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Water Treatment and Desalination

Mona M. Amin Abdel-Fatah and Ghada Ahmed Al Bazedi

Abstract

Water covers a large area of the earth that reaches about three quarters of the surface of this planet, but we cannot say that all of this water is fresh or drinkable; according to many statistics, the percentage of fresh water reaches about 1% of the total water on earth. But with the great need for fresh water, whether for drinking or other purposes such as agriculture, the search for water treatment methods has become much larger. One of the most important of these methods that have been developed is desalination of seawater using desalination plants; therefore, we will address here the most important methods used in desalination and water treatment.

Keywords: desalination, water treatment, pretreatment, reverse osmosis, nanofiltration

1. Introduction

Water treatment and purification are the procedures of getting rid of unfavorable chemicals, natural contaminants, as well as suspended solids from water. The aim is to deliver water for certain applications. Water is disinfected for drinking, but water treatment may also be intended for different purposes, including chemical, medical, pharmacological, or other industrial applications. This method includes the physical methods such as sedimentation, distillation, and filtration; biological methods e.g. slow sand filters or biologically activated carbon; chemical methods such as coagulation, flocculation, and chlorination in addition to the use of electromagnetic methods such as ultraviolet light.

Desalination has developed a management water alternative resource by allowing the use of oceans, the greatest reservoirs in the world. Desalination is implemented in more than 100 countries around the world, including the United Arab Emirates, Oman, Malta, Portugal, Greece, Italy, India, China, Spain, Cyprus, Saudi Arabia, Japan, and Australia. Worldwide, the desalination plant produces over 3.5 billion gallons per day of potable water. Seawater desalination technology, reachable for decades, made remarkable strides in many arid areas of the world such as the Middle East, the Mediterranean, and the Caribbean. The potential of an RO desalination plant has increased from 1990 to 2020 [1–3].

Seawater and brackish water are the two most important sources that include desalination technology. The seawater desalination area dominated the international industry specifically due to the outstanding abundance of saltwater resources. Rising wide variety of initiatives in the utility area are expected to improve seawater desalination market.

Brackish water is expected to obtain importance, with an increase in 29% of contracts inside the first half of 2017. However, the presence of constrained

reservoirs of brackish water across the globe will probably result in a constrained market boom in this segment.

The water desalination market place worldwide was estimated as USD 15.0 billion in 2017 and is anticipated to make out a wholesome increase with CAGR 7.8% over the projected period. Increasing water crisis throughout the world is the key aspect to drive the market needs for water desalination over the coming years [4, 5].

2. Water treatment technologies

The targets of a water treatment are to eliminate undesirable constituents in the water, making it useful for drinking or matching a specific purpose in industrial applications. Generally, different techniques are presented to eliminate the impurities including microorganisms, suspended solids, and organic materials and other dissolved inorganic or environmental tenacious pharmaceutical contaminants.

The selection of the technique depends on the properties of the water to be treated, the treatment system capital cost, and the requirements predicted of the treated water. The methods discussed below are some of the regularly used methods in water treatment and distillation plants. A few or more may additionally now are not employed according to the treatment plant scale and the characteristics of (feed/source) water [6].

2.1 Pretreatment methods

2.1.1 Pumping

The water to be treated must be drawn out from its source or directed into the piping system or storage tanks by pumps. To evade adjoining contaminants to the water, this bodily substructure ought to be made from excellent materials and assembled so that unplanned contamination does not take place.

2.1.2 Screening

The initial stage in treating surface water is to take away large solids, for example, sticks, debris, leaves, and other massive specks that may affect the following purification/treatment steps. The majority of deep groundwater does not require screening before other purification steps.

2.1.3 pH adjustment

The pH value of natural water is close to 7, while seawater pH values vary from 7.5 to 8.4 in the moderate alkaline range. Water can have extensively fluctuating pH values reliant on the geology of the water aquifer or basin and they have an impact on of contaminant involvements. If the water is acidic (with a pH value less than 7), sodium hydroxide, lime, or soda ash can be employed to raise the pH at some point during the water treatment processes. The addition of lime increases the calcium ion concentration; as a consequence, the water's hardness level is increased. For acidic waters, "compelled draft degasifiers" may be an advantageous method to increase the pH value, by way of stripping "dissolved carbon dioxide" from the treated water.

