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# A review of draw solutes in forward osmosis process and their use in modern applications

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ABSTRACT

Forward osmosis (FO) is one of the emerging membrane technologies which has gained renewed interest recently as a low energy desalination process. The central to FO process is the draw solution (DS) and the membrane because both play a substantial role on its performance. Hence, the selection of an appropriate DS is crucial for the process efficiency. Many DS have been tested so far for a wide range of modern applications and this paper aims to review the various aspects of the DS in the process performance and provides valuable information regarding the selection criteria of suitable DS. Several general DS properties such as the osmotic pressure and the water solubility can affect the process performance. Other intrinsic properties to specific novel DS such as the emerging magnetic nanoparticles (MNPs) can also have an impact on the process efficiency and have to be evaluated. Separation and recovery of the DS are one of the major challenges facing the development of FO process. The recovery process should not be energy intensive, otherwise the FO process cannot be comparable with other pressure-driven processes. Thermolytic solutions such as ammonia carbonates are considered as the promising DS for desalination applications; however, their recovery process efficiency relies on the availability of low-grade heat. MNPs are emerging and effective DS for desalination and can be readily recovered by a magnetic field or conventional membrane processes. However, the aggregation of MNPs due to their magnetic properties has been issued. The vast numbers of studies on the use of NaCl as DS for the treatment of impaired water open up the possibilities of using seawater or reverse osmosis brine streams as suitable DS for such purpose. Fertilisers were also suggested as DS for seawater and wastewater treatment when the diluted DS can be used directly for irrigation. The development of an adequate and efficient DS coupled with a low-cost energy recovery system is crucial to the performance of the process and to achieve success for the large scale of FO.

*Keywords:* Forward osmosis; Draw solutions; Desalination; Wastewater reuse

## 1. Introduction

One of the most significant challenges of this century is in meeting the increasing freshwater demand for drinking water supplies, food production and other industrial needs to support the enormous population growth [1]. In response to this increasing water demand, intensive research on finding alternative solutions to supplement insufficient freshwater sources has been carried out, particularly in the field

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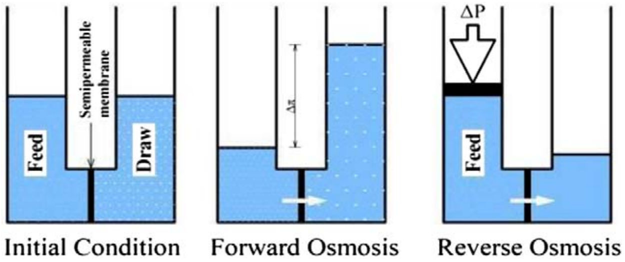

Fig. 1. The principles of osmotic processes: forward osmosis (FO) and reverse osmosis (RO).

of desalination. Reverse osmosis (RO) is currently the most commonly used desalination technologies because of its merits over other conventional thermal desalination technologies. Although the performance of RO desalination plants now consumes significantly lower energy than the RO desalination over several decades ago, the energy required for desalination still remains high due to the thermodynamic limit of the membrane desalination processes. Therefore, in order to comply with water, energy and environmental issues, a desalination technology that consumes much lower energy is essential.

Forward osmosis (FO) (also known as manipulated osmosis or engineered osmosis) is one of the emerging membrane technologies as it has the ability to desalinate seawater or brackish water at low-cost energy compared to traditional processes. The novelty of this process lies in utilising the natural osmotic process for desalination rather than the hydraulic pressure as in RO. Fig. 1 explains the fundamentals of osmotic processes.

When saline feed water and the highly concentrated solute termed as the draw solution (DS) (other usual terms are osmotic agent, draw agent, etc., but DS is to be used in this review) are separated by a semi-permeable membrane, water moves from the saline water (lower solute concentration) to the concentrated DS (higher solute concentration) due to osmotic gradient, while retaining the solutes on both sides of the membrane. Hence, the driving force in FO process is created naturally by the difference in osmotic gradient between the feed stream and the DS, and this process offers many advantages such as lower energy cost and significantly lower membrane fouling potential [2]. Therefore, there has been a growing interest in studying the FO process, particularly for desalination applications.

Although there are currently some commercial applications of FO [3–7], there are still a number of challenges that need to be overcome in order to achieve an effective large-scale stand-alone FO process. One of these key challenges is in developing a suitable DS that can generate a high osmotic pressure to produce high water flux while being easy to reconcentrate and recover at lower energy cost. The selection and/or development of suitable DS are therefore one of the big challenges to achieve the commercialisation of FO process, especially for desalination for drinking water production.

Even if the number of research publications on FO has recently increased, more efforts have been focused on the development of new membranes and process performance, but little on the improvement of DS. However, the performance of the FO process greatly depends on the selection of an appropriate DS. Hence, the aims of the current study are to review the various aspects of DS in the performance of the FO process for modern applications such as desalination, wastewater treatment or energy production. This study also intends to provide valuable information to readers for the selection of suitable DS. The review begins with a discussion on DS characteristics that directly influence the process performance. Then, a classification of different types of DS used so far in this process is described and a review on DS separation and recovery processes is proposed. Finally, the use of DS in various modern applications is reviewed and criteria for the selection of suitable DS are proposed.

