Desalination: A Means of Increasing Irrigation Water Sources for Sustainable Crop Production

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Abstract

Globally, water resources for agricultural production have been on the decline. This is associated with increase in water demand over limited resources and poor quality water that adversely affects crop quality and yield and deteriorates soil properties. Even though soil salinity has been affecting agriculture for thousands of years, significant research has been conducted only in the past 100 years. Desalination, which is the process of reducing the salt content in water to an acceptable level, could be an alternative for improving water quality, thereby increasing water sources and reducing the competition among various users of water. Thus, desalination could lead to improved crop quality, improved crop yield, enhanced all-year round crop production, and as such become an important tool for effective agricultural water management.

Keywords: salinity, reverse osmosis, forward osmosis, irrigation water, crop production

1. Introduction

As more than 60% of rainfall, the primary source of water for agriculture is lost to evapotranspiration [1], with the continuous increase in human population and its resultant increase in water demand which is expected to nearly double its size in the next 50 years, the exploitation of the available water resources and the advent of climate change with its global warming effect on available water for crop production, the search for new, sustainable and drought-proof water resources is inevitable [2]. He further stated that since agricultural activities consume more than 60% of the total water demand, using treated wastewater for irrigation can reduce depletion of groundwater significantly. In Refs. [1, 3], it was stated that water-scarce countries especially the Middle East countries located in the arid and semi-arid zones will have to rely more on the use of non-conventional irrigation water resources such as saline aquifers to partly alleviate water scarcity. Although, the present freshwater resources may soon be insufficient to meet the growing demand for food [4], most of these drought-proof water resources contain dissolved solids and chemicals such as salts. The application of these water resources for irrigation purposes often result to the detrimental effect of salinization of soils, environmental degradation and low crop yield.

Salinization is one of the land degradation processes rendering millions of hectares of land unproductive for crop cultivation. It was stated in Ref. [5] that salinization is one of the most serious land degradation problems facing the world. According to El-Swaify [6], salinity is when an 'excessive' amount or concentration of soluble salts occurs in the soil, either naturally or as a result of mismanaged irrigation water. Although, he further reported that salt-affected soils are most abundant in arid regions worldwide, the extent of saline soils is variable [7], whereas Yan et al. [5] stated that soil salinity vary in time and space. Salts are often introduced into soil and water systems via the use of excessive inorganic fertilizers which are leached or washed away as runoff into underground water bodies used for irrigation purposes. According to El-Swaify [6], salts in soil and irrigation water may be either naturally present as products of geochemical weathering of rocks and parent materials or derived directly from sea water flooding, spray or intrusion into groundwater sources and/or caused by irrigation mismanagement, particularly when internal soil drainage is impeded. Due to the presence of salts, most saline lands are virtually uncultivated in the dry season because of strong salinity and lack of water in good quality and quantity [7]. According to Gleick [8], almost half of the human population suffers insufficient access to portable water, and water scarcity in agriculture has been considered to be a global crisis [9].

Hence, desalination, which is any process that removes salt from water [10] to produce desalinized water, is increasingly considered a source of water for agriculture [4]. Even though soil salinity has been affecting agriculture for thousands of years, significant research has been conducted only in the past 100 years [11]. Thus, this review highlights some of the effects of salinity on soil and crop growth and yield, and some possible methods of desalinization of water and soil resources for optimum utilization in a crop production system.

2. Effects of salinity on soil and crop

Different salts, cations and anions vary in their effects on plants and soils, and as such differences in ionic compositions of soil solutions and waters with similar electrical conductivity values may lead to dissimilar effects [6]. Salinity may adversely affect soil structure and other physical properties, and this could finally be transmitted to crop growth and development. For instance, the breakdown of soil structure can exacerbate salt effects on crops through increased surface crusting, germination inhibition and reduced permeability, porosity and aeration [6]. In Ref. [12], it was reported that soil infiltration rate was greatly affected by sodicity and electrolyte concentration of the irrigation water. In Ref. [13], it was reported that increasing salinity and sodicity resulted in a progressively smaller, more stressed microbial community which was less metabolically efficient. Saline soils have been reported to contain sufficient salts at the root zone to impair crop growth [7]. Also, Corwin et al. [14] noted salinity as one of the most significant soil properties influencing cotton yield in a response model. In Ref. [15], it was reported that the emergence of sunflower and maize was affected by salinity and that the higher the salinity, the lower the leaf area and the dry matter production.

2.1. Desalination

Desalination describes a range of processes which are used to reduce the amount of dissolved solids in water [16]. Also, Nofal [17] defined desalination as the removal of excess salt and other minerals from water in order to get fresh water suitable for drinking water, animal consumption and irrigation purposes. It is used to produce clean water from water sources containing dissolved chemicals, and in most cases, water sources are salty, producing fresh water from sea water or brackish water [16]. They further stated that natural waters may be classified approximately according to their total dissolved solid (TDS) values as listed in **Table 1**. Desalination is a water saving alternative to brackish water irrigation even though its diffusion as a viable method of water treatment has been limited by high costs and concern about the lack of plant nutrients in desalinated water [17]. In Ref. [4], it was also confirmed that desalination not only separates the undesirable salts from the water but also removes ions that are essential to plant growth. Although, a recent report concludes that the costs of desalination remain prohibitively expensive for full use by irrigated agriculture [18], for high value cash crops like green-house vegetables and flowers, its use may be economically feasible [4]. According to Smith and Shaw [16], low-cost methods of desalination by distillation are also available.