Increasing the pH value of water (alkaline water) helps "coagulation and flocculation" processes to operate correctly and additionally supports reducing the risk of dissolving "lead" from pipes or from solder used in pipe fittings. Adequate alkalinity furthermore lessens the iron pipe corrosion in water. In some cases, to

reduce pH, acid, such as carbonic acid, hydrochloric acid, or sulfuric acid, may also be added to alkaline water. Alkaline water (above pH 7.0) does no longer essentially indicate that some metals like lead or copper will not be dispersed from the plumbing gadget into pumped water. The probability of dissolving hazardous materials like lead in water is limited remarkably to defend surfaces of metal pipes as a result of the capability of water to precipitate "calcium carbonate." The precipitate of calcium carbonate is a function of different parameters including pH, temperature, the mineral content, calcium concentration, and alkalinity.

2.1.4 Coagulation and flocculation

The first step in most regular water treatment tactics is the adding of special chemicals to facilitate the elimination of suspended constituents found in water. These suspended constituents may originate from inorganic sources such as "clay" and "silt" or organic sources such as "algae," "bacteria," "viruses," and other naturally occurring "organic matter." Inorganic and natural particles make contributions to the turbidity and complexion of water.

Adding coagulants of inorganic nature such as "aluminum sulfate (or alum)" or "iron(III) salts" like "iron(III) chloride" may trigger countless instantaneous chemical and physical interactions. By using inorganic coagulants, the particles are neutralized in seconds at a very low cost. Also, iron and aluminum ions start to form precipitates containing metal hydroxide. The metal hydroxide precipitates conglomerate into larger particles under natural tactics such as Brownian action and throughout instigated mixing, which is denoted as the "flocculation process." Amorphous metallic hydroxides are regarded as "floc." Amorphous aluminum and iron(III) large hydroxide molecules adsorb and tangle suspended particles, leading to an easier removal of particles through consequent methods like filtration and sedimentation [6–11].

Aluminum hydroxides are fashioned inside a pretty limited pH range: 5.5 to about 7.7. Iron (III) hydroxide can shape over a higher pH vary consisting of pH degrees lower than are effective for alum, typically: 5.0 to 8.5.

In literature, there is an interesting debate and a relative confusion over the utilization of the two terms, coagulation and flocculation: where does coagulation stop and flocculation take place? In plants used for water purification, a high energy is usually needed, speedy mix unit method (with a short detention time, usually in seconds) whereby the coagulant chemical compounds are delivered accompanied by basins of flocculation (detention instances vary from 15 to 45 minutes) at which large paddles or different gentle mixing low energy units to embellish the formation of floc. So, coagulation and flocculation methods continue once coagulants containing metal salt are added.

2.1.5 Sedimentation

The effectiveness of a sedimentation system depends on the suspended particles' "settling velocity," the volume/area of the tank, and the flow rate through the tank. Design sedimentation tanks are calculated within an overflow rate range between 0.5 and 1.0 gallons per minute per square foot (1.25–2.5 m per hour). Generally, sedimentation tank efficiency is not a feature of retention time or the tank depth. However, the tank should be enough to not disturb the sludge formed by water currents, and settled particle interactions are boosted. Near the sludge level on the bottom of the tank, the particle concentrations in the settled water amplify, and taking into consideration settling velocities can make bigger difference due to the accumulation of suspended particles. Typical retention time for sedimentation process diverges from 1.5 to 4 hours and tank depth varies from 10 to 15 ft. (3–4.5 m) [11].

2.1.6 Dissolved air flotation (DAF)

Dissolved air flotation is regularly employed to treat water when suspended particles do not settle down easily in the water by sedimentation. Following the coagulation and flocculation processes, the treated water is directed to the DAF system tanks. Diffusers of air on the tank's base are used to create excellent bubbles of air attached to floc causing a suspended floating mass of the required floc. The floating floc blanket is eliminated from the floor and clear water is drawn from the base of the tank of DAF. DAF system is essential for water that contains algae blooms with low turbidity and high coloration [12–15].

