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Review on Desalination using Reverse Osmosis: An insight on Advancements, Challenges

Senthilnathan Nachiappan[1]*, Selvaraju Sivamani[1], Shamal Mohammed Said Samhan Almasahli[1]
[1]Chemical Engineering, College of Engineering and Technology,
University of Technology and Applied Sciences, Salalah

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ABSTRACT

Desalination using reverse osmosis is expected to play an important role in addressing global water stress. Tremendous advances have occurred in RO technology in recent years. The present review discusses the recent engineering trends in the RO process. The significance of energy reduction by pressure retardation, increased biorecovery of resources, small-to-large plant philosophies, and inclusion of nanocarbon polyamide and cellulose triacetate membranes in large plants are presented. An economic analysis illustrates the critical nature of feed solution salinity and brine disposal in the least cost of treatment. Real-time control and monitoring, clearing the path for increased energy recovery and zero-liquid discharge options, are described. These advances still exist in the backdrop of the world's largest desalination plant using SWRO. RO models have evolved to describe the effect of feed solute, selective layer permeability, added mass transfer resistances, reduced hydrodynamic, and fixed charge effects. A great challenge includes understanding and learning to predict the operational lifetime. The prospects for improved fouling diagnostics and fouling-resistant approaches require clarity and are discussed. While SWRO has reached a mature state, other RO applications have strong potential.

1. Introduction

Though reverse osmosis has numerous industrial, medical, food, chemical, and environmental water treatment applications, its success largely depends on design, capital cost, and operating cost. This can only be done when one not only understands the basic mechanistic concepts and challenges of reverse osmosis but also puts them in the right economic perspective (Nthunya et al.2022; Pearson et al., 2021; Zaidi & Saleem, 2021). As an engineering tool, reverse osmosis can optimize crucial operations such as zero liquid discharge, selective removal of contaminants, increasing recovery of available fresh water, and optimized recovery of available energy. Though the basic concept of reverse osmosis has been known for more than two centuries, its foundational theories and commercialization are only a few decades old, and as such, it is expected that more recent trends in the past decade will be best to understand the potential in addressing the many challenges that the world faces today.

In the upcoming review, efforts have been made to further discuss the key foundational aspects and lay out those recent trends in reverse osmosis that are overlooked. Indeed, reverse osmosis has been ever-changing since its commercial inception in the 1960s. However, reports in the literature tend to only focus solely on a current technology, finished product, application, or specific environmental and economic challenge (Al-Aghbari, 2022; Boyce, 2024; Saith, 2022). This review provides an engineering perspective with a twist by elaborating recent trends and making a critical analysis of the use of current and future technologies of reverse osmosis.

2. Fundamentals of Reverse Osmosis

The reverse osmosis is one of the most important methods of desalination of water in the twenty-first century. This principle of reverse osmosis is based on the fact that the solvent may be extruded through a semi-permeable membrane. Water is pushed against a membrane under weak pressure, from which some substances are separated (Okampo & Nwulu, 2021; Shalaby et al.2022; Feria-Díaz et al.2021). The supply pressure must be higher than the osmotic pressure in the volume of concentrated solution. It is this difference in pressure that forces the water through the pores of the membrane, while substances that are larger in size and, as such, are not able to pass through the pores of the membrane remain accumulated. The purity of water depends on the number of these formed on the membrane. Since the pressure active technological progress began, reverse osmosis has also undergone significant progress in becoming the method of desalination of sea and brackish water. In addition, reverse osmosis has other broader applications in various fields, from the food industry and beverages to electric power, running costs, and laboratory analyses. Reverse osmosis offers an affordable high-quality drinking water supply;

it is used in large industrial plants for the production of pure water. In the last few years, reverse osmosis has also been spreading in smaller facilities due to the decreasing prices of membranes, which are becoming more durable and have a longer lifespan. For these reasons, reverse osmosis has become the fastest-growing branch of water desalination.

2.1. Principles of Osmosis and Reverse Osmosis

The incredible yields of pure water through seawater and brackish water desalination technologies usually happen through high-pressure reverse osmosis processes. RO membranes are recognized by their symmetric or asymmetric dense layers on a support. Their separation and purification mechanisms are determined through the membrane material and transport processes. While the membrane's final performance is a result of all the membrane layers combined, the RO process is, otherwise, a result of the membrane components combined and their unit designs creating a crossflow that provides membrane performance and capacity (Phuntsho et al.2020; Liang et al.2022; Scheepers et al.2023).

Osmosis is the process of moving a solvent through a semi-permeable membrane from a region of low solute concentration to a region of higher solute concentration, in order to achieve equal solute concentrations on both sides of the membrane. The pressure of the solute on the side of the membrane with the higher solute concentration necessary to support the concentration gradient and stop more particles from moving to that side is called osmotic pressure, and the process is said to have reached osmotic equilibrium when the osmotic pressure reaches this level and the flow ceases. If reverse behavior outside the equilibrium state is wanted, hydrostatic pressure higher than osmotic can be applied.

2.2. Membrane Technology

Membrane technology has undergone a significant evolution in terms of improving efficiency, purity, and possibilities for wider application for desalting brackish and salt waters, as well as treating sewage, especially when it is designed for reclamation as part of ecological management and preservation of worldwide water reserves. This ever more feasible technology is based on membrane devices, which are employed by providing a selective barrier to separate and/or concentrate dissolved or dispersed components with the least possible use of chemicals. Although membrane separation methods have been employed for a long time, it is only in the last few decades that membrane processes have achieved economic viability and technical validity, which have resulted in sustainable water treatment.

Several technical differences can distinguish general membrane industrial applications: organic or inorganic nature, external or immersed structure, form, and disposition of the separation layer. Each of these large groups has even more specific market segments (Baker, 2023; Iulianelli & Drioli, 2020; Obotey Ezugbe & Rathilal, 2020; Li et al., 2023). The majority of the membrane biotechnologies use polymer-based materials, which usually have an external structure and are presented in tubular, hollow fiber, or, more recently, spiral coil configurations. The use of ceramic membranes and submerged modules has been increasing, mainly because of their reliability, durability, and ease of application, as well as their longer lifespan, even with the added cost. The composition of organic membranes can be varied, with polyamide, polysulfone, and polyvinylidene fluoride being the most common. The porous support can be fabricated from polymers, sintered ceramics, or metallic materials. Flocculation, sand filtration, and, in particular, the traditional processes associated with standard activated carbon are some principal pretreatments used for surface water to reduce fouling and to safeguard against the occurrence of harmful algal toxins in the raw water treatment. The process is an adoption of the bio-membrane reactor, using immersion membrane ultrafiltration with the composite.

3. Recent Advancements in Reverse Osmosis

Molecular filtration systems and separation techniques have been recognized as essential systems for the development of several large and important industries. For porous materials and membranes in these industries, several techniques for fabricating them, in all of their forms, have received considerable attention over the recent past (Iulianelli & Drioli, 2020; Liu et al.2020; Wang et al.2021). One of the most popular membrane techniques is reverse osmosis, involving a semipermeable membrane featuring a large number of applications. Osmosis is a natural process in conventional conditions, where water moves from a dilute area into a more concentrated one through a semipermeable membrane when concentrating a solute containing a ply. Reverse osmosis is a process conducted under pressure, forcing water to move from a more concentrated solution to a dilute one through a specific class of membranes called semipermeable membranes, producing salt separation efficiencies from 98% to nearly 100%, depending on a number of factors.

Recent chemical and biological engineering developments have led to broad applications of single or combined processes of reverse osmosis. The recent developments concerning the membrane, the membrane modules, and the reverse osmosis plant from laboratory to pilot scale to full industrial application are reviewed. The use of spacers and their hydrodynamics, along with the increasing applications in agriculture, wine, and the pharmaceutical industry, combined with the possible integration within hybrid processes, are also explained. The new and important thorny problems related to the control of fouling, violation of the critical flux, and scaling are presented. Finally, the advancement of nanofiltration and high-performance recycling recent developments, which are clearly demonstrated by energy calculations, are taken into account. It is clear from this review that the reported progress will significantly affect and improve reverse osmosis technology in its applications, apart from requiring several additional efforts, especially those related to the management of fouling problems.

3.1. Innovative Membrane Materials

As the needs for cleaner water increase, the development and testing of alternative materials and components used within the construction of reverse osmosis membranes become important. These approaches not only focus on the characteristics and features of the component itself, but also on the effects it has in conjunction with the entire membrane structure. These materials are designed to increase the performance and efficiency of the membrane, advance flexibility in the treatment of specialty or challenging applications, and broaden the capabilities of the membrane's integrity. This approach also aims to lessen the negative effects produced by that component or material. Some important alternative materials and components are: improved selective filtration capabilities as well as broader operating parameters for current materials; novel anti-biofouling and self-cleaning components; proper component support and polymer matrix enhancement; and reduced degeneration or change over time within the entire membrane matrix and additives used within the membrane.

Currently, the advancements of RO membranes are made with the goal of enhancing performance, i.e., increasing rejection, decreasing fouling, improving flux, and minimizing energy consumption for water treatment. Given that the performance of RO membranes is essentially determined by the membrane constituents, researchers have dedicated much effort to improving the properties of these materials. In this subsection, we summarize the major innovative advances in membrane materials or modules proposed or reported within the last decade, including selective layer materials, antifouling layers, and support layer materials. We also briefly present the nonwoven mat, metal, and other membrane module materials. The effects of improving membrane performance and ensuring long-term stability will be critically discussed based on selected demonstrations. The impacts of various additives for the selective layer are also discussed.

3.2. Enhanced System Designs

Incorporating new developments such as the use of energy recovery devices and different membrane module configurations has further improved the performance of reverse osmosis systems. Energy recovery devices used in RO systems have other alternatives as well in improving the energy efficiencies of membrane filtration systems by recycling and thus reducing the load of concentrate on the membrane module itself (Mansour et al.2020; Harby et al., 2021; Li et al.2021). There are four main types of energy recovery devices: hydraulic, rotary, turbocharger, and isobaric, each using different technologies. Sizing, selection, and performance analysis of energy recovery devices in the design of RO-ED and RO-PRO systems have been described.

The RO-ED system uses electrical energy to draw water through the membrane from high salinity feed to low salinity product and is usually combined with energy recovery devices to recycle concentrate and thus recover high efficiency. An iterative methodology was used to compare performances of the seawater RO-ED system and the seawater RO with isobaric chamber pressure exchanger for use in seawater desalination. Software has been developed for the dimensioning of the RO-ED system. The RO-PRO system can also be combined with the energy recovery device. The study attributed the superior process performance of RO-PRO compared to RO-ED to the reverse hydraulic pressure difference of a pressure retarded osmosis process and a higher osmotic pressure of a draw solution.

4. Engineering Applications of Reverse Osmosis

This section presents reverse osmosis applications for water, food and dairy, pharmaceutical, power, oil, and gas industries. The principles and prediction of long-term performance of reverse osmosis for radium and water reuse or desalination are discussed with field examples. Feedwater pretreatments and antiscalants are presented to ensure the reliability and longevity of the reverse osmosis operation.

Reverse osmosis has been the most efficient and economical way to remove biological contaminants and radium from drinking water. Increasing public awareness of water shortage and contaminants in drinking water has generated renewed interest in reverse osmosis, and significant efforts have been made to address industry challenges. Bench, pilot, and full-scale facilities, in co-located and stand-alone configurations, have been used to evaluate the long-term performance of reverse osmosis treatment for radium removal under different site conditions (Matin et al., 2021; Feria-Díaz et al.2021; Ahmed et al.2022). In addition, reverse osmosis has been employed to recover and treat water from acid mine drainages. Brackish water from well fields or surface water represents an alternative source of water supplies that can be desalinated effectively by reverse osmosis. With the economic feasibility of brackish water desalination, new well fields are being developed from saline groundwater, and other existing fields are being converted to desalination applications from tube wells. Ongoing successful reverse osmosis installations for brackish water desalination are taking place throughout the country. A regional desalination center has been established to implement the research into a development community system that can benefit from the process improvements.

4.1. Desalination Plants

Desalination plants are designed for both freshwater generation from seawater or brackish water and salt and impurity removal for industrial use to enable intensive cultivation of fish and marine products. Although thermal desalination methods still have some market share, membrane methods like reverse osmosis are dominant in new construction. The problem with giving an exact figure for the size of the desalination market is the difficulty in determining server plant sizes, but at the end of 2008, the desalination cumulative capacity had reached 45 million m3/day and was being increased by an average of over 10% per year. The main reason for the development of the world desalination market, especially in certain regions, is the high availability of feed seawater for coastal arid or semi-arid regions, the increase in water demand due to the rapid growth of coastal cities, and the shortage of freshwater resources and potable water due to drought or over-extraction of groundwater resources.

Moreover, tariff regulation, which used to be one of the main market barriers of desalination, is now gradually being reduced thanks to the improvement in membrane technologies and the increase in unit capacity of a single plant. The economics of desalination is spurring growth because new technologies and optimization of energy use have resulted in a low price of less than $1/m3 or even $0.5/m3 for RO and, therefore, affordable to coastal countries with weak purchasing power. Decreased public acceptance of RO facilities, along with many concerns of the public and project developers due to environmental impacts, the large carbon footprint of many RO plants, and other factors are also important challenges.

4.2. Wastewater Treatment Systems

Pollution of drinking water resources has been continually rising because of increased industrialization, population growth, rate of urbanization, and cultural lifestyles spread among populations. To reduce this pollution of surface water bodies and containment of groundwater pollutants, the world's attention has been drawn to wastewater treatment in recent years (Yang et al.2022; Chowdhary et al.2020;

Mishra2023). These pollutants include disease-causing agents, inorganic chemicals such as heavy metals, nutrients such as nitrate and phosphates, organic chemicals such as polychlorinated biphenyls, dioxins, and perfluorooctanoic acid, oil and grease, and suspended solids. Proper control of these pollutants is essential. Industrial wastewater emits numerous pollutants, including a higher percentage of undissolved suspended solids than domestic waste. Oil removal from the industrial effluent is a crucial stage, requiring periodic moving-bed biofilm reactors to enable biological treatment. Then other treatment processes aimed at treating the less bio-refractory organic chemicals, inorganic compounds, metals, and nutrients draw attention. Although biological processes are economically feasible and environmentally compatible, such high-strength wastewaters suffer from some of the major post-treatment process concerns related to biosolids disposal, odor emissions, and sensitivity to toxic shocks. At times, the wastewater volume is less, and cost-efficient treatment is needed.

5. Economic Analysis of Reverse Osmosis Systems

The growing population and the industrial and agricultural development in India lead to a continuous rise in demand for drinking water and water for various uses. Of all sources of water, surface water and groundwater, groundwater pumping is always the most reliable, especially in urban areas (Scanlon et al.2023; Mautner et al.2020; Wilopo et al.2021). However, no essential development is noticed in the field of water quality in regard to environmental policy. Nearly 80% of sewage water, including industrial effluents, goes to untreated water bodies due to the present treatment facilities' inefficiency. Sometimes there is a discharge of sewage water into water bodies for a considerable time, leading to water pollution and making water unsuitable for use. The demand for reusable water is comparatively higher and can be proven for various applications such as cooling water, industrial processes, equipment cleaning, etc. Industries located around a city, or an industrial area use and discharge a considerable amount of water. A significant amount of per capita water is required in the location, and there is also an exchange in usage between the pollutants in the surrounding environment. There is a scarcity of land to discharge sewage water to drain and purify via natural means. Therefore, effective treatment is required before discharge. As India is known for its abundant solar resources, most Indian cities and industrial areas have space availability for photovoltaic panel sets. Therefore, we developed the solar support reverse osmosis photovoltaic system, keeping industrial and biofertilizer uses in mind.