## 2. DS characteristics affecting FO process performance

There are several factors that can influence the performance of the FO process and these factors are, in general, related to the DS characteristics, FO membrane properties and operating conditions. Although only the DS characteristics that influence the process performance are discussed in this section, it is important to note that membrane properties influence the performance of some DS and therefore it is also important to consider how these membrane properties also affect the process performance.

All the general DS characteristics and their impacts on the process performance are listed and summarised in Table 1, but more details are provided on the next section.

### *2.1. Assessment of the performance of FO process*

Before discussing the factors influencing the performance of the FO process, it is important to understand the methods of assessing this performance. Water flux is one of the primary methods used for evaluating any membrane process performance. In

Table 1
General DS characteristics affecting FO process performance and their impact on the process performance

| DS characteristics | Impact on FO process performance |
|---|---|
| Osmotic pressure | A high DS osmotic pressure and low feed solution osmotic pressure induce high water fluxes across the membrane |
| Water solubility | High solubility induces high osmotic pressure and therefore can achieve high water flux and high recovery rates |
| Viscosity/ diffusivity | A low viscosity combined with high diffusivity leads to high water fluxes |
| Molecular weight (MW) | Small MW solutes produce higher osmotic pressure than larger MW for equal mass of DS but induce higher reverse draw solute flux than larger MW DS |
| Concentration | Water flux increases at higher DS concentration but the increase is non-linear. At higher DS concentration, dilutive CP drastically increases resulting in less effective water flux improvement |
| Temperature | Higher temperature would not only afford higher initial fluxes and higher water recoveries but also induce more adverse effects on membrane scaling and cleaning |
| Other characteristics | In addition, specific characteristics of a particular draw solute may also influence the FO process performance. For example, a new class of DS can display unique properties. Such properties can be particle sizes or particle agglomeration due to special magnetic properties when using magnetic nanoparticles (MNPs). Some DS can also act as precursor to scaling and membrane fouling during reverse diffusion when DS containing $SO_4^{2+}$ and $Mg^{2+}$ are used, respectively |

fact, in any pressure-based membrane process, pure water permeability is one of the basic parameters useful for assessing membrane performance. Similarly, the performance of FO process, whether it is specifically for assessing the performance of DS or the performance of the membranes, is all assessed in terms of pure water flux. The latter provides an easy way of comparing the performance of FO process under different situations.

Reverse draw solute flux is also an important parameter that has to be assessed when evaluating the performance of FO process. In fact, several studies [8,9] have demonstrated that this phenomenon can jeopardise the process. Reverse salt diffusion can decrease the net osmotic pressure across the membrane which results in flux decline. Moreover, reverse salt transport is not only an economical loss, but can also complicate concentrate management. In fact, accumulation of DS solutes in the feed solution may induce toxicological challenges for sensitive receiving environment or affect adjacent treatment processes [8] if contaminants such as nitrate, phosphate or heavy metals present in the feed concentrate. Models to describe reverse draw solute transport through semi-permeable membrane in FO process have been extensively discussed in other studies [8,10]. Phillip et al. [11] showed that the reverse flux selectivity—the ratio of the forward water flux to the reverse solute flux—is a key parameter in the design of the pressure-driven membrane processes. The reverse salt transport of a solute can be monitored continuously by electrical conductivity when pure water is used as feed solution during FO performance tests.

Finally, FO process performance can also be evaluated by determining the process recovery rates. For some specific application (e.g. desalination), other parameters (e.g. salt rejection) can also be measured for assessing the process performance.

### *2.2. DS properties affecting FO process performance*

The performance of FO process greatly depends on the selection of suitable DS as it is the main source of the driving force in this process. The primary characteristics essential for any DS are high solubility in water and high osmotic pressure, much higher than the feed solution.

The osmotic pressure ($\pi$) of the ideal dilute solution is defined based on the theory proposed by Van't Hoff [12] as shown below.

$$\pi = n\left(\frac{c}{\mathrm{MW}}\right)RT \tag{1}$$

where $n$ is the number of moles of species formed by the dissociation of solutes in the solution, $c$ is the solute concentration in g/L of solution, MW is the molecular weight of the solute, $R$ is the gas constant ($R = 0.0821$) and $T$ is the absolute temperature of the solution. However, this equation is limited to extremely dilute solutions and is generally used for the determination of large MW [13]. For general solutions, the osmotic pressure can be given by the concentration dependence osmotic equation [14], also known as virial equation, as shown below.

$$\pi/cRT = 1 + Bc + Cc^2 + Dc^3 + \cdots \tag{2}$$

where $B$, $C$ and $D$ are the osmotic virial coefficients that can be determined empirically by fitting experimental osmotic pressure data, and generally the determination of $B$ and $C$ is sufficient to reproduce observed data [13].

From the above equations, it is clear that, the osmotic pressure is a function of solute concentration, number of species formed by dissociation in the solution, MW of the solute and the temperature of the solution and therefore does not depend on the types of species formed in the solution. A solute with small MW combined with high water solubility can generate higher osmotic pressure (on equal mass basis) and therefore can lead to higher water fluxes [15].

Besides osmotic pressure, the performance of FO process is however affected by other properties of the DS such as the diffusion coefficient [12] as shown in the following equation.

$$K = \frac{t\tau}{\varepsilon D_s} \tag{3}$$

where $K$ represents the solute resistance to diffusion within the membrane support layer, $t$, $\tau$ and  represent the thickness, tortuosity and porosity of the membrane porous support layer, respectively, and $D_s$ represents the diffusion coefficient of the solute. The value of $K$ is an inverse function of the $D_s$. indicating that solutes with higher diffusion coefficient will have lower resistance and can more readily diffuse through the membrane support layer and therefore have lower ICP effects. Solutes with lower MW usually have higher diffusion coefficient compared to those with larger MW; however, many studies have demonstrated that DS with very small MW showed higher reverse salt diffusion [16–20] which could potentially have an adverse impact on the FO performance, especially when high-quality product water is required. Solutes of higher MW have lower diffusion coefficient and therefore tend to cause more severe ICP effects.

The DS concentration also significantly influences the performance of the process. Most studies have shown that higher water fluxes can be achieved by increasing the DS concentration [21–24]. However, contrary to the theoretical solution-diffusion model, which establishes a linear relation between water fluxes and DS concentration, experiments have shown that this relation is non-linear. Linear relation is observed at lower concentrations, but at higher DS concentration, a logarithmic relationship has been visually observed. This is mainly attributed to ICP effects in the porous support layer which is greater at higher permeate flux resulting in less effective water flux improvement. Tan and Ng [25] have even demonstrated that the very high increasing DS concentration could potentially reduce the water flux to a value which is too low for efficient permeate production.

Finally, similar to pressure-based membrane process, FO process is also affected by DS temperature because the properties of DS and feed solution such as osmotic pressure, viscosity and diffusivity are affected by temperature. Water fluxes in FO process improved significantly at higher DS temperature as observed by most studies [24,26–28]. These studies attributed this enhanced water flux due to reduced water viscosity and therefore enhanced mass transfer. Besides viscosity, the diffusion coefficient of the DS also increases at higher temperature which consequently decreases the value of $K$ (solute resistance to diffusion within the membrane support layer, refer Eq. (2)) and therefore increases the water flux [24,27]. However, this relation between temperature and water flux is more complex as some recent studies have demonstrated that higher temperature will also induce more adverse effects on membrane scaling in the presence of certain scaling species, which may result in water flux decline. In fact, Garcia-Castello et al. [26] and Zhao and Zou [28] observed that, at higher temperature, more compact crystals are deposited onto the membrane surface which reduces the efficiency of water cleaning. Hence temperature can enhance water flux to a certain critical point when membrane scaling starts to affect process performance by causing flux decline.

Despite the general characteristics mentioned before, other specific DS characteristics can impact on the process performance, depending on the application. One good example can be the presence of scale precursor ions. In fact, Achilli et al. [18] demonstrated that when using DS containing scale precursor ions (e.g. $Mg^{2+}$, $Ca^{2+}$, $Ba^{2+}$, $SO_4^{2-}$ and $CO_3^{2-}$), mineral scaling will likely occur on the membrane surface when the feed solution concentration is above the solubility limit. Hence, the use of DS which are likely to cause scaling (e.g. $CaCl_2$, $MgSO_4$, $KHCO_3$, $NaHCO_3$ and $Na_2SO_4$) is strictly limited to application involving the use of pure feed solution such as the food industry, otherwise it can have potential adverse effects on the process performance.

Recent studies on new classes of DS such as MNPs or micelles showed that these novel DS feature unique properties that may also impact on the process efficiency. For instance, due to their magnetic properties, MNPs have a tendency to agglomerate and this phenomenon has to be avoided (using surface coating for instance) as it could cause membrane fouling and therefore decrease the process performance by lowering the water flux.

## 3. Classification of osmotic DS

A wide range of DS have been proposed and tested since the mid-1960s. They can be generally classified as inorganic-based DS, organic-based DS and other compounds including emerging DS such as MNPs or RO brines. The sub-classification would include such as electrolyte (ionic) solutions and non-electrolyte (non-ionic) solutions depending on whether the solution is made up of charged ions or neutral/non-charged solutes, respectively.

### *3.1. Inorganic-based DS*

The majority of FO studies have investigated inorganic-based compounds as DS, and they are still extensively utilised nowadays. Inorganic-based DