalination process can be released again in the sea and may damage marine life. These can have a significant impact on marine life, as well - especially in more sensitive or enclosed ecosystems. Some effective strategies were proposed to reduce the environmental impact of brine disposal, such as dilution with seawater prior discharge, diffuser system for enhancing mixing and dispersion as well development of environment-friendly alternatives like managing or utilizing produced brines. For instance, brine can be treated to obtain minerals which are valuable like magnesium and lithium, or it is also used in aquaculture and as fertilizer. The desalination industry is researching ways to make plants both more energy efficient and sustainable. Examples of green desalination are Green chemicals, energy-efficient technology and full environmental monitoring with management.[49, 50]

We are experiencing a boom in desalination, a process that implies the transforming of saline water into clean and drinkable fresh water used to shrink regions afflicted by short less potable recourse all around but not least on the planet. This technology has made a lot of advancements and top tier players along with some large-scale desalination plants achieved fresh water in various dry areas where they have gained significant market share. Despite that, the economic and environmental issues surrounding desalination - including cost considerations, energy consumption or environmental impacts - are crucial in deciding on its long-term sustainability viability. Advances in technology have reduced the cost of desalination, especially RO - but it is still an expensive option and requires a significant amount of energy. Decreasing energy consumption anywhere and increasing renewable energy integration is crucial in lowering the environmental footprint of desalination. The environmental footprint, especially from GHG emissions and the discharge of brines must be mitigated to minimize adverse impacts on marine ecosystems and reduce carbon burden resulting from desalination plants. Fresh water is only becoming there as demand for it continues to skyrocket, so weighing the good against bad a price of desalination has never been more paramount. More research and development, support from policies and innovative methods are crucial in making desalination technologies more sustainable and efficient. Overcoming these challenges and harnessing the benefits of desalination could be essential to meeting global water demands in a secure, sustainable way for decades to come.[8, 51]

Advancements in Desalination Technologies

The global need to find solutions for dealing with water scarcity has propelled desalination technologies forward that have come a long way over the last few years. These include improvements in membrane technology, the development of energy recovery and efficiency strategies, implementation with renewable energy sources to reduce operating costs or reliance on fossil fuels for power supplies (+ e.g., advances in pretreatment + post-treatment processes). The following section takes a closer look at these areas within context of recent advancements and what it means for desalination.

Innovations in Membrane Technology

Modern desalination processes are based on membrane technology including Reverse Osmosis (RO), Nanofiltration (NF) and Forward Osmosis (FO). These processes have benefited significantly from recent developments in membrane materials and design, which has made them more efficient, sustainable, and cost-competitive.

Improved membrane materials such as thin-film composites and innovative polymer blends, that possess increased permeability and selectivity. These membranes can provide higher water fluxes and salt rejection rates, lowering energy requirements and operational expenditures. Graphene oxide membranes and carbon nanotubes have shown potential as they offer a high strength of the membrane material with higher permeability. Membrane fouling, of which calcium carbonate scaling is an example), reduces the desalination efficiency while increasing maintenance costs. Membrane longevity and performance have been improved dramatically by the advancement of anti-fouling/anti-scaling coatings, exemplified by hydrophilic/superhydrophobic surfaces. This coating will prevent the contamination from sticking and forming a biofilm, allowing high water throughput to be continued longer before cleaning is required. One example of a novel membrane application is biomimetic, inspired by the mechanism used in biological systems to transport water across membranes. By incorporating natural proteins - such as aquaporins and other functional motifs from native organisms - manufacturers can improve both water permeability performance while maintaining high levels selectivity for different contaminates. By operating at the kinetic and thermodynamic limits of nature, these membranes present a potentially transformative solution to what is today one of our greatest challenges in providing clean water.[52-55]

Progress in the manufacturing of uniform ultrafine membranes has been made through developments in techniques such as electrospinning and 3D printing. By tailoring the properties of membranes to meet specific desalination applications, this research combines membrane synthesis techniques in order to improve overall desalting efficiency. But the design is not key for energy recovery and efficiency improvements. For desalination, there is still a large cost factor in the form of energy consumption. The new desalination processes have also been designed to reduce the energy intensity of these technologies at a time when many regions are facing water scarcity.[56]

Energy Recovery Devices (ERDs)

Pressure exchangers and turbochargers are examples of the advancement in ERDs that have significantly improved how efficient a RO desalination system can be. The new devices snatch energy from the high-pressure brine stream, effectively cutting in half the amount of energy that would otherwise need to be consumed for this process. With modern ERDs recovering 98% of the energy from the brine, this will result in significant cost savings and reduced environmental impact. Research in low-energy membrane processes such as Forward Osmosis (FO) and Pressure Retarded Osmosis (PRO), tend to be promising tools for reducing the energy demand. The FO process uses a natural osmotic pressure gradient to pull water through the membrane and PRO generates energy by the difference in pressure between fresh and saline water. These are processes that allow more energy-efficient alternatives to the RO desalinations we describe elsewhere. Hybrid water desalination systems that combine two or more membrane processes such as RO and FO can better utilize energy depending on input conditions. For instance, if we integrate FO with RO, this will result in a reduced energy requirement for pre-treatment and have the potential to also improve feedwater quality resulting in lower operational costs (CIP etc.) and extend membrane life. Recent advancements in thermal desalination processes like Multi-Effect Distillation (MED) and Vapor Compression Distillation (VCD) have targeted with the aim of improving heat transfer efficiency to lower energy consumption Such innovations in heat exchanger design, waste heat recovery and low temperature distillation techniques serve to make these processes much more competitive with membrane-based desalination.[57-60]

Renewable Integration

The combination of desalination methodologies with renewable energies is the most beneficial way forward for sustainable and cost-effective water production. In a number of recent developments in this regard, it has been planned to use solar,wind and geothermal energy for desalination processes. Solar power is among one of the most appealing renewable energies for desalination, especially in sunny countries with high sea readily available. Numerous technologies of solar desalination systems include direct solar thermal distillation and photovoltaic (PV) powered RO. Technological developments in solar collectors, thermal storage and photovoltaic performance have increased the technical feasibility of commercially scaling up solar desalination. Disposal of brine from desalinationplants can be a problem, especially in arid regions. Wind-Powered Desalinationmay provide the necessary carbon-free renewable water production0. There have been a number of wind-powered RO systems that work well in different coastal areas and make use of constant winds, which means these devices can get enough power to function. Further developments in tools like wind turbines and energy storage can make wind-powered desalination even more cost competitive. Geothermal power is the energy available from Earth creation heat just below of their surface offer a reliable and constant supply as no doubt she be fit drinking water synagogue. The heat exchangers allow the geothermal energy to supply power for desalination through thermal methods or generate electricity directly powering membrane-based systems. Source: Across geothermal-rich regions we have recently seen big scale proof-of-concept geothermal desalination projects By using various renewable energy resources including solar, wind or geothermal etc. can increase the efficiency and reliability of desalination plants as well. It helps stabilize renewable sources so that more energy is made available - reducing the need for fossil fuels. Energy storage technologies like large batteries and thermal storages are indispensable for efficient integration of renewable energy with desalination.[61, 62]

Pre- and Post-Treatment Process Enhancements

Efficient pretreatment and post-treatment processes form the foundation to achieve high levels of both desalination process conditions as well sustainable long-term operation. Recent developments in these areas have been aimed at bettering water quality and reducing biofouling or scaling as well increasing the overall sustainability of desalination operations. As mentioned above, the preparation is crucial before going to desalination; it will protect the membrane of scaling and fouling. Such innovations in pre-treatment include the use of advanced filtration methods, such as ultrafiltration (UF) and microfiltration (MF), to remove suspended solids and biomacromolecules. Chemical pre-treatment processes, including the use of anti-scalants and biocides, have also been developed to further improve performance while minimizing environmental impact. So, the use of electrochemical processes in application such as electro-oxidation, and electrodialysis are applied at laboratory scale for treating industrial waste streams. Through the applications of electrical current, these processes destabilize and remove colloidal particles (including organic matter) as well as reduce bacteria found in source waters to allow downstream desalination unit operation at much higher efficiency. The desalinated water needs to be retained for a acceptable residual time which is usually done by post-treatment processes before reaching the end users in networks as it has an important role in improving drinking quality requirements. Post-treatment improvements consist of advanced oxidation processes (AOPs) and activated carbon filtration to eliminate non-revenue producing contaminants including disinfection by-products and trace organic compounds. Water quality and taste are being improved by optimizing the application of remineralization techniques that add essential minerals to desalinated water.[46, 63]

Brine Management and Resource Recovery

Treating the leftover concentrated brine byproduct of desalination presents a large environmental problem. Zero-liquid discharge (ZLD) systems, and resource recovery technologies are more recent innovations in brine management. ZLD systems work to rid liquid waste by reclaiming water and boron from the brine, while resource recovery technologies aim for salt, metals (together with lithium) together other beneficial molecules. This can help minimize the environmental impact of brine disposal, as well as offering new revenue opportunities for desalination plants. Improvements have been made in the ability to produce clean water from sea water and this has led to more efficient, cost-effective, and sustainable production of pure water when starting with salty sources. Advances in membrane technology - such as high-performance filter materials and anti-fouling coatings, have also greatly improved desalinationmembranes. Metadata. Smaller scale developments, such as energy recovery devices and hybrid systems have decreased the overall amount of energy used in desalination processes and its integration with renewable sources like solar or wind has made it a more sustainable option. Advances in pre-treatment and post treatment systems have also led to an increase in water quality, a lower occurrence of fouling, scaling along with general savings on the overall footprint. While the pre-treatment technologies are to promote desalination membrane protection while increasing efficiency, effective post treatment methods need to safeguard produced water quality compliance besides brine waste management and resource recovery. These improvements in desalination technologies will be essential for global water security as the world continues to suffer from acute and chronic problems of freshwater resources. Further study and development will be required to address remaining obstacles for effective desalination on a more significant scale over time. Using these technological advancements in the desalination industry can greatly help to alleviate some of the tensions on water use and availability, thus contributing to sustainable development.[64-67]

Challenges in Desalination

Scarcity of water is one of thecritical issue globally and the use of desalination was expected to increase on a large scale in order to get potable quality water with more reliability from sea & brackish water.These span technical, economic, environmental, and social sectors meant individually for innovative solutions in each area while strategically to be aligned. This part is a closer look at these barriers.

Energy demand is of paramount importance in desalination and one of the biggest challenges. Current desalination techniques, including multi-stage flash distillation (MSF), and multiple-effect distillation (MED) are very energy expensive. Even so, it still requires considerable energy to pressurize the seawater through membranes. This consumes more energy running operational costs and increases the carbon footprint (a major problem, especially in how we are all trying to do what we can against climate change). These strategies focus on energy recovery devices and the reduction in conventional energy use replaced by some or all renewable sources of power. *** The good news is that the energy consumption of RO plants has decreased due to their use of energy recovery devices, whichincludes pressure exchangers. Still, there is also much work to be done with even more creative technology and material solutions that can cut systemic energy consumption on top of this.[68, 69]

However, desalination processes can cause large environmental footprints. Most prominently, this includes the return of brine (a salty byproduct that results from desalination) back into the sea. Disposal of brine can also be detrimental to marine ecosystems as it raises salinity levels in the vicinity, while chemical use during desalination (cleaning agents and anti-scalants) results in toxic manufacture discharges into surrounding seaways. It allows marine lives to be affected, even die from the disruptions it causes. Additionally, desalination plants require a great deal of chemical additives to dispel fouling and scaling the membrane which too may result in negative environmental consequences. The increased necessity for green chemicals and brine-management alternatives include not only better concentration technologies but economic methods of dealing with brines like minimization, valorization, or zero-liquid discharge (ZLD) systems.[70, 71]

Desalination is not economical, with copious amounts of capital and operational requirements being two major hurdles to its wider adoption (especially in the developing world) These costs are affected by many things including the technology such as sedimentary processes, energy prices and the size of the plant etc. Small and decentralized systems are suited to dry, remote areas although these can be expensive options due to the significant costs of solar cells compared with running similarly sized plants from scaleable fossil fuel or nuclear power. For proper economic sustainability, advances in membrane technology itself and energy efficiency as well as the production of more low-cost materials are needed. Furthermore, in this process of making desalination a more accessible and affordable solution, innovative financing models as well as public-private partnerships also have an important role to play.[72]

Membrane fouling and scaling are major problems of Reverse osmosis (RO) and other membrane-based desalination technology. Fouling results from the deposition of organic and inorganic materials on top of the membrane surface, hindering its efficiency with not only an increase in operational costs but also a decrease or even cessation in filtration capabilities leading to downtime. Similarly, scaling, where mineral salts precipitate out of solution are a major headache. Fouling and scaling may also need membranes to be cleaned more frequently or replaced, which in turn adds operational costs but additionally often has an environmental cost with the use of cleaning chemicals. The solution needs to include improved anti-scaling and -fouling coatings, more advanced pretreatment processes as well as an increased resilience of the membrane materials themselves.[73, 74]

It is worth mentioning that the conventional desalination technologies, like MSF, MED and RO have reached a relative maturity level compared to new processes such as Forward Osmosis (FO), Membrane Distillation (MD) and Capacitive De-ionization (CDI). These emerging technologies offer a much more energy efficient and cleaner alternative to chemical methods yetis plagued by scale-up operation challenges. For example, forward osmosis encounters problems with respect to the draw solution including poor compatibility in regenerating (and controlling reverse solute flux) of the draw solute. Temperature polarization and

membrane wetting are two major bottlenecks of MD which can lower its efficiency due to decreased driving force and reduced lifetime. Capacitive deionization is a promising approach for brackish water desalination, however it does not work well in seawater due to its low capacity of ion removal.[75]
It takes a lot of infrastructure investment to build and maintain desalination plants. This includes the entire physical facility, including not just the plant but its pipelines, intakes, and outfalls (on water), as well as energy supply systems. That makes the logistics of bringing desal water to where it is needed complex and, in many cases -- such as with large parts of California's existing ailing plumbing system or developing geographically challenging areas like an Indian-peninsular island chain --- also quite expensive. In addition, desalination plants need to be carefully engineered for tolerating extreme marine environments and natural calamities like tsunamis or hurricanes which further make infrastructure development more complex and costly. Facing such infrastructure and logistical challenges requires the development of advanced materials, robust engineering practices, as well strategic planning.[76]
There is a wide variation in public opinion and social acceptability of desalination. Growing concerns about the environmental implications, high costs, and even water privatization could make these an impossible to sell to local communities/stakeholders. The role of communication transparency and community involvement are essential in creating public confidence and acceptance. Policy & regulatory frameworks also influence the uptake and performance of desalination (+ other type) projects. Legal uncertainty, wrong incentives or red tape can be reasons why desalination techniques do not develop. There is a need for legislators to create transparent, enabling and dynamic legislation that fosters innovation but solidifies environmental protection and social equity.[77]
For desalinated water to be suitable for human consumption, extremely strict quality controls are implemented. Moreover, it can eliminate most impurities; however, the problem of its application remains for trace contaminants such as bromide and boron ions or relevant organic molecules. If left unmitigated, these contaminants can be hazardous to human health. High-quality water must be constantly monitored and treated at an elevated level, which sometimes can hike prices or render the process more complex. Further and continuing research on novel detection methods and improved treatment technologies is absolutely necessary to protect the health of our communities.[78-80]

Desalination Success Stories Worldwide

Desalination is a key component to help address the global water scarcity challenge, delivering fresh water by removing salts and impurities through process of seawater & brackish water. The worldwide success of some desalination projects has demonstrated its ability to provide water security for arid regions, expanding cities and areas affected by climate change. This portion details a selection of high-profile desalination projects worldwide, including their respective technologies and scales of impact.[81]

1. Jubail, Distillation of Sea Water Plant at Saudi Arabia

The Jubail Desalination Plant is one of the largest desal facilities on earth. This plant is operated by the Saline Water Conversion Corporation (SWCC) and employs multi-stage flash distillation (MSF) as well reverse osmosis technology. Operated by a subsidiary of King Abdullah Economic City (KAEC) the Jubail plant has capacity over 1.4 million cubic meters per day, serving both the Eastern Province as well as Riyadh and producing potable water for public use. The project is vital in meeting the water needs of Saudi Arabia's industrial and domestic users by securing a dependable supply, even as it will feed one of the driest regions on earth.[82]

2. Carlsbad Desalination Plant (USA)

The United States has just one: the Carlsbad Desalination Plant near San Diego. The plant produces about 50 million gallons of fresh water a day, using reverse osmosis to extract the salt from brackish groundwater and turning it into drinking water. It provides enough for more than 300,000 residents in San Diego County - or some one-tenth of Agua Hedionda Municipal Water District's customers' needs. The plant, which has been operational since 2015 showed that large-scale desalination was possible in the USA especially during severe drought periods. Carlsbad is also a benchmark for sustainable desalination projects because of its energy recovery systems and how visible Carlsbad has been in demonstrating care towards the environment.[83]

3. Location: Israel (Ashkelon Desalination Plant)

Israel is even breaking new ground when it comes to desalination, and the Ashkelon Desalination Plant remains a beacon of light in Israel's water management expectations. Inaugurated in 2005, the facility produces about 330000 cubic meters of processed water per day using reverse osmosis. The plant, opened in 2013, is part of Israel's world-leading desalination infrastructure which supplies more than 80% of the nation's domestic water use. Successful of Ashkelon city is due to advanced membrane technologies, high energy efficiency and major brine disposal strategies those make us an example for other nations.

4. Israel Sorek Desalination Plant

In Israel, the Sorek Desalination Plant (initial operations from 2013) is another major project of this type. Sorek, one of the biggest reverse osmosis plants in the world, slakes about 624 thousand cubic meters per day. INNOVATIVE SYSTEM DESIGN The plant features the market's largest-diameter membranes, improving efficiency and reducing costs Sorek enhancement to the national water system development of Israel, which supplies significant amounts high-quality drinking water while establishing new operational benchmarks for large-scale seawater desalination.[84-86]

5. Fujairah Desalination Plant, UAE The water paid for by the government is actually from this Fujarah desal plant.

Fujairah Desalination Plant in the United Arab Emirates is a hybrid plant using multi-stage flash distillation and reverse osmosis technologies.It will be considered one of the largest hybrid desalination plants globally with a production capacity of ca. 600,000 cubic meters per day. The UAE wishes to limit its over-reliance on external water by increasing the role of desalination, and Fujairah is pivotal for not only slaking the north's thirst but also providing energy. The dual technology plant maximizes production rate with the least amount of energy consumption in bringing a greater understanding to sustainable water management.[87-89]

6. Seawater Desalination Plant in Perth, Western Australia

A few of these were resolved by Australia's initially huge scope seawater desalination plant, the Perth Seawater Desalination Plant in 2006. The plant, which is located in Kwinana, Western Australia and use reverse osmosis technology to generate some 144,000 cubic meters of fresh water per day. This helped to stem shortages blamed on the continual droughts and in the lower two-thirds of the country, declining rains. Wind farms drive the plant, with a strong emphasis in Australia toward incorporating renewable strategies into desalination.[90, 91]

7. Desalinizacion de aguas (Barcelona, Spain)

The largest desalination plant in Europe is the Barcelona Desalination Plant, which has a capacity of 200,000 cubic meters per day and began operating on May 2nd., 2009. Employing reverse osmosis technology, the plant supplies Barcelona and its metropolitan area with drinking water an essential buffer when there is less rain to refill up reservoirs during drought. The plant is one of Spain's attempts to maintain reliable water supplies through desalination, combined with the overhaul or current irrigation practices making them more efficient in relation to overall consumption.[92]

8. Shuaiba Desalination Plant, Kuwait.

The Shuaiba Desalination Plant is one of the oldest and largest desalt plants in Kuwait. The plant, which was built using multi-stage flash distillation technology, can produce 800,000 cubic meters of potable water per day. Desalinated water, necessary to meet the country's needs 100%, is mostly produced by Shuaiba. The operation history of the plant is an evident of how efficient and stable thermal desalination technologies can be in providing large water supplies.[93, 94]

9. Al-Jubail Water and Power Co, Saudi Arabia

A large desalination plant using multi-effect distillation (MED) and reverse osmosis I operation by the Al-Jubail Water And Power Company (JWAP), Saudi Arabia. JWAP has a daily capacity of around 800,000 cubic meters and is used for water as well as power production for Jubail industrial city and the surrounding area. Combining the two water treatment technologies MED and RO with each other is an arduous way to increase system efficiency accompanied by process sustainability, proving a multitude of side effects about a typical desalination method.[95]

10. Victoria Desalination Project, Australia

Another of Australia's most important desalination plants, the Wonthaggi-based Victoria Desalination Project. The facility came online in 2012 and utilizes reverse osmosis to generate as much as 450,000 cubic meters of fresh water per day. The dam was constructed to address the dire drought circumstances as well as a reduction in water reserves within the area. The facility features environmentally conscious designs for using renewable energy, as well as measures to prevent harm to marine life caused by seawater uptake and disposition of the brine concentrate.[96]

The technology of desalination has been developed at an astonishing rate over the last few decades and our innovative solutions for water scarcity can take care of most parts of the world. However, the future of desalination depends on improving current challenges and making it more sustainable and cost-effective. The present section of the paper elaborates on several futuristic paths in desalination technology, with prime emphasis to some innovative as well as developed methods that could transform this arena. The biggest issue the desalination world faces is that it uses a lot of energy. Further innovative steps will be aimed towards more energy efficiency and renewable energizing. Energy reuse devices will increase in numbers as energy consumption falls, which e.g. include pressure exchangers and energy recovery turbines (as explained here). In addition, adding solar and wind energy to the desalination solution drastically decreases the carbon footprint associated with brine. Hence, to maintain a stable as well sustainable energy supply for desalination processes these should be protected with hybrid systems combining renewable solutions and conventional power sources. Thermal methods still dominate but membrane-based desalination processes, especially Reverse Osmosis (RO) have gained ground because of their lower energy consumption as compared to thermal alternatives. Future research will be devoted to the design and synthesis of novel membrane materials with superior permeability, selectivity and resistance against fouling. This field of study, including graphene oxide membranes, carbon nanotubes and other nanomaterials have been shown to provide significant steps toward better desalination efficiency. If developed, these materials could significantly lower operational costs and prolong the life of membranes to help make desalination economically feasible.[97]

Brine Disposal To mitigate this, future technologies have started to develop higher brine treatment efficiency while principal conservation strategies. Of late, zero liquid discharge (ZLD) systems are considered an alternative for brine reuse by recovering useful salts and minerals from it. And those schemes turn waste into resources - generating both economic value and a lower environmental footprint. Novel concepts, etc., forward osmosis (FO) and membrane distillation (MD), are being investigated to increase concentrate brine go through resource recovery. Different desalination technologies can be combined for maximum efficiency and cost-effectiveness. Producing fresh from seawater: Hybrid processes are advantageous because of the complementary strengths/weaknesses offered by RO, FO, and MD. For example, the coupling of RO with FO can help lower energy consumption and improve water recovery rates. Hybrid systems can also be customized for particular feedwater qualities and operating conditions, offering versatile and cost-effective desalination alternatives.[98] Introduction of Artificial Intelligence (AI) and Machine Learning (ML) techniques in the process to control desalination operations, ensures efficient performance at minimum costs. With AI and ML algorithms, more significant amounts of operational data can be analyzed to predict fouling in the membrane, optimize energy consumption or improve maintenance scheduling. Desalination plants could become more efficient and reliable if these technologies can be used for real-time monitoring, adaptive control. And more AI allows predictive maintenance, reducing downtime and wear of desalination equipment. Future trends to address these water scarcity issues are decentralized modular desalination units which allow flexible and scalable solutions. These smaller, modular units can be moved to remote or off-grid locations where they provide a local water supply. These decentralized systems could take the pressure off from huge-scale infrastructure and lead way to more robust water supply network. Future developments in portable or containerized desalination units are expected to have a significant impact on disaster relief and small communities that need water, as well as industrial application. Creation of new desalination processes that are energy friendly operates at lower temperature and pressure. Membrane Distillation (MD) and Capacitive Deionization (CDI): MD and CDI operate under much milder conditions with respect to the conventional approach. In the case of MD, a temperature gradient is used to push water vapor through a hydrophobic membrane and it can run at lower energy input requirements than RO. Likewise, CDI utilizes an electric field to extract ions from water and performs well as a lower energy replacement for brackish desalination.[99-101]

Pre-treatment of feedwater is crucial for maintaining desalination membrane integrity and performance. This area will see further developments with respect to the development of better, i.e., more durable and cheaper pre-treatment methods. Advanced oxidation processes (AOPs), biofiltration and ultrafiltration are methods employed to enhance feedwater quality by eliminating organic and inorganic pollutants. Advanced pre-treatment can minimize the fouling of membranes, decrease maintenance costs and extend the operating life-time desalination installations. Abstract The search for new materials to be applied in water desalination leads the research into an important field of investigation. Aquaporins, which replicate natural water channels, are one material that is being investigated for their potential to increase both the flux and selectivity of RO membranes. Moreover, anti-fouling coatings and high-performance filtration materials can also enhance the durability of desalination plants. One of the predicted possibilities is that researchers will find new material breakthroughs which could mean desalination becomes an economic and energy efficient reality. For future desalination technologies it is crucial to consider the interdependence between water and energy resources. Thus, it is pivotal to come up with innovations that cater the nexus of these two in order for desalination practices to remain sustainable. On an overall level, the sustainability of desalination can be improved by using integrated approaches that combine water and energy optimization opportunities. For instance, energy efficiency is enhanced in thermal desalination if waste heat from the industrial processes or power plants are used. Further, coupling desalination with energy storage could improve water supply reliability and stability.[102-104]

Conclusion

Today, desalination is a technology that plays an indispensable role in the ever-increasing global water stress landscape. Today, desalination is a secure water source in the face of mounting population growth, climate change and industrialization that continues to threaten global freshwater supplies. The present review has highlighted that the advancement of desalination technology, its drawback, and needs: more future developments are appealing for improving this field. At present, reverse osmosis (RO) and multi-stage flash distillation (MSF)-both established technology categories-dominate the sector thanks to their demonstrated efficacy at scale. As a result of these technologies, it is not only able to benefit from the water resources but also assist many countries with low freshwater potential (Saudi Arabia, Israel and United Arab Emirates) in getting their hands around hundreds 1. Still, the heavy energy consumption and its environmental consequences linked to desalination are tough problems. The primary emphasis for future desalination development is energy efficiency. The use of innovative energy recovery devices and the integration of renewable energies in desalination plants is expected to decrease their energy footprint.[105, 106] For example, pressure exchangers in RO systems and adoption of solar and wind power can reduce operation costs drastically as well has have a positive impact on the environment. In conjunction with new membrane innovations, i.e. graphene oxide membranes and carbon nanotubes are expected to enhance efficiency (permeability/selectivity/fouling resistance) of desalination technology at an advanced level - making us reach 100% in effluent disposal mechanism by the end of this decade. Emerging technologies also tackle vital brine management. The development of Zero liquid discharge (ZLD) systems and resource recovery strategies for the conversion of brine waste into valuable resources are on the rise, to minimize environmental degradation. They have processes such as Forward Osmosis (FO) and Membrane distillation(MD) etc. do concentrate brine for enabling salts / minerals separation. However, hybrid desalination systems that integrate a variety of treatment technologiesprovide an opportunity to maximize efficiency and cost benefits. Hybrid systems can obtain higher water recovery and lower specific energy when making the best use of the advantages associated with different methods such as RO, FO. The systems are flexible to varying feedwater qualities and operating conditions, allowing customization based on a variety of desalination requirements. Water treatment operations are poised to be transformed by the introduction of artificial intelligence (AI) and machine learning -powered desalination. Thanks to AI and ML, your operational data can be analyzed even more accurately when it comes to predicting membrane fouling or the optimal use of energy -so you have time instead for optimizing maintenance measures. This monitoring and control in real-time can increase reliability and improve the utilization rates of desalination plants, thereby minimizing system downtime as well as operating costs. Decentralized and modular desalination units are an important step forward in offering flexible, scalable solutions for water scarcity. Housed in a 20-ft container, the units can be used for remote or off-grid applications providing water on-site and reducing dependence of lengthy infrastructural acculturation. Compact and transportable desalination plants are invaluable for disaster relief as well, in addition to supplying water to low population areas and industry. Other alternatives to conventional desalination such as membrane distillation (MD) and capacitive deionization (CDI), for low temperature, pressure-driven, processes are also emerging. Such technologies work at a temperate zone that will necessarily lessen energy usage in comparison with conventional processes. Advanced pollution control techniques such as advanced oxidation process (AOP), biofiltration and ultrafiltration can be used for enhanced pre-treatment of raw water, leading to improved feed-water quality which minimizes fouling on the membrane resulting in lower operational cost. Further progress in desalination technology will come from innovative materials such as aquaporins, and anti-fouling coatings. With such flexibility, these materials can help improve water permeability and selectivity as well as system durability that led to energy efficient desalination. Consequently, it is of immense importance to regard the water-energy nexus in desalination for sustainability. This paper presents an overview of the state-of-the-art integrated desalination processes that maximize efficient use and recovery of both water and energy resources to improve sustainability. For instance, integrating desalination with waste heat from industrial processes or power plants and energy storage systems would fall under this description of an integrated approach. Although desalination technology has advanced, continued research and innovation are needed to address existing problems so as to make it more sustainable. Framing around energy efficiency, advanced materials and AI incorporation as well sustainable approaches could justify desalination for securing water supplies globally across generations. The future directions proposed in this review show promise for developing more efficient, sustainable, and affordable desalination technologies to deliver a robust water supply with ever rising challenges on the global scale.

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aAssistant Professor, Department of Basic Science and Humanities, Institute of Engineering & Management-Salt Lake Campus, University of Engineering & Management, Kolkata, India
bAssociate Professor, Department of Basic Science and Humanities, Institute of Engineering & Management-Salt Lake Campus, University of Engineering & Management, Kolkata,India
cResearch Assistant, IIFR Lab, Department of Basic Science and Humanities, Institute of Engineering & Management-Salt Lake Campus, University of Engineering & Management, Kolkata, India

References:

- *Elimelech M., Phillip W. A. -The Future of Seawater Desalination: Energy, Technology, and the Environment. Science, 333 (2011) 712-717.*
- *Zolghadr-Asli B., McIntyre N., Djordjevic S., Farmani R., Pagliero L., Martínez-Alvarez V., Maestre-Valero J. F. -A review of limitations and potentials of desalination as a sustainable source of water. Environmental Science and Pollution Research, 30 (2023) 118161-118174.*
- *Al-Addous M., Bdour M., Rabaiah S., Boubakri A., Schweimanns N., Barbana N., Wellmann J. -Innovations in Solar-Powered Desalination: A Comprehensive Review of Sustainable Solutions for Water Scarcity in the Middle East and North Africa (MENA) Region. Water, 16 (2024) 1877.*
- *Toth A. J. -Modelling and optimisation of multi-stage flash distillation and reverse osmosis for desalination of saline process wastewater sources. Membranes, 10 (2020) 265.*
- *Chandwankar R. R., Nowak J.- Thermal Processes for Seawater Desalination: Multi-effect Distillation, Thermal Vapor Compression, Mechanical Vapor Compression, and Multistage Flash; Springer (2024) 465-502.*

- *Prajapati M., Shah M., Soni B. -A comprehensive review of the geothermal integrated multi-effect distillation (MED) desalination and its advancements. Groundwater for Sustainable Development, 19 (2022) 100808.*
- *Annamalai M., Kannappan T. -Experimental studies on solar multi-effect sea water desalination system. Solar Energy, 259 (2023) 246-256.*
- *Almasoudi S. M., Bassam J. -Desalination technologies and their environmental impacts: A review. Sustainable Chemistry One World,(2024) 100002.*
- *Muthuvairavan G., Natarajan S. K.- Large-scale solar desalination system; CRC Press (2023) 169-199.*
- *Rahimi-Ahar Z., Hatamipour M. -Exergy analysis of thermal desalination processes: a review. Clean Technologies and Environmental Policy, 26 (2024) 1335-1362.*
- *Harby K., Emad M., Benghanem M., Abolibda T. Z., Almohammadi K., Aljabri A., Alsaiari A., Elgendi M. -Reverse osmosis hybridization with other desalination techniques: An overview and opportunities. Desalination,(2024) 117600.*
- *Zubair M. M., Saleem H., Zaidi S. J. -Recent progress in reverse osmosis modeling: An overview. Desalination, 564 (2023) 116705.*
- *Kucera J. -Reverse osmosis. John Wiley & Sons,(2023)*
- *Wen H., Liu Z., Xu J., Chen J. P. -Nanofiltration membrane for enhancement in lithium recovery from salt-lake brine: A review. Desalination,(2024) 117967.*
- *Zhang L., Hu M., He B., Pei H., Li X., Matsuyama H. -A review of the nanofiltration membrane for magnesium and lithium separation from salt-lake brine. Separation and Purification Technology, 354 (2025) 129169.*
- *Sim G., Pishnamazi M., Seo D., Kong S. R., Lee J., Park Y., Chae S. R. -Recent advances in electrodialysis technologies for recovering critical minerals from unconventional sources. Chemical Engineering Journal,(2024) 154640.*
- *Kabir M. M., Sabur G. M., Akter M. M., Nam S. Y., Im K. S., Tijing L., Shon H. K. -Electrodialysis desalination, resource and energy recovery from water industries for a circular economy. Desalination, 569 (2024) 117041.*
- *Patel S. K., Lee B., Westerhoff P., Elimelech M. -The potential of electrodialysis as a cost-effective alternative to reverse osmosis for brackish water desalination. Water Research, 250 (2024) 121009.*
- *Meng J., Shi X., Wang S., Hu Z., Koseoglu-Imer D. Y., Lens P. N., Zhan X. -Application of electrodialysis technology in nutrient recovery from wastewater: A review. Journal of Water Process Engineering, 65 (2024) 105855.*
- *Ibraheem B. M., Aani S. A., Alsarayreh A. A., Alsalhy Q. F., Salih I. K. -Forward osmosis membrane: review of fabrication, modification, challenges and potential. Membranes, 13 (2023) 379.*

- *Abounahia N., Ibrar I., Kazwini T., Altaee A., Samal A. K., Zaidi S. J., Hawari A. H. -Desalination by the forward osmosis: advancement and challenges. Science of The Total Environment, 886 (2023) 163901.*
- *Chang Z. H., Sum J. Y., Lau W. J., Ang W. L., Teow Y. H., Ooi B. S., Yeap S. P. -Current State-of-the-Art of Non-Reverse Osmosis-like Forward Osmosis Technology. Journal of Membrane Science,(2024) 123209.*
- *Lawal D. U., Antar M. A., Ismaila K. G., Khalifa A., Alawad S. M. -Hybrid multi-stage flash (MSF) and membrane distillation (MD) desalination system for energy saving and brine minimization. Desalination, 548 (2023) 116231.*
- *Gontarek-Castro E., Castro-Muñoz R. -How to make membrane distillation greener: a review of environmentally friendly and sustainable aspects. Green Chemistry,(2024)*
- *Chen Y., Yang S., Wang Z., Elimelech M. -Transforming membrane distillation to a membraneless fabric distillation for desalination. Nature Water, 2 (2024) 52-61.*
- *Liu H., Jacob K. I., Wang Y. -Scaling in membrane distillation (MD): Current state of art insight on mechanisms and Membrane design. Desalination,(2024) 117539.*
- *Yu F., Yang Y., Zhang X., Ma J. -Application of capacitive deionization in drinking water purification. Separation and Purification Technology,(2024) 129285.*
- *Wang H., Liu Y., Li Y., Xu X., Liu X., Yao Y., Lu T., Pan L. -Tactics for boosting the desalination stability of capacitive deionization. Chemical Engineering Journal,(2024) 153808.*
- *Ma J., Zhou R., Yu F. -Hotspots and future trends of capacitive deionization technology: a bibliometric review. Desalination,(2023) 117107.*
- *Tauk M., Folaranmi G., Cretin M., Bechelany M., Sistat P., Zhang C., Zaviska F. -Recent advances in capacitive deionization: A comprehensive review on electrode materials. Journal of Environmental Chemical Engineering,(2023) 111368.*
- *Saleem M. W., Ali S., Usman M., Chaudhary T. N., Ullah A., Arslan M., Hameed A. U. -Integration of capacitive deionization and forward osmosis for high water recovery and ultrapure water production: concept, modelling and performance analysis. Environmental Technology,(2024) 1-22.*
- *Ali A., Quist-Jensen C. A., Jørgensen M. K., Siekierka A., Christensen M. L., Bryjak M., Hélix-Nielsen C., Drioli E. -A review of membrane crystallization, forward osmosis and membrane capacitive deionization for liquid mining. Resources, Conservation and Recycling, 168 (2021) 105273.*
- *Ahmed F. E., Khalil A., Hilal N. -Emerging desalination technologies: Current status, challenges and future trends. Desalination, 517 (2021) 115183.*
- *Abushawish A., Bouaziz I., Almanassra I. W., AL-Rajabi M. M., Jaber L., Khalil A. K., Takriff M. S., Laoui T., Shanableh A., Atieh M. A. -Desalination*

pretreatment technologies: current status and future developments. Water, 15 (2023) 1572.

- *Mahmoudi A., Bostani M., Rashidi S., Valipour M. S. -Challenges and opportunities of desalination with renewable energy resources in Middle East countries. Renewable and Sustainable Energy Reviews, 184 (2023) 113543.*
- *Belmehdi F., Otmani S., Taha-Janan M. -Global trends of solar desalination research: a bibliometric analysis during 2010–2021 and focus on Morocco. Desalination, 555 (2023) 116490.*
- *Liu T.-K., Ye J.-A., Sheu H.-Y. -Exploring the social acceptability for the desalination plant project: Perceptions from the stakeholders. Desalination, 532 (2022) 115757.*
- *Williams J. -Desalination in the 21st century: a critical review of trends and debates. Water Alternatives, 15 (2022) 193-217.*
- *Scotney T., Pinder S.- The business of desalination; River Publishers (2022) 597-643.*
- *Goosen M., Mahmoudi H., Alyousef Y., Ghaffour N. -Solar desalination: A review of recent developments in environmental, regulatory and economic issues. Solar Compass, 5 (2023) 100034.*
- *Cai Y., Wu J., Shi S. Q., Li J., Kim K.-H. -Advances in desalination technology and its environmental and economic assessment. Journal of Cleaner Production, 397 (2023) 136498.*
- *Elsaid K., Kamil M., Sayed E. T., Abdelkareem M. A., Wilberforce T., Olabi A. -Environmental impact of desalination technologies: A review. Science of the total environment, 748 (2020) 141528.*
- *Shokri A., Fard M. S. -Techno-economic assessment of water desalination: Future outlooks and challenges. Process Safety and Environmental Protection, 169 (2023) 564-578.*
- *Youssef P., Al-Dadah R., Mahmoud S. -Comparative analysis of desalination technologies. Energy Procedia, 61 (2014) 2604-2607.*
- *Ziolkowska J. R. -Is desalination affordable?—regional cost and price analysis. Water Resources Management, 29 (2015) 1385-1397.*
- *Alawad S. M., Mansour R. B., Al-Sulaiman F. A., Rehman S. -Renewable energy systems for water desalination applications: A comprehensive review. Energy Conversion and Management, 286 (2023) 117035.*
- *Soliman M. N., Guen F. Z., Ahmed S. A., Saleem H., Khalil M. J., Zaidi S. J. -Energy consumption and environmental impact assessment of desalination plants and brine disposal strategies. Process Safety and Environmental Protection, 147 (2021) 589-608.*
- *Ghalavand Y., Hatamipour M. S., Rahimi A. -A review on energy consumption of desalination processes. Desalination and Water Treatment, 54 (2015) 1526-1541.*

- *Sirota R., Winters G., Levy O., Marques J., Paytan A., Silverman J., Sisma-Ventura G., Rahav E., Antler G., Bar-Zeev E. -Impacts of Desalination Brine Discharge on Benthic Ecosystems. Environmental Science & Technology, 58 (2024) 5631-5645.*
- *Nielsen K., Schlenk D., Esbaugh A., Mondon J. -Potential environmental impacts of coastal desalination intake structures: Urgent data gaps and policy needs. Environmental Science & Technology Letters, 11 (2024) 384-393.*
- *Shokri A., Sanavi Fard M. -A comprehensive overview of environmental footprints of water desalination and alleviation strategies. International Journal of Environmental Science and Technology, 20 (2023) 2347-2374.*
- *Ali I., Hasan S. Z., Garcia H., Danquah M. K., Imanova G. -Recent advances in graphene-based nano-membranes for desalination. Chemical Engineering Journal,(2024) 149108.*
- *Nwokediegwu Z. Q. S., Obaigbena A., Majemite M. T., Daraojimba O. H., Oliha J. S., Dada M. A. -Review of innovative approaches in water infrastructure: Sustainable desalination and public-private partnerships. International Journal of Science and Research Archive, 11 (2024) 324-332.*
- *Wijewardane S., Ghaffour N. -Inventions, innovations, and new technologies: Solar Desalination. Solar Compass, 5 (2023) 100037.*
- *Birniwa A. H., Habibu S., Abdullahi S. S. a., Mohammad R. E. A., Hussaini A., Magaji H., Al-dhawi B. N. S., Noor A., Jagaba A. H. -Membrane technologies for heavy metals removal from water and wastewater: A mini review. Case Studies in Chemical and Environmental Engineering,(2023) 100538.*
- *Castro-Muñoz R. -A critical review on electrospun membranes containing 2D materials for seawater desalination. Desalination, 555 (2023) 116528.*
- *Okampo E. J., Nwulu N., Bokoro P. N. -Economic and Reliability Assessment of Hybrid PRO-RO Desalination Systems Using Brine for Salinity Gradient Energy Production. Sustainability, 14 (2022) 3328.*
- *Ahmed A., Alghamdi A., Ahmed S. -Techno-economic analysis of a pressure retarded osmosis (PRO) - seawater reverse osmosis (SWRO) hybrid: a case study. Frontiers in Energy Research, 12 (2024)*
- *Schunke A. J., Hernandez Herrera G. A., Padhye L., Berry T.-A. -Energy Recovery in SWRO Desalination: Current Status and New Possibilities. Frontiers in Sustainable Cities, 2 (2020)*
- *Sutariya B. -A mathematical investigation into the limited use of energy recovery devices in brackish water reverse osmosis processes. Chemical Papers, 77 (2023) 6409-6418.*
- *Pang Y., Zhang J., Ma R., Qu Z., Lee E., Luo T. -Solar–Thermal Water Evaporation: A Review. ACS Energy Letters, 5 (2020) 437-456.*
- *Gohil P. P., Desai H., Kumar A., Kumar R. -Current Status and Advancement in Thermal and Membrane-Based Hybrid Seawater Desalination Technologies. Water, 15 (2023) 2274.*

- *Costa F. C., Ricci B. C., Teodoro B., Koch K., Drewes J. E., Amaral M. C. -Biofouling in membrane distillation applications-a review. Desalination, 516 (2021) 115241.*
- *Lee C.-H., Ho H.-J., Chen W.-S., Iizuka A. -Total Resource Circulation of Desalination Brine: A Review. Advanced Sustainable Systems, 8 (2024) 2300460.*
- *Liu C., Lowenstein T. K., Wang A., Zheng C., Yu J. -Brine: Genesis and Sustainable Resource Recovery Worldwide. Annual Review of Environment and Resources, 48 (2023) 371-394.*
- *Backer S. N., Bouaziz I., Kallayi N., Thomas R. T., Preethikumar G., Takriff M. S., Laoui T., Atieh M. A. -Review: Brine Solution: Current Status, Future Management and Technology Development. Sustainability, 14 (2022) 6752.*
- *Kumar A., Naidu G., Fukuda H., Du F., Vigneswaran S., Drioli E., Lienhard J. H. V. -Metals Recovery from Seawater Desalination Brines: Technologies, Opportunities, and Challenges. ACS Sustainable Chemistry & Engineering, 9 (2021) 7704-7712.*
- *Dhakal N., Salinas-Rodriguez S. G., Hamdani J., Abushaban A., Sawalha H., Schippers J. C., Kennedy M. D. -Is Desalination a Solution to Freshwater Scarcity in Developing Countries? Membranes (Basel), 12 (2022)*
- *Zheng Y., Cáceres González R. A., Hatzell M. C., Hatzell K. B. -Challenges and Roadmap for Solar-Thermal Desalination. ACS ES&T Engineering, 3 (2023) 1055-1082.*
- *Fthenakis V., Xu P., Zhang Z., Sitterley K., Lugo A., Wang H., Kuravi S., Kota K., Dani N., Atia A., Kurup P., Miara A. -Review of solar-enabled desalination and implications for zero-liquid-discharge applications. Progress in Energy, 6 (2024) 032004.*
- *Ghasemi M., Sedighi M., Usefi M. M. B. -A comprehensive review on membranes in microbial desalination cells; processes, utilization, and challenges. International Journal of Energy Research, 46 (2022) 14716-14739.*
- *Salajeghe M., Ameri M. -Evaluation of the energy consumption of hybrid desalination RO-MED-FD to reduce rejected brine. Environmental Progress & Sustainable Energy, 43 (2024) e14312.*
- *Maftouh A., El Fatni O., Bouzekri S., Rajabi F., Sillanpää M., Butt M. H. -Economic feasibility of solar-powered reverse osmosis water desalination: a comparative systemic review. Environmental Science and Pollution Research, 30 (2023) 2341-2354.*
- *Atasoy A. D., Topal A. D. -Reverse osmosis treatment system for landfill leachate: Operation conditions, advantages and challenges. Environmental Research and Technology, 5 (2022) 119-127.*
- *Abumadi F. A., Koujan M., Laoui T., Atieh M. A., Khalil K. A. -Capacitive Deionization Water Desalination Technology, Process Optimization and Cost Analysis - A Review. Advances in Science and Technology, 129 (2023) 19-25.*

- *Chebli H., Fornarelli F., Bellantuono N. -Comparison of Desalination Technologies and Assessment of Their Sustainability. Journal of Physics: Conference Series, 2648 (2023) 012021.*
- *Sneegas G., Seghezzo L., Brannstrom C., Jepson W., Eckstein G. -Do not put all your eggs in one basket: social perspectives on desalination and water recycling in Israel. Water Policy, 24 (2022) 1772-1795.*
- *Ahsan Y., Waheed Qurashi A., Yasmeen R. -Desalination of Saline Water: A Review: Desalination of Saline Water. MARKHOR (The Journal of Zoology), 3 (2022) 08-12.*
- *Noori Sepehr M., Jafari N., Molaei Tavani S. -Assessing the quality of water output from desalination plants and water tankers in Qom and comparison with national standards and WHO. jehe, 8 (2021) 465-476.*
- *Wang Z., Ye A., Liu K., Tan L. -Optimal Model of Desalination Planning Under Uncertainties in a Water Supply System. Water Resources Management, 35 (2021) 3277-3295.*
- *Jones E., Qadir M., van Vliet M. T., Smakhtin V., Kang S.-m. -The state of desalination and brine production: A global outlook. Science of the Total Environment, 657 (2019) 1343-1356.*
- *Aljohani N. S., Kavil Y. N., Al-Farawati R. K., Aljohani N. H., Orif M. I., Ghandourah M. A., Bahshwan S. M., Aloufi F. A., Halawani R. F., Salam M. A. -The assessment of environmental parameter along the desalination plants in the Kingdom of Saudi Arabia. Open Chemistry, 21 (2023)*
- *Lykkebo Petersen K., Heck N., G. Reguero B., Potts D., Hovagimian A., Paytan A. -Biological and Physical Effects of Brine Discharge from the Carlsbad Desalination Plant and Implications for Future Desalination Plant Constructions. Water, 11 (2019) 208.*
- *Israel's largest desalination plant Sorek B employs DuPont's FilmTec membranes. Membrane Technology, 2021 (2021) 1-1.*
- *Cohen E. - In Preprints; Preprints, 2024.*
- *Kramer I., Tsairi Y., Roth M. B., Tal A., Mau Y. -Effects of population growth on Israel's demand for desalinated water. npj Clean Water, 5 (2022) 67.*
- *Sanza M. A., Bonnélyea V., Cremerb G. -Fujairah reverse osmosis plant: 2 years of operation. Desalination, 203 (2007) 91-99.*
- *Lee Y. S., Lee Y. G., Jung D. H., Jung H. H., Kim J. H. -Application of World Ocean Atlas data for estimating the relative performance of a new construction of SWRO desalination plant. Desalination and Water Treatment, 15 (2010) 5-10.*
- *Mitra S. S., Sharma M. K., Rybar S., Bartels C., Pelegrin L. -Fujairah SWRO — management of membrane replacement. Desalination and Water Treatment, 10 (2009) 255-264.*
- *Morgan R. -The Allure of Climate and Water Independence: Desalination Projects in Perth and San Diego. Journal of Urban History, 46 (2020) 113-128.*

- *El Saliby I., Okour Y., Shon H. K., Kandasamy J., Kim I. S. -Desalination plants in Australia, review and facts. Desalination, 247 (2009) 1-14.*
- *Martínez-Medina M. À., Pérez-Martín M. Á., Estrela T. -Desalination in Spain and the Role of Solar Photovoltaic Energy. Journal of Marine Science and Engineering, 12 (2024) 859.*
- *Al-Mutairi E. S., Rashed I., El-Halwany M., Mosaad M. A. -Environmental Impact Assessment of Water Desalinating Systems: Kuwait as a case study. Mansoura Engineering Journal, 49 (2024) 5.*
- *Hamoda M. F. -Desalination and water resource management in Kuwait. Desalination, 138 (2001) 385-393.*
- *Wazeer I., Khan S. U.-D., Al-Mutaz I. S., AlAteeq I. M., Chafidz A., Khan S. U.-D. -Assessment of the design, operation, and economy of the seawater reverse osmosis plant in Al-Jubail region, Saudi Arabia. Desalination and Water Treatment, 222 (2021) 60-80.*
- *Heihsel M., Lenzen M., Behrendt F. -Desalination and sustainability: a triple bottom line study of Australia. Environmental Research Letters, 15 (2020) 114044.*
- *Angelakis A. N., Valipour M., Choo K.-H., Ahmed A. T., Baba A., Kumar R., Toor G. S., Wang Z. -Desalination: From ancient to present and future. Water, 13 (2021) 2222.*
- *Ghernaout D. -Desalination engineering: environmental impacts of the brine disposal and their control. Open Access Library Journal, 7 (2020) 1-17.*
- *Chekifi T., Benmoussa A., Boukraa M. -Desalination Powered by Renewables: A Challenge and an AI Opportunity. Water Resources Management,(2024) 1-43.*
- *He Q., Zheng H., Ma X., Wang L., Kong H., Zhu Z. -Artificial intelligence application in a renewable energy-driven desalination system: A critical review. Energy and AI, 7 (2022) 100123.*
- *Ray S. S., Verma R. K., Singh A., Ganesapillai M., Kwon Y.-N. -A holistic review on how artificial intelligence has redefined water treatment and seawater desalination processes. Desalination, 546 (2023) 116221.*
- *Loreti Hupsel A., Borges C. P., da Fonseca F. V., Barbosa G. M. -Evaluation of pretreatment routes for seawater desalination by nanofiltration. Water Science & Technology, 89 (2024) 454-469.*
- *Ennouhi M., El Aggadi S., Belmaghraoui W., Dahhou M., Azzouzi L. -Efficiency in Optimizing the Pre-treatment Process in Water Desalination. NanoWorld J, 9 (2023) S431-S437.*
- *Poirier K., Lotfi M., Garg K., Patchigolla K., Anthony E. J., Faisal N. H., Mulgundmath V., Sahith J. K., Jadhawar P., Koh L. -A comprehensive review of pre-and post-treatment approaches to achieve sustainable desalination for different water streams. Desalination,(2023) 116944.*

- *Song X., Jia L., Wei Z., Xiang T., Zhou S. -Nature-inspired sustainable solar evaporators for seawater desalination. Journal of Materials Chemistry A, 12 (2024) 613-633.*
- *Xiao Y., Chen H., Li M., He Q., Oo T. Z., Zaw M., Lwin N. W., Hui K. N., Luo M., Tang D. -Ionic liquid redox flow desalination of seawater. Desalination, 574 (2024) 117284.*