The solar support reverse osmosis system is designed to work with or without extra electric power (maximum water recovery). It uses abundant solar power generation during the day and charges it in the battery, then uses the battery power during the night for the RO plant. It is designed to care for two types of water sources: tap water during cloudy days and saline water during sunny days (Mohammed et al.2023; Lai et al., 2021; Shalaby et al.2022; Rahimi et al.2021). The solar photovoltaic panel generates DC power, and the generated power charges the battery; then, the battery can draw DC power to operate the inverter, which converts DC into AC power, making it ready for the RO system and motor pump. The system uses very low power (12 VDC/18 VDC/24 VDC motor, after 3 W utilized for the salt-wedge enhancement of the consequent reverse osmosis membrane and released through drainage, and only a 2 W motor for water delivery to different usage points: drinking water, biofertilizer, and, if at a remote site, industry water requirement below 2000 ppm having industrial uses according to its pollutant level). The system uses a reverse osmosis membrane module to remove all types of pollutants present in water. The permeate water uses an ultraviolet lamp and mineral candle to ensure biofertilizer requirements; the first one kills almost all types of germs and other biological components, and the second system removes hardness present in the water. The system has a conductivity sensor that senses the salt concentration present in water. The RO module utilizes the maximum power and generates hard water through the module, acting as a mediator to improve the system efficiency of the solar support RO plant. Finally, the system uses a duty cycle to operate the motor and increase the module's lifetime. The system uses a water flowmeter to measure the water supplied to the connected devices. The duty cycle and MPPT help to operate the system effectively. It extends the overall life of the RO membrane module and DC power water pump with high energy efficiency.

6. Challenges in Reverse Osmosis Technology

The adversely impacting consequences of climate change, for instance, prolonged periods of drought, can lead to an increased demand on reverse osmosis units as a result of the tendency to use surface water or brackish water sources. In coming years, it is envisioned that, without human intervention, the current climate trends are likely to worsen. This situation will be made worse by the dilution of pollutants into reusable water streams. This has the potential to have a major impact on the effectiveness of RO desalination. As such, it is key that the difficulties and challenges are addressed in a responsible manner to ensure water supplies are safeguarded. Currently, there are no standards that define what is and is not a high-performance industrial RO membrane. Contrary to well-established electrical engineering standards, membrane materials and wet-end assembly are fundamental challenges in the development of RO technologies and the needs of the water sector.

Standardization does not exist also in relation to pressure vessels. For example, membrane performance and RO processing are parameters that can cause uncertainties in terms of membrane life and performance, and introduce problems in reaching the water quality required. The application of standard methods for producing, measuring, and qualifying RO membranes could be improved, and the service time of the membrane could be extended. Currently, along the assembly line, membranes are tested for specific parameters such as flow, conductivity, turbidity, adsorption, gas chromatography, mass spectrometry, etc., that offer some information but are not conclusive on membrane performance. The wet end of the RO operates under extremely harsh environmental conditions characterized by high pressure, transmembrane hydraulic pressure gradients, high-temperature differences, and shear stresses. In recent years, the growth in large RO plants due to scale and the ability to search and obtain novel and diverse feed sources linking with a water intake system has allowed practical guidance to be obtained and a more thoughtful approach to design to identify information regarding the many influences on performance during wet operation. It is generally avoiding critical monitoring of wide streams within the process design of the filtration process and in the complexity of the filtration and plug and seal sub-processes.

6.1. Scaling and Fouling Issues

Reverse osmosis (RO) membranes face several critical issues during long-term operations. The main issues are scaling and fouling induced by remaining solutes that cannot pass through the membranes. To eliminate these issues, it is important to select feedstock solutions free of these scaling and fouling influences. Pretreatment processes such as the removal of metals, hardness, and organics are also essential to improve the efficiency of the RO process. In this review, many available solutions and some proposed new advances are presented to improve the efficiency of RO membranes. A suggested improvement, fouling-induced surface patterns, can be introduced to create rough surfaces on the membrane material that may help to achieve an antifouling effect on the membrane surface. Scaling and fouling are the main issues for reverse osmosis (RO) membranes that are causing critical challenges to ensure efficient, long-term RO operations. The fouling issues are gradually induced by remaining solutes that cannot pass through the RO membranes. The available solutions to eliminate these issues are presented in this subsection. The reduction of foulants from the feedstock is another way of avoiding the fouling issue, which is also part of the membrane preparation steps. Another proposed idea is to create fouling-induced surface patterns on the membrane surface to replace the smooth surface of the RO membranes. The patterns on membrane material for RO processes can enhance the antifouling effect on the membrane surface and introduce rough surface properties to achieve a long-term antifouling effect of up to 12 months. A commercial solution, which can prolong the RO membrane life up to 100 days, is the use of a bio-dispersant.