2.1.7 Filtration

Rapid sand filters are the most frequent types of filters used. Water flows vertically through the sand bed with "activated carbon" layer or "anthracite coal" above it. The upper layer eliminates natural components, affecting taste and odor. The gap within particles of sand is mostly bigger than the smallest particle suspended in water, making simple filtration not adequate. Majority of particles pass through the layers. However, some are trapped in the gap areas or adhere to the sand particles. Effective filtration depends on the volume of the sand filter. The filtration rate of the filter is the key for its proper operation: if the upper layer of sand filter blocks all the particles, the sand filter would rapidly clog [10, 16–18].

The cleaning mechanism of the sand filter is done where water is directed rapidly upward via filtering the opposite direction ("back flushing or backwashing") to dispose of set in or undesired particles. Preceding this step, compressed air may also be used to blow up the compacted media of filter to resource the "backwashing" process, known as air scouring. The contaminated water may be dumped, alongside the sludge produced in the sedimentation tank; alternatively, it could be recycled and mixed with the feedwater inflowing to the treatment plant, which is not regularly used because it reintroduces an expanded volume of contaminated water with bacteria into the feedwater.

Pressure filters are usually used in water treatment plants. It works on the same concept as rapid gravity filters; the main difference is that the medium of the filter is contained inside a vessel where water is enforced under pressure through the filter medium. Benefits of gravity filters are [10, 12, 16–18] as follows:

- Sieves much smaller particles than other sand filters do.

- Sieves effectively all particles larger than their specified pore sizes.

- Water flows through them quite rapidly.

- They can endure a difference of pressure across them of around 2–5 atmospheres.

- Easily cleaned "back flushed."

2.1.8 Storage

Water may be saved/stored in the backside tanks for intervals between few days and several months allowing a natural process of biological purification to occur. This is particularly vital if the treatment is done through slow filters of sand.

Storage tanks also furnish a safeguard against short periods of drought/water shortage or permit maintenance of water supply system at some point of temporary pollution incidents in the supply system.

2.1.9 Prechlorination

In many vegetations, the influent water is used to be chlorinated in order to decrease the boom of fouling organisms on the pipes and the used tanks. Because of the attainable negative first-class effects, this has largely been discontinued.

2.1.10 Other treatment methods

- **Ion exchange:** In these systems, zeolite-packed columns or ion exchange resin is employed to remove undesired ions. The widely used water softening case eliminates Ca^+ and $Mg2+$ ions with Na^+ or K^+ ions. In addition, ion exchange resins are furthermore used to hinder heavy metal such as mercury, lead, and arsenic [19–21].

- **Ultrafiltration membranes:** Polymeric or ceramic membranes with microscopic pores are employed to remove dissolved matter averting the coagulant usage. This type of pressure-driven membrane is also used to remove bacteria, viruses, end toxins, and other pathogens, as well as it removes most water turbidity [22–25].

3. Desalination technologies

There is no single technique of desalination. The earliest methods were based totally on distillation or thermal evaporation of seawater on a large scale. Some initial distillation plants have been employed for the desalination brackish water, but high cost prevented substantial implementation of this method in different regions around the world.

The foremost exclusion was few countries in the Arabic Gulf region where excess or less expensive strength is existing. Started in the 1970s, more plant life has been hooked up the use of membranes. Membrane technologies were employed to desalinate both brackish water and seawater, though they are more typically used to desalinate brackish water since cost relatively increases with the water's salt content.

Various membrane technologies can withdraw microorganisms and many natural contaminants. Also, membrane typically has lower capital costs and requires much lower energy compared to thermal systems. However, thermal desalination systems are distinguished with producing water containing decreased salt content compared to membrane (typically much less than 25 mg/l (ppm) total dissolved solids (TDS) as produced in thermal systems in contrast to around 500 ppm in water produced from membrane systems).

The different types of desalination technology include the following:

- Distillation

  ○ Multistage flash (MSF) distillation

  ○ Multiple-effect distillation (MED)

  ○ Vapor-compression (VC)

- Ion exchange

- Membrane processes

  ○ Electrodialysis (ED)

  ○ Reverse osmosis

  ○ Nanofiltration (NF)

  ○ Membrane distillation (MD)

  ○ Forward osmosis (FO)

- Others

3.1 Multistage flash distillation

Distillation is the most established desalting process where MSF technology is regularly used for seawater desalination. "Dual-purpose" (electric power and potable water production) applications are performed using thermal desalination processes, as well as thermal processes are used for applications that are not applicable to be performed by RO or electrodialysis reversal (EDR), for example, feedwater with high salinity (greater than 50,000 mg/l TDS) or where the feedwater conditions would negatively affect the performance and the membrane life. Recent developments in the MED and VC technologies have led to lower capital costs and reduced amount of auxiliary power consumed, which make these processes cost-effective to MSF distillation [26–28].

Generally, multi-stage flash distillation (MSF) and reverse osmosis (RO) desalination processes account for about 80% of the world's desalination water production capacity. In the Middle East (particularly Arabian Gulf countries), MSF units are widely used and represent over 40% of the world's desalinated water production capacity. In North Africa, MSF and RO desalination plants seize about 40% each of the desalination market (shown in **Figure 1**).
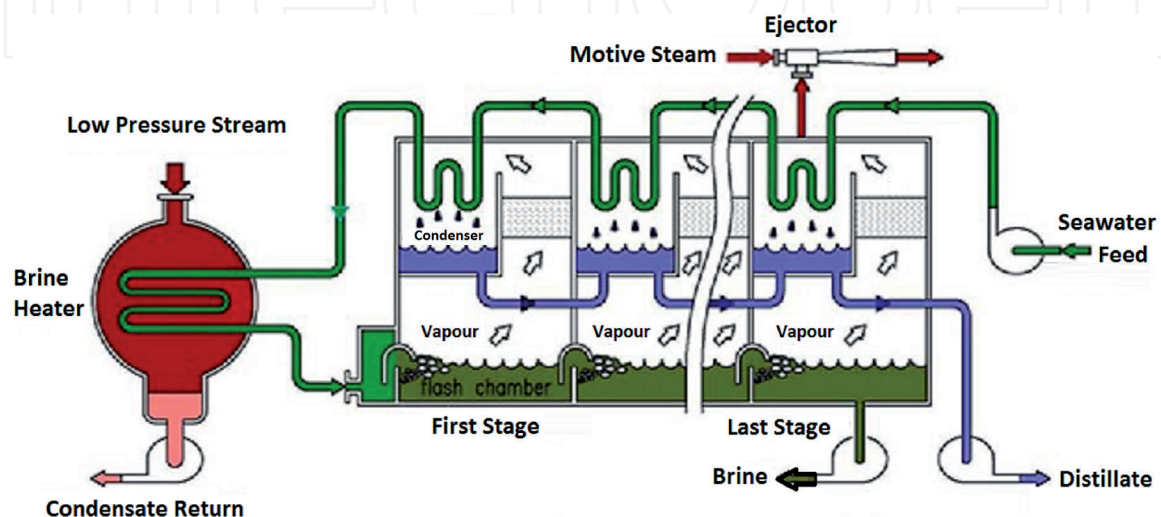

Figure 1.
MSF desalination technology.

3.2 Multiple-effect distillation

The multiple-effect distillation process can be applied in different capacities; for example, small MED plants with a capacity limit to 500 m^3/day were acquainted with the desalination topic in the 1960s. Continuous technological improvements prompt the increase in unit production capacity. The typical number of stages adopted ranges from 8 to 16 stages [28] (shown in **Figure 2**).