2.2. Prospects of desalinized water for agriculture

Due to the impact of climate change which has led to uncertainty in the amount and duration of rainfall for crop production, 69% of global water supply is being channelled for irrigation purpose [19]. As a result, present fresh water resources may soon be insufficient to meet the growing demand for food [4]. Although, at present, sea water desalination provides 1% of the world’s drinking water, desalinized water is increasingly considered a source of water for agriculture [4]. In some countries, farmers have already adopted the use of desalinized

Type of water	Total dissolved solids (mg/L)
Sweet waters	0–1000
Brackish waters	1000–5000
Moderately saline waters	5000–10,000
Severely saline waters	10,000–30,000
Seawater	More than 30,000

Source: Smith and Shawerji [16].

Table 1. Classes of natural waters.

brackish water for crop production. For instance, Mechell and Lesikar [20] reported that ~22% of water desalinated in Spain are used for agricultural irrigation purposes, whereas an Australian survey found that 53% of the population envisioned desalinated water usage for irrigation of vegetables as highly likely.

2.3. Benefits of desalination

Desalination is a water saving alternative to brackish water irrigation [17]. By implication, it could increase the possible sources of water for irrigation, and as such enhance sustainable all-year round crop production. According to Ref. [4], the low level of salinity of desalinized water is an extra benefit, because the salts [especially Sodium (Na^+) and Chlorine (Cl^-)] damage soils, stunt plant growth and harm the environment. Hence, desalinized water could improve the quality of irrigation water thereby reducing the possibilities of the incidence of soil salinity with its consequent adverse effect on crop growth and yield via its deteriorating effects on soil properties. Furthermore, desalination could increase the size of land area for cultivation, the number of crops (including salt sensitive crops) cultivated, improve crop quality, increase crop productivity and increase the broad band of water use for other purposes [17]. Desalination has been reported to improve farmers' income [17].

2.4. Techniques in desalination

According to Refs. [10, 21], techniques used in a desalination process essentially separates saline water into two parts, hence, two streams of water are produced.

(a) Treated water that has low concentrations of salts and minerals.

(b) Concentrate or brine, which has salt and mineral concentrations higher than that of the pre-treated water.

It is often associated with electrical generation plants, from which both electricity and waste heat are available [16]. Some of these desalination methods could be relatively expensive, whereas others such as desalination by distillation could be low-cost methods. According to Refs. [10, 21], the two major types of technologies used for desalination can be broadly classified into thermal technologies (multi-stage flash distillation, multi-effect distillation and vapour compression distillation) and membrane technologies (electrodialysis/electrodialysis reversal and reverse osmosis), with reverse osmosis, and distillation followed by condensation being two main desalination methods [16]. In Ref. [10], it was stated that both technologies need energy to operate and produce fresh water. However, the most appropriate method can be selected on the basis of the total dissolved solids (TDS) value of the raw water (**Table 2**).

2.5. Thermal technologies

These technologies involve the eating of saline water and collecting the condensed vapour distillate to produce pure water [10]. In Ref. [21], it was reported that thermal distillation technologies are widely used in the Middle East, primarily because the region's petroleum reserves keep

Process	Total dissolved solid value (mg/L)
Ion exchange (not described here)	500–1000
Electrodialysis	500–3000
Reverse osmosis (standard membranes)	500–5000
Reverse osmosis (high-resistance membranes)	Over 5000
Distillation	Over 30,000
Source: Smith and Shawerji [16].	

Table 2. Suitability of desalination process based on the total dissolved solids.

energy cost low. However, thermal technologies have rarely been used for brackish water desalination, because of the high cost involved [10]. According to Refs. [6, 21], thermal technologies are grouped into three major large scale processes, i.e., multi-stage flash distillation (MSF), multi-effect distillation (MED) and vapour compression distillation (VCD). They stated that solar distillation, which is another thermal technology, is typically used for very small production rates.

2.5.1. Multi-stage flash distillation (MSF)

This process of distillation involves the use of several (multi-stage) chambers [10]. According to Ref. [21], this process sends the pre-treated saline water through multiple chambers as illustrated in **Figure 1** [22]. In the MSF process, each successive stage of the plant operates at progressively lower pressures. In Ref. [21], it was explained that the pre-treated saline water is heated and compressed to a high temperature and high pressure, and the pressure is reduced as the water progressively passes through the chambers, causing the water to rapidly boil. In other words, the pre-treated water is first heated under high pressure as it is passed into the first ‘flash chamber', where the pressure is released, causing the water to boil rapidly, resulting in sudden evaporation or ‘flashing', which continues in each successive stage, because the pressure at each stage is lower than that of the previous stage [10]. The vapour produced by the flashing is then condensed on a heat exchanger tubing that runs through each stage and collected as fresh water. Generally, only a small percentage of the pre-treated saline water is converted into vapour and condensed [10].

2.5.2. Multi-effect distillation (MED)

The MED process has been used since the late 1950s and the early 1960s [10]. According to Ref. [21], the MED employs the same principles as the MSF process except that instead of using multiple chambers of a single vessel, MED uses successive vessels (**Figure 2**), i.e., MED occurs in a series of vessels, using the principles of evaporation and condensation at reduced ambient pressure [21]. Here, water is produced by a series of evaporator vessels at progressively lower pressures. Water boils at lower temperatures as pressure decreases, such that the water vapour of the first vessel serves as the heating medium for the second, and so on [10]. According to Ref. [21], the multiple vessels make the MED process more efficient, while [10] stated that the more the vessels, the higher the performance ratio of the MED.

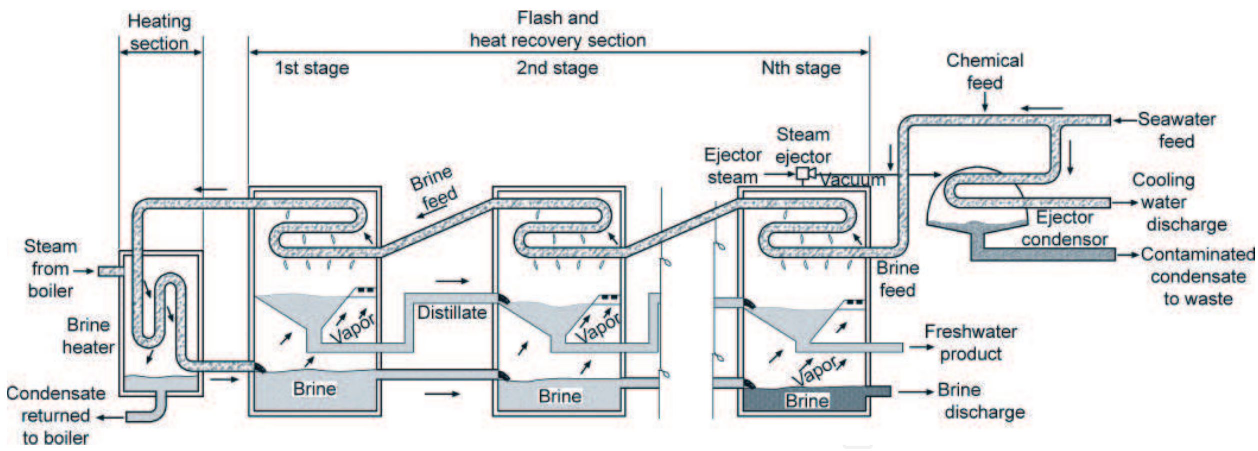

Figure 1. An illustration of the multi-stage flash distillation (MSF) process (Source: Buros, 1990).

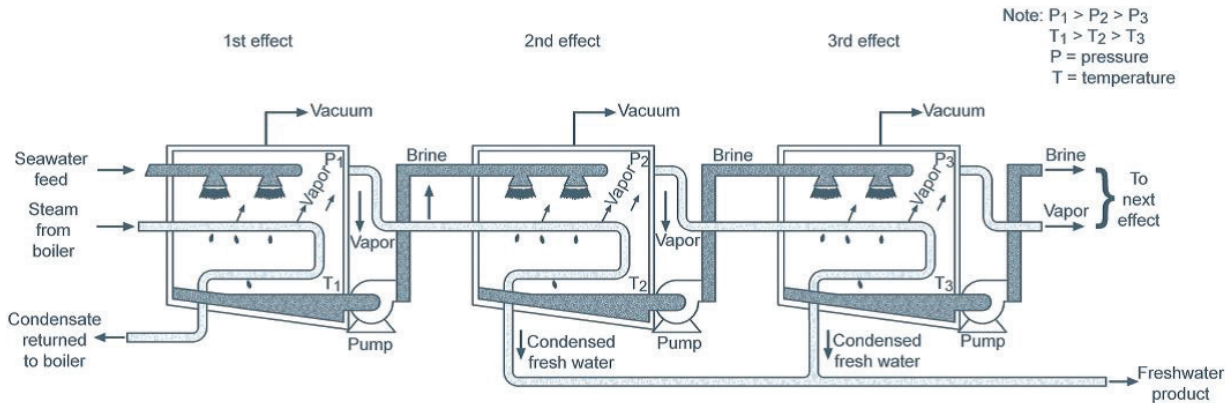

Figure 2. A schematic diagram of a multi-effect distillation (MED) process (Source: [22]).