6.2. Energy Consumption

The power demand for a seawater RO plant can be analyzed by the following simple equation: $P = \sigma/Q$ where P = power demand (kilowatts or MW) σ = conversion factor Q = quantity of water desalinated Hence, energy intensity is quite high in RO plants, which is discussed in the section that follows. Different models have been suggested to calculate power consumption. However, there are some basic rules to estimate the power consumption of an RO plant, which are stable with almost no correlation with type or capacity. At the present time, a great deal of effort is being made to reduce energy consumption in RO systems, and significant progress in reducing energy consumption has been achieved in recent years. Industrial RO systems consume a significant amount of power, which constitutes a major portion of the total operating cost of RO desalination. The power consumption of industrial RO systems is a function of several parameters, such as the quantity and quality of feed water, system configuration, recovery rate, membrane specifications and modification processes, and equipment design.

7. Types of Reverse Osmosis Systems

Several types of RO systems are in operation. This review categorizes them into three general categories in order to provide more context for the reader: conventional or single pass, concentrate recycling, and two-pass.

7.1. Conventional or Single Pass RO System The conventional or single pass system is the simplest type of RO system and is often found in applications such as desalination, food, and beverage industries. The system has been utilized for the treatment of brackish or seawater to less than 800 mg/L TDS for drinking and irrigation purposes. This is a single-stage design where the feed water is only passed in a single stage before being split into permeate and concentrate streams. These systems allow TFC more commonly due to ease of following the first RO stage with a second stage of TFC in the same housing or via another bank of spiral membranes. Since the concentrate stream is discharged into the environment, disposal of the stream is regulated by environmental agencies due to zero water recovery in this process. However, the system offers a high percentage of solute in the feed to be removed, low operating cost, with lower modular cost along with lower maintenance.

7.2. Concentrate Recycle Reverse Osmosis (CRRO) System Wastewater treatment plants, dairy industry, food and beverage, and electroplating industries usually use CRRO systems. These advanced versions play an important role in increasing the recovery of RO to almost 85%, and TDS of the concentrate is switched to coolers, baro-mechanical steam compressors, baro-mechanical evaporators, and MVR to enhance recovery. The RO permeate flowing out of the bottom can be used, for example, in boiler water makeup, CIP rinse, and further treatment with EDI technology.

7.3. Two Pass Reverse Osmosis System The two-pass reverse osmosis system is designed to allow ultra-treatment of high silicon contents to remove such radicals at depth by stage I and thus protect ST2. Feed water flows from the security filter to stage I RO, then passes through the stage II RO membrane and finally into the active carbon column. According to the actual situation, stage I and stage II RO can be operated in parallel to treat water from the stage II diffusion pool, so as to obtain both micro output and big output. By adding an RO recycle loop between stage I and stage II to form double action ultra-treatment form. Depending on the task volume, the two-pass RO system uses the method to protect the two-pass RO, which combines the best elements of the single stage and the two-pack closures. Generally achieving up to 92% recovery, the system uses the CIP/SIP system every time it cleans. This high recovery system can attract paint recovery and synergy, allowing less wastewater to be produced.

7.1. Brackish Water RO Systems

A large percentage of RO plants are treating brackish water with TDS values of 3,000–15,000 mg/L. Very high fluxes are possible for this application, as high as 70–85 L/m²/h, given the right feed water conditions. At lower fluxes (40 L/m²/h), couplings of concentrate recycle and spiral wound configurations provide a manageable option for feed and concentrate flow rates, pressure requirements, and specific energy consumption (Ansari et al.2021; Mahabror & Zulkarnain2021; Sharma et al.2020; Pearson et al., 2021). This would generally increase if precoating were employed. Concentrating recycle for this application is beneficial, if not necessary. Concentrate recycle reduces the minimum required driving force to less than 120 bar for 50% recovery and can be about 100%–300%. Another benefit of high concentration in operation is less frequent cleaning.