3.3 Vapor-compression

Vapor-compression distillation technology is commonly employed for seawater desalting plants within small to medium scale. There are two methods of VC: mechanical vapor-compression (MVC), which is usually electrically driven, or a thermal vapor-compression (TVC). Vapor-compression plants have been built in a variety of configurations [28, 29].
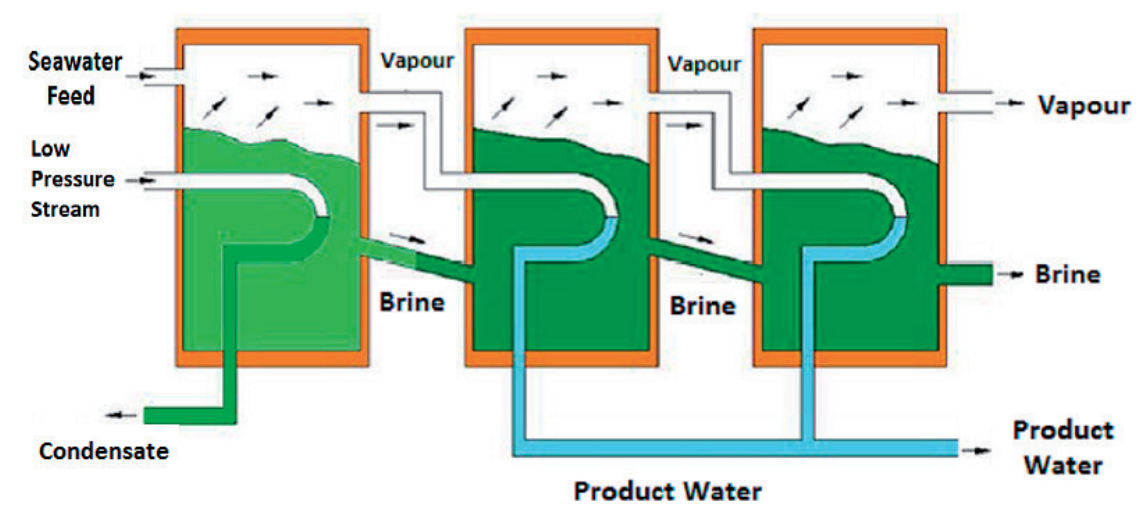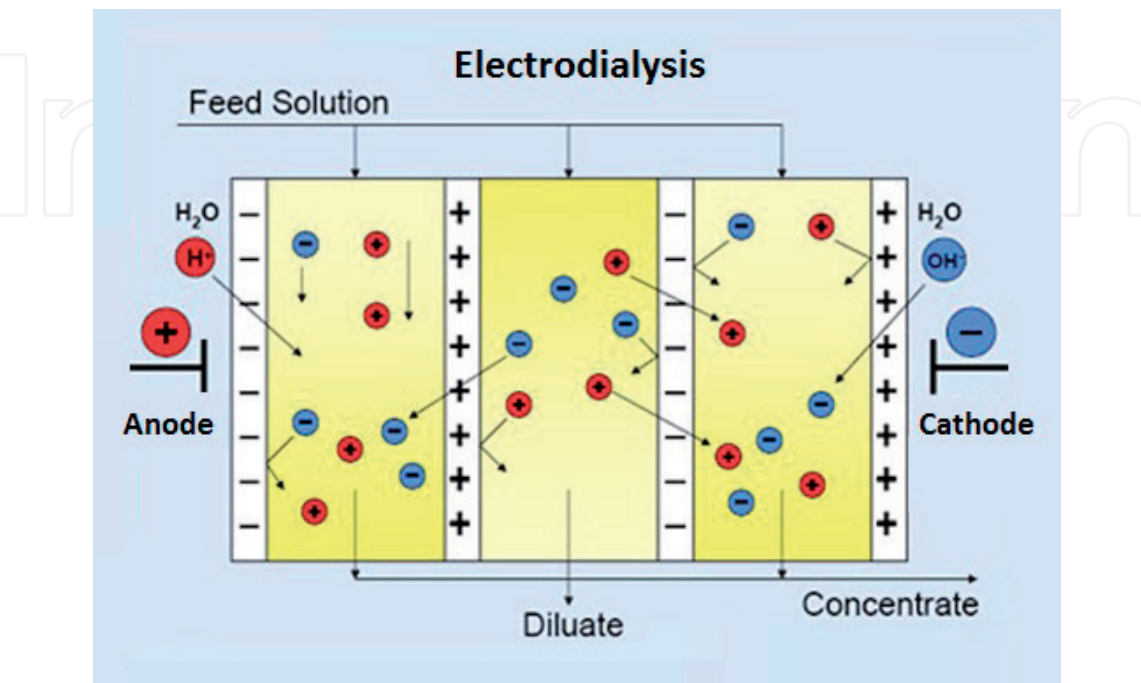

Figure 2.
MED schematic diagram.

Figure 3.
*Ion exchange in electrodialysis unit.*

3.4 Electrodialysis and electrodialysis reversal

Electrodialysis desalination process is in some way similar to "ion exchange" treatment process, but it differs in utilizing both cation and anion selective membranes to separate charged ions as shown in **Figure 3**. Improvements to ED process, an electrodialysis reversal process, were introduced where it utilizes regular automatic polarity reversal, which helps in decreasing fouling process [30–32].

Water is handed between a negative electrode and a high-quality electrode. Ion exchange membranes permit solely high-quality ions to transfer toward the negative electrode from the feedwater and negative ions to the positive electrode. Similar to ion exchange treatment process, pure water is produced by deionization. Complete elimination of ions from water is likely to occur if the proper settings are met. Normally, a reverse osmosis system is used for water pretreatment to eliminate natural contaminants, and carbon dioxide is removed with gas switch membranes. Treatment efficiency of 99% is possible if the feed stream is fed to the RO system.

3.5 Reverse osmosis

Reverse osmosis (RO) membrane is known as hyper filtration and is the supreme filtration known. Reverse osmosis allows the removal of small particles and dissolved organic matter. It is also employed to purify different fluids including glycol and ethanol, rejecting other ions and contaminants preventing them from passing through the membrane. Reverse osmosis is commonly used in water treatment. Reverse osmosis is employed to generate water that meets the required specifications needed in place [20, 22, 24].
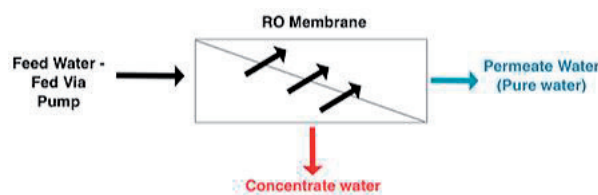
Reverse osmosis membrane is a semipermeable membrane allowing fluid that is to be purified to permit through the membrane and rejecting contaminants in the reject stream. Most reverse osmosis systems use cross flow mechanism to decrease membrane cleaning periods. As the fluid flows through the reverse osmosis membranes, the downstream, remove the reject away from in concentrated reject water (brine) [33–36].

The reverse osmosis process is a pressure-driven process to drive the fluid through the membrane using pressure pump. The pressure increases as the driving forces increase. So, the required driving force increases as the concentration of the reject stream increases.

Reverse osmosis is able to reject proteins, particles, bacteria, salts, sugars, dyes, and other contaminants that are distinguished with a molecular weight greater than the 150–250 daltons range. The reverse osmosis separation of ions is assisted by charged particles. This means that charged dissolved ions will more likely be rejected by the membrane compared to uncharged ones, like organics. The particle will be mostly rejected as the charge and the particle size increases.

When a semipermeable membrane is used to separate two water (or other solvent) volumes, water is going to flow from the low solute concentration side to the high solute concentration side. By applying an external pressure on the higher concentration side, the flow could be stopped or reversed.

In such a case, the phenomenon is called "reverse osmosis." If there are solute molecules only on one side of the system, then the pressure that stops the flow is

called the osmotic pressure. The movement of a "solute molecule" within a solvent is overdamped by the solvent molecules that surround it. In fact, the solute movement is wholly determined by fluctuations of the collisions with nearby solvent molecules. So, the average thermal velocity of the molecules is the same as if they were free in the gas phase.

The solute transfers momentum to a wall when the solute is blocked by the wall, and consequently, a pressure on the wall is generated. The pressure on the wall will be the same as the ideal gas pressure of the same molecule concentration, which is attributed to the fact that the velocity is the same as that of free molecule. Therefore, the osmotic pressure π can be calculated by Van't Hoff formula equation (1):

$$\pi = c\,R\,T \tag{1}$$

where c is the molar solute concentration, R is the gas constant, and T is the absolute temperature. This formula is the same as the pressure formula of the ideal gas.

Due to their modular design concept, RO desalination has a wide range of capacities from large capacities as 395,000 m^3/day to small units down to 0.1 m^3/day.

3.5.1 Problems faced by reverse osmosis membranes

The membrane surface fouling throughout operation reduces the membrane productivity, and if the fouling conditions continue, the salt rejection will suffer. There are three sources for membrane fouling: particles entrained in feedwater, build-up of sparingly soluble minerals, and by-products as a result of growth of microorganisms [25].

A frequent cleaning is required to handle these conditions, which is costly and leads to a shorter service life of the membrane elements. In general, the suspended solids should be eliminated from the feed to the membranes, and for the membrane plant to function well, a suitable pretreatment for the feed is needed. Sparsely soluble minerals are mainly barium and silica, and these contribute to hardness. Microorganism's growth is most pronounced within the temperature range of 30–45°C [36–38].

3.5.2 Feedwater limitations prior to the RO permeates

The following are the feedwater limitations prior to the RO membranes set by the permeate manufacturers. The pretreatment process should take into consideration the following guidelines that are shown in **Table 1**.

Feed iron, aluminum, and manganese	Not more than 0.05 mg/l
Feed bacteriological content	0
Feed chlorine or other oxidants	0
Feed SDI after filtration	<3
Feed organic content (TOC, BOD_5, COD)	0
Feed oil, hydrocarbons, grease content	0
Feed H_2S	0
Suspended solids	<1.0 mg/l
Feed barium, strontium, fluoride	Traces

Table 1.
Feedwater limitations prior to RO permeate.

3.6 Nanofiltration

Nanofiltration is accomplished using a membrane with a pore size of 0.5 and 2 nm and operating pressures between 5 and 40 bars. NF is used to treat solutions that contain organic molecules, sugars, and multivalent salts. Charged nanofiltration membrane rejects ions with negative charge, such as phosphate or sulfate. Non-charged nanofiltration membrane rejects dissolved matter and uncharged in accordance of the shape and size of the molecule, while for positively charged ions, the rejection is affected by the membrane charge and according to the membrane fouling mechanism [17, 32, 34].

Though NF membrane started at the end of the 1970s, NF membrane was used in the 1980s as a separating membrane system, mainly aiming at softening and organic removal. NF membranes have been used commonly in the 1990s. After that, the use ranges of nanofiltration membranes have expanded massively in different applications. Large plants were constructed using NF membranes, for example, the Mery-sur-Oise plant in France (140,000 m^3/day of permeate) in the 1990s.

NF membranes are produced by many membrane manufacturers. The membrane materials are mostly made of polymers like poly-ether-sulfones, aromatic poly(acrylonitrile), polyamides, and poly(phenylene oxide) as well as from different alterations of them. The enhanced permeate flux, the wider membrane pores and less retentive is the membrane.

NF membranes comprise of an active skin layer, which determines the properties of separation, and the structure that supports the porous layer, attributing to the membrane's mechanical strength. The skin layer of the membrane could be connected to the support structure integrally, such as membranes prepared via "phase inversion" (immersion precipitation) process. These membranes have distinguished pores in the nanometer range at the active surface layer. Also, the skin layer can be considered as an extra layer of coating on a tailor-made support structure. The Torell-Meyer-Sievers model (TMC) and the hybrid model assumed a dense skin layer, while the space-charge model and the Donnan-Steric Pore model (DSPM) assumed a porous skin layer. The models were applied in predicting the mechanism of rejection in NF membranes in aqueous solutions [33–35].

NF process is widely used in many industries including treatment of drinking water as well as treatment of wastewater. Operating conditions including temperature, pressure, and pH can affect the energy consumption of NF, which can be reduced by optimizing these parameters. Many researchers studied the effect of operating temperature on the neutral solutes and water transport across NF membranes. The mass transfer and pressure drop are directly affected by the operating parameters and the energy consumption as well. A comparison was done by employing NF process to process streams in the temperature range (T > 50°C) compared to NF at normal temperatures (T 25°C). The high-temperature process stream alters the separation operation attributed to the changes in the active layer of the membrane, which are temperature-dependent. Also, the temperature may affect directly or indirectly a change in viscosity, causing different effects like increased water flux, reduced pressure drop, and increased external mass transfer (lower concentration polarization) [33–35].