2.5.3. Vapour compression distillation (VCD)

The VCD can function independently or in combination with other thermal distillation processes such as the MED [10, 21]. According to Ref. [23], the heat for evaporating the pretreated saline water comes from the compression of vapour, rather than the direct exchange of heat from steam produced in a boiler (**Figure 3**). It usually involves the use of a mechanical compressor to generate heat for evaporation [10]. Vapour compression distillation unit are commonly used to produce fresh water for small- to medium-scale purposes such as resorts, hotels and industrial applications [21].

2.5.4. Solar distillation

This involves the use of solar energy for water desalination as shown in **Figure 4**. Also, Buros [21] stated that although the designs of solar distillation units vary greatly, the basic principles are the same. They explained that the sun provides the energy to evaporate the saline water, and the water vapour formed from the evaporation process then condenses on a clear glass covering before it is collected as fresh water in the condensate trough. The clear glass or

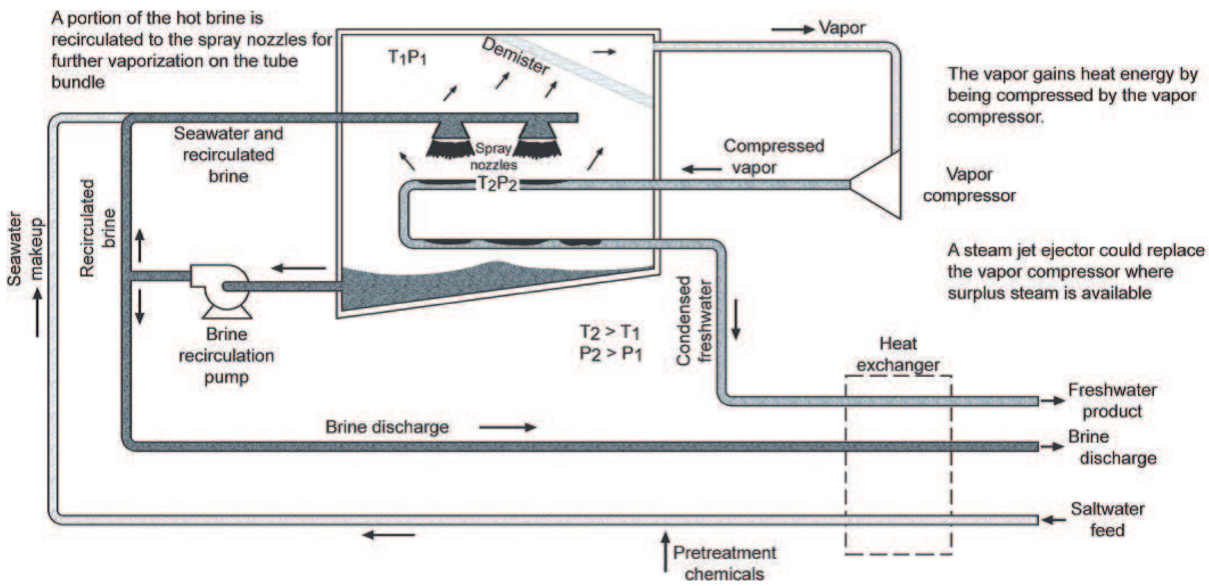

Figure 3. An example of a vapour compression distillation (VCD) process (Source: [22]).

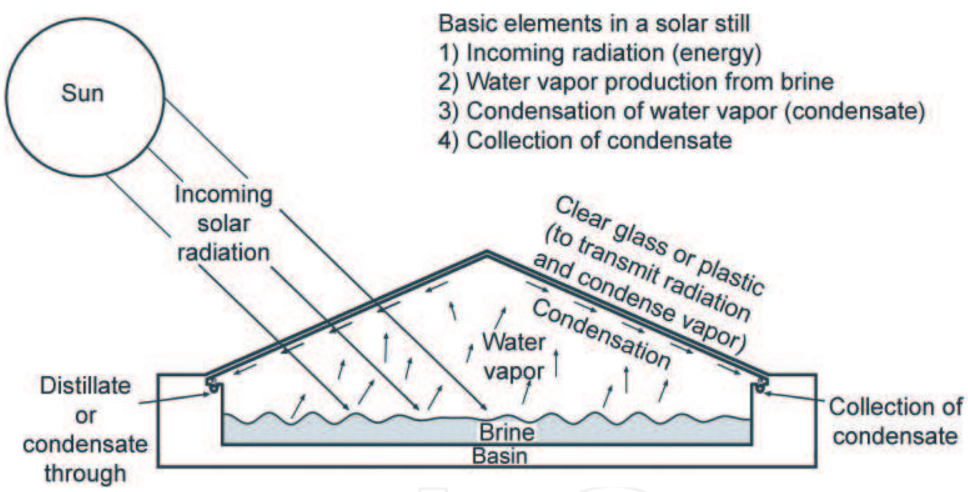

Figure 4. An example of a solar still distillation process (Source: [22]).

plastic covering is used to transmit radiant energy and also to allow water vapour to condense on its interior surface before it is collected as fresh water. Alike VCD, solar desalination is generally used for small-scale operations [21].

2.6. Membrane technologies

According to Ref. [21], there are several membrane treatment processes, including reverse osmosis, nanofiltration, ultrafiltration and microfiltration. These processes involve the use of a barrier, which is a membrane, and a driving force. The membranes contain pores which differ in sizes according to the type of process (**Figure 5**). It was explained in Ref. [21] that membrane technologies often require that the water undergo chemical and physical pre-treatment

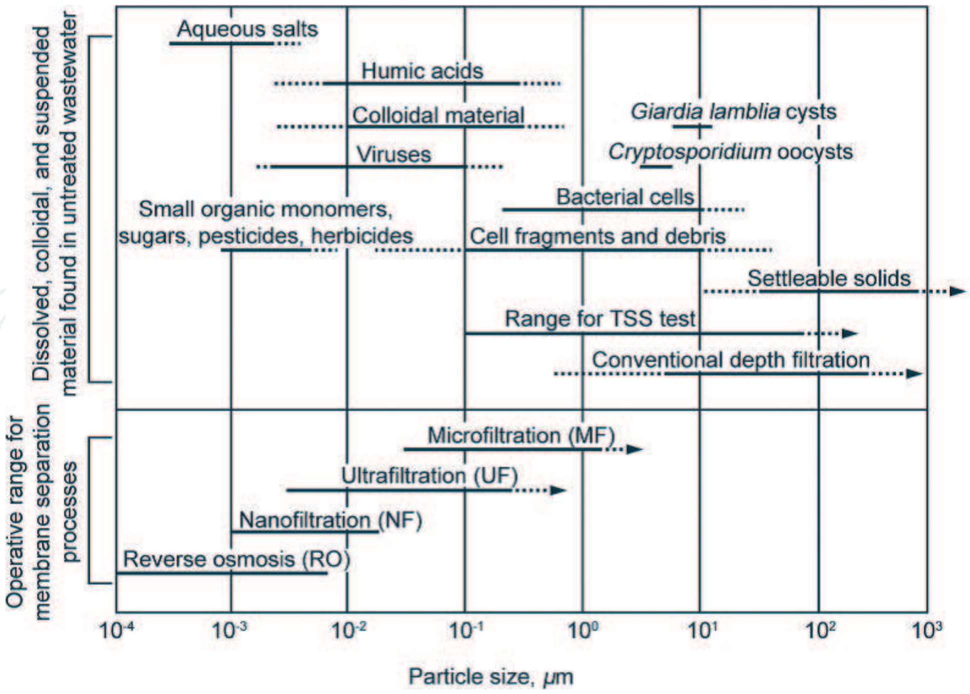

Figure 5. An illustration of the range of nominal membrane pore sizes for reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) (Source: [23]).

to limit blockage by debris and scale formation on the membrane surfaces. The general characteristics of membrane processes are presented in **Table 3**. Membrane technologies can be subdivided into two broad categories: electrodialysis/electrodialysis reversal (ed/edr) and reverse osmosis (RO) [10]. According to Ref. [21], the driving force used in electrodialysis or electrodialysis reversal is an electrical potential, whereas that used in reverse osmosis is a pressure gradient.

2.6.1. Electrodialysis and electrodialysis reversal (ED/EDR)

This is a voltage-driven membrane process in which an electrical potential is used to move salts through a membrane, leaving fresh water behind as product water [10]. In Ref. [21], it was explained that the membrane used for ED/EDR are built in such a way that they only allow passage of either positively or negatively charged ions, but not both. Here, ionic molecules, such as sodium, chloride, calcium and carbonate in saline water, that are known to cause adverse effects on soil and crop productivity are removed from the treated water as the cations are attracted to the negative electrode, whereas the anions are attracted to the positive electrode while passing through selected membranes. According to Ref. [10], the membranes are usually arranged in an alternate pattern, with anion-selective membrane followed by a cation-selective membrane. He further explained that during this process, the salt content of the water channel is diluted, while concentrated solutions are formed at the electrodes. Concentrated and diluted solutions are created in the spaces between the alternating membranes, and these spaces bound by two membranes are called cells [10]. The pre-treated saline

Membrane process	Membrane driving force	Typical separation mechanism	Operating structure (pore size)	Typical operating range (μm)	Permeate description	Typical constituents removed
Microfiltration	Hydrostatic pressure difference or vacuum in open vessels	Sieve	Macropores (>50 nm)	0.08–2.0	Water + dissolved solutes	TSS, turbidity, protozoan oocysts and cysts, some bacteria and viruses
Ultrafiltration	Hydrostatic pressure difference	Sieve	Mesopores (2–50 nm)	0.005–0.2	Water + small molecules	Macromolecules, colloids, most bacteria, some viruses, proteins
Nanofiltration	Hydrostatic pressure difference	Sieve + solution/ diffusion + exclusion	Micropores (<2 nm)	0.001–0.01	Water + very small molecules, ionic solutes	Small molecules, some hardness, viruses
Reverse osmosis	Hydrostatic pressure difference	Solution/ diffusion + exclusion	Dense (<2 nm)	0.0001–0.001	Water + very small molecules, ionic solutes	Very small molecules, colour, hardness, sulfates, nitrate, sodium, other ions
Dialysis	Concentration difference	Diffusion	Mesopores (2–50 nm)	–	Water + small molecules	Macromolecules, colloids, most bacteria, some viruses, proteins
Electrodialysis	Electromotive force	Ion exchange with selective membranes	Micropores (<2 nm)	–	Water + ionic solutes	Ionized salt ions

Source: Metcalf and Eddy [22].

Table 3. General characteristics of membrane processes.

water passes through all the cells simultaneously to provide a continuous flow of desalinated water and a steady stream of concentrate from the stack [10]. Although the ED was originally conceived as a seawater desalination process, it has generally been used for brackish water desalination [10].

According to Refs. [10, 21], the EDR functions in a similar way as the ED. However, El-Swaify [6] explained that the only exception to the EDR operating on the same general principle as the ED unit is that both the product and the concentrate channels are identical in the EDR, whereas Buros [21] also explained that the polarity or charge of the electrodes is switched periodically in the reverse process. Immediately following reversal, the product water is removed until the lines are flushed out and the desired water quality restored [10]. They explained that the reversal in flow of ions helps to remove scaling, slimes and other debris from the membranes before they accumulate in large amount, thus extending the system's operating life.

2.6.2. Reverse osmosis

In relation to thermal processes, reverse osmosis is a relatively new process that was commercialized in the 1970s [10, 24]. Currently, it is the most widely used method for desalination in the United States [10]. This process of desalination uses a pressure gradient as the driving force to move high pressure pre-treated saline water through a membrane that prevents the salt ions from passing, thus, yielding the product water stream and a concentrated brine stream as shown in **Figure 6**, respectively [10, 21]. In other words, reverse osmosis utilizes hydraulic pressure to offset osmotic pressure and induces mass transport of water across a semi-permeable membrane [25]. This is simply applying pressure (in excess of the osmotic pressure) to the saline water [16]. Osmotic pressure (π) is calculated using the Van't Hoff equation:

$$\pi = MRT \tag{1}$$

where M is the molar concentration of dissolved species; R is the ideal gas constant and T is the temperature on the Kelvin scale.

According to Ref. [10], high pressure pumps supply the pressures between the range of 150 psi for slightly brackish water to 800–1000 psi for salt water, to enable the water to pass through the membrane and have the salt rejected. It is worthy to note that the membrane is easily torn and needs to be supported carefully [16]. Due to the fact that the membrane of the reverse osmosis process consists of small pores, the salt water needs to be filtered first to remove particles which might damage the membranes, while chemical additives may be added to prevent biological growth and scaling [16, 21]. This is very important as the membrane surfaces must remain clean [10].

The individual spiral reverse osmosis membrane element through which the high pressure pre-treated saline water flows are constructed in a concentric spiral pattern that allow alternating layers of pre-treated water and brine spacing, reverse osmosis membrane and a porous product water carrier (**Figure 7**) [21]. The porous product water carrier allows the fresh water to flow into the centre of the membrane element to be collected in the product water tube. According to Ref. [10], the reverse osmosis processes are used for desalinating brackish water (TDS > 1500 mg/L) and seawater. Although membrane desalination processes using reverse osmosis or nanofiltration are diffusion-controlled membrane processes [25], also, Krishna [10]

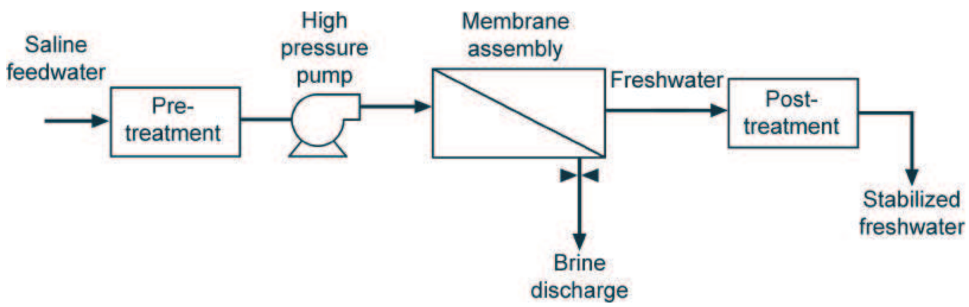

Figure 6. Basic components of a reverse osmosis membrane treatment process (Source: [21]).

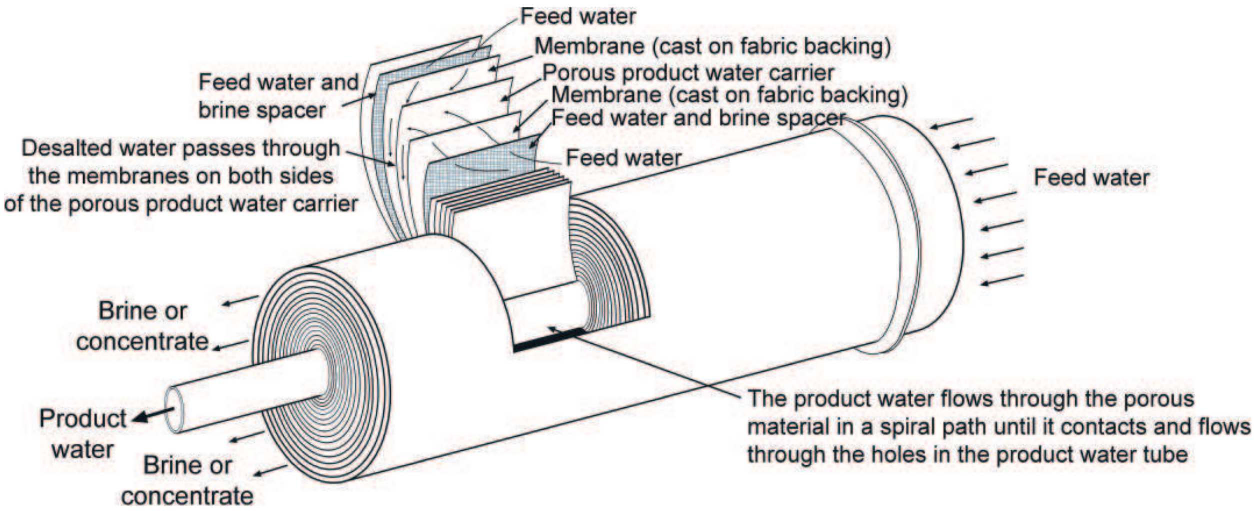

Figure 7. Dissected view of a spiral reverse osmosis membrane element (Source: [22]).

explained that unlike nanofiltration, which is a membrane process that is used for the removal of divalent salt ions such as calcium, magnesium and sulphate, reverse osmosis is used for the removal of sodium and chloride.

According to Ref. [26], following mass balance equations are commonly used to describe reverse osmosis and nanofiltration membrane process performance. Equation (2) indicates mass balance for water flow:

$$Q_f \rho_f = Q_p \rho_p + Q_c \rho_c \tag{2}$$

where Q_f is feedwater flow rate (m^3/d); ρ_f is density of feedwater; Q_p is permeate flow rate (m^3/d); ρ_p is density of permeate; Q_c is concentrate flow rate (m^3/d) and ρ_c is density of concentrate.

Equation (3) describes mass balance for solute flux:

$$Q_f C_f = Q_p C_p + Q_c C_c \tag{3}$$

where C_f is feedwater solute concentration, units of mass per volume (mg/L); C_p is permeate solute concentration, units of mass per volume (mg/L) and C_c is concentrate solute concentration, units of mass per volume (mg/L).

2.6.3. Forward osmosis

Forward osmosis is used to describe the use of osmosis as a salt-water separation mechanism through an engineered membrane. It is an emerging membrane treatment process that belongs to the class of osmotically driven membrane processes [25]. It was first presented by Cath et al. [27] and could also be called direct osmosis. Unlike reverse osmosis where pressure is applied to the pre-treated saline water and a low salinity permeate is produced, forward osmosis involves a semi-permeable membrane which separates a high osmotic pressure 'draw' solution from the pre-treated saline water with relatively lower salinity and osmotic pressure. Here, water is drawn across the membrane by natural osmosis, restricting the passage of salts at the membrane surface. In Ref. [25], it explained that when equal volumes of a dilute feed solution and a concentrated draw solution are separated by a semi-permeable membrane, water flows into the concentrated draw solution, which has a higher osmotic pressure. This flow continues until chemical equilibrium is reached. The increase in water column height in the high osmotic pressure chamber at equilibrium equates to the difference in osmotic pressure between the dilute and concentrated solutions. Thus, forward osmosis uses the osmotic pressure differential ($\Delta\pi$) across the membrane, rather than the hydraulic pressure differential as in reverse osmosis, as the driving force for transport of water through the membrane. The transport of water in forward osmosis is described in Eq. (4):

$$J_W = K_W(\sigma\Delta\pi - \Delta P) \tag{4}$$

where J_W = water flux; $\Delta\pi$ *is* differential osmotic pressure across the membrane; K_W is water permeability coefficient of the membrane; σ is reflection coefficient (a measure of the relative permeability of a particular membrane to a particular solute) and ΔP is differential applied pressure across the membrane.

Past research has shown that forward osmosis membranes are good barriers to a broad range of contaminants, including bacteria, protozoa, viruses and other dissolved organic and inorganic constituents in contaminated water [27]. Also, in comparison to other desalination processes such as the multi-stage flash, multi-effect distillation and reverse osmosis, McGinnis and Elimelech [28] estimated that the forward osmosis has relatively lowest relative energy consumption (**Figure 8**). The authors estimated that forward osmosis with a thermally decomposing draw solution [such as in the forward osmosis low temperature distillation (FO-LT) process which incorporates the use of low-quality heat for thermal decomposition of the draw solution and recovery using distillation columns] would use less than one-third the work energy of reverse osmosis for desalination.