Another special consideration for these plants is the high recovery in conjunction with high scaling potential. The concentration of scaling species must be limited while avoiding pretreatment processes that make better economics unsound. Specialized cleaning-in-place chemical cleaning schedules can partially compensate for limitations in concentrate conditions and minimize SDI, silica, and metal levels. Semi-automatic, automated, and real-time monitoring of dissolved species is a necessity, as is instrumentation to track solids build-up depths and to ensure its prevention, and irrigation of overall conditions of O-rings, flow balance, and sufficiently robust construction materials to warrant long-term, continuous operation. Using the most advanced membranes and technology has a measurable impact on NPW and provides the tools for addressing the challenges of high-performing and economic brackish water plants.

7.2. Seawater RO Systems

Seawater reverse osmosis systems were introduced in the early 1970s and have become a viable source of community supply, especially in arid countries. Several developments of this application can be identified, but there has been a slowdown in new research activities in the last five years. The first commercial plants were reduced capacity units and operated at a brackish water rate of conversion. The application was driven by the presence of highly concentrated salt brine discharges from the desalination plants, but mainly because the salt brine discharges from the electro-dialysis reversal systems were unacceptable on beaches close to leisure resorts. The trend in plant capacity has been steadily growing; most new installations exceed 2,000 m3/day and several units over 20,000 m3/day.

There are several seawater reverse osmosis systems in Middle Eastern countries, especially in Saudi Arabia, Kuwait, the UAE, and Oman. Large-scale seawater reverse osmosis systems have become competitive in operation with vaporization processes, but not yet in initial production costs. The average operating costs for desalting seawater are of the order of $1/m3 for seawater intake directly from the sea. The development of larger capacity seawater reverse osmosis systems seems to be limited by the size of seawater pumps and costs for intake pipelines. It seems that production capacity could be increased to 80 m3/m2/day in well-designed plants. The main problem with seawater reverse osmosis systems is the selection of suitable membrane elements and pre-treatment procedures. Of the membranes, spiral wound polysulfones and cellulose acetates have been used and have shown the best characteristics for seawater applications. The selection of the membrane should depend on the type of available pre-treatment systems and operational design parameters. The falling values of seawater reverse osmosis system product water increase with increasing salt concentrations, pressure, and temperature of the feed seawater.

8. Conclusion and Future Outlook

Closing the discussions, raising clean water production is becoming mandatory due to global water stress. Global freshwater availability versus demand is continually evolving as a result of population rise and increasing affluence. Population increases and the migration of people to urban areas add complexity to the challenges water scarcity is creating. In the next two decades, more than 3 billion people may suffer a water shortage. The challenges are not only freshwater scarcity but also require integral solutions to ensure sanitation and human health are maintained. Over 80% of sewage in developing countries is discharged without treatment. This increases the occurrence of diseases and causes pollution. Regarding the water scarcity problem, it is worth remembering that nearly 97.5% of the global runoff water is from seas with inaccessible salts, and almost 70% of fresh water supply is stored in frozen glaciers. Humanity has access to a little less than 1% of global freshwater in aquifers and less than 1% in surface water.

In conclusion, reverse osmosis is an important technology for desalting activities and has advanced over the decades. Various improvements have been implemented over the years to enhance system performance, lower operation and production costs, and extend the equipment's useful life. The challenge of future RO systems is to find the best solution to use available renewables with zero carbon emissions. If this is done, what global installed capacity will be able to achieve? Given the complete implementation of the tables along with the two-stage two-pass RO system, there are several economic benefits of using two-pass RO that include efficiencies in operation and maintenance of the system. There is a versatile design for water producers by differentiating output qualities in stages. The process can be simplified by decreasing the driving force between stages and improving local thermodynamic equilibrium through the heat exchanger. Finally, the global research on two-stage RO has mainly focused on locating different membrane-supporting materials, pairing them with newer, more efficient membranes, and making profound improvements. Desalination processes currently use various membrane configurations operating in tandem to increase the total rejection force. Zero-emissions renewable energy technologies make an agreement and become a two-stage RO proposal. As indicated, it is a reliable, environmentally friendly, and economically viable way to have clean water in a world whose many parts are threatened today, and undoubtedly in the future, with water stress.

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