3.7 Membrane distillation

Membrane distillation can be defined as a procedure of water desalination membrane presently in constrained commercial use. Membrane distillation represents a hybrid process of distillation and RO using a hydrophobic synthetic membrane to allow the drift of water vapor across the membrane pores and to prevent the solution.
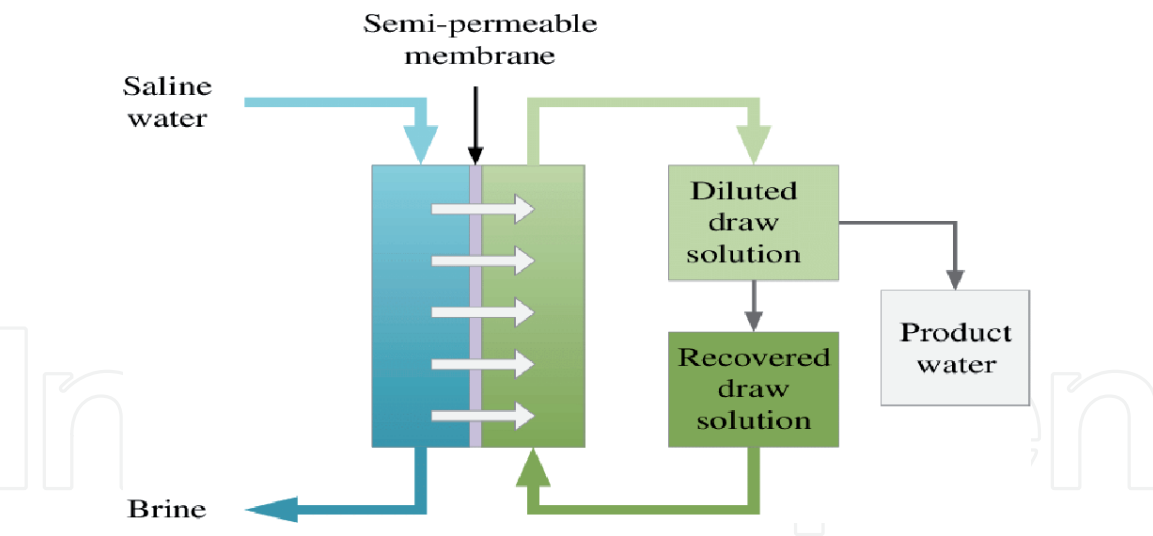
Figure 4.
Forward osmosis.

The vapor pressure difference of the liquid across the membrane is the pressure difference [39–41].

Membrane distillation utilizes the temperature difference across a membrane to vaporize water from a brine solution and condense clear condensate on the chilled side.

3.8 Forward osmosis

Forward osmosis is quite a recent commercial process used for water desalting using a gradient of salt concentration (osmotic pressure) as the driving force through the membrane. If or in case the feed (e.g., seawater) is at one side of the membrane, on the other side of the membrane, there is the higher osmotic pressure "draw" (reusable) solution. As a natural migration process, the water from the feed solution will migrate to the draw solution deprived of employing an external pressure through the membrane. Then, the diluted solution is treated to separate the draw solution from the product [22, 35], as shown in **Figure 4**.

4. Conclusion

We conclude this chapter with a definition of some water treatment and desalination processes used, and we discussed several methods for removing pollutants from water, for example, coagulation and flocculation, sedimentation, clarification, and filtration. As for removing soluble salts, we mentioned some other methods, including ion exchange, thermal processes, and membranes. And also biological issues are removed by disinfection.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

MSF	multistage flash distillation
MED	multiple-effect distillation

VC	vapor-compression
ED	electro-dialysis
RO	reverse osmosis
NF	nanofiltration
MD	membrane distillation
FO	forward osmosis
EDR	electro-dialysis reversal
TDS	total dissolved solids
MVC	mechanical vapor-compression
TVC	thermal vapor-compression
DAF	dissolved air flotation
π	osmotic pressure
c	molar solute concentration
R	gas constant
T	absolute temperature
TMC	Torell-Meyer-Sievers model
DSPM	Donnan-steric pore model

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