2.7. Application of desalinated water in irrigated agriculture

According to Ref. [1], the amount of fresh groundwater or agricultural activities is negligible and exists only in some locations. He further stated that desalination of brackish and saline water seems to be promising, especially in the absence of any other alternative. In spite of this, the cost of desalinated water are still too high for full use of this resource in irrigated agriculture, with the exception of intensive horticulture or high-value cash crops, such as vegetables and flowers grown in greenhouses [29]. In Refs. [1, 29], reverse osmosis was reported to be the preferred desalination technology for agricultural uses because of the cost reductions driven by improvements in membranes in recent years. An example of countries that have adopted the application of desalinated water for irrigated agriculture is Spain. According to Ref. [30], Spain has more than 300 treatment plants with most of the plants processing brackish water, and located in coastal areas or within 60 km of the sea. It was also noted in Ref. [29] that small and medium size brackish water desalination plants, with a capacity of less than 1000 m^3/d (11.6 L/s), are common because they adapt better to individual farmer requirements and to

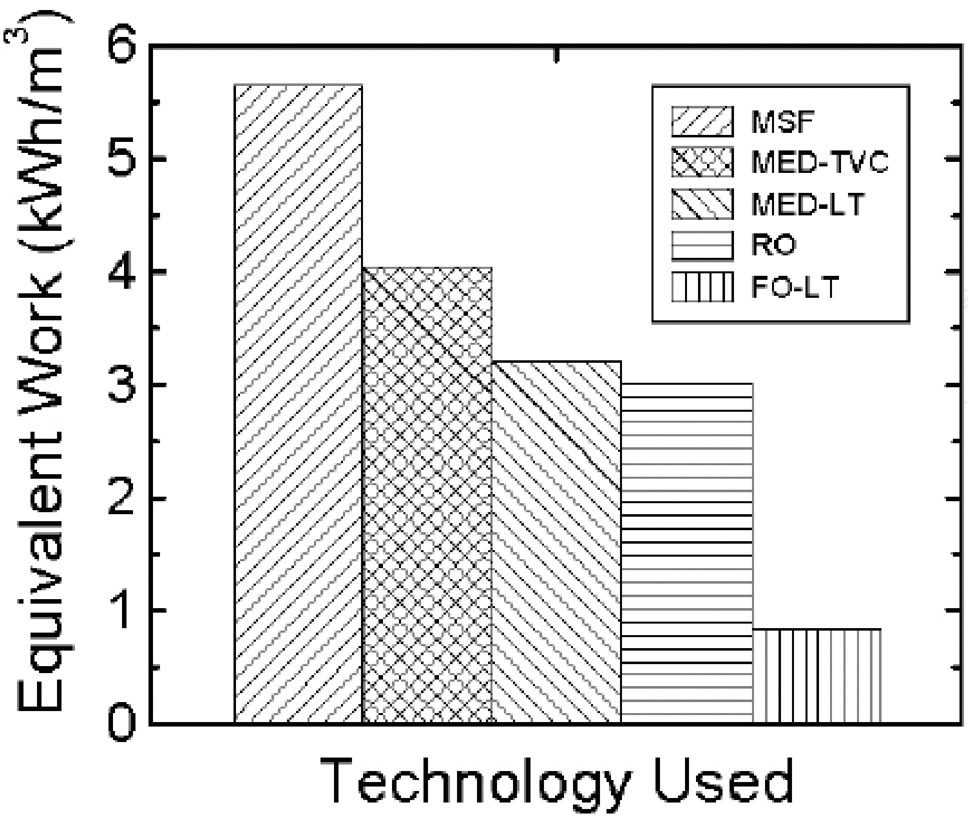

Figure 8. Estimated energy consumption for desalination processes (Source: [29]).

the existing hydraulic structures. As irrigated agriculture does not require the strict standards that apply for drinking-water requirements, opportunities appear to exist for the adoption of high-quality desalinated water, and in this way, the final cost of a cubic metre of irrigation water can be reduced [29].

3. Conclusions

Salinity arises from various natural and human-induced processes and is a major phenomenon that deteriorates soil properties, thus limiting the potentials of soils for sustainable crop production. Desalinated water is usually of high quality and can have less negative impact on soils and crops in comparison with direct use of brackish water. Thus, water desalination could have positive impacts on agriculture and the environment, such as increasing water availability and recycling poor-quality water. The use of osmotic and distillation mechanisms to recover high quality water from wastewater effluents and saline waters could be high-tech demanding especially when considering desalination of large volume of water for irrigation and other forms of utilization.

Although, the use of low-tech distillation methods could be easily adopted by peasant farmers in rural communities, the use of reverse osmosis has been said to be the most suitable for irrigated agriculture. As some of the processes involved in desalinizing saline water for sustainable crop production could be expensive, it could also be cost-effective, owing to the fact that desalination could save water for agricultural production, increase the amount and types of crops grown, the area of land cultivated and as such improve the quality of crop yield and farmers' income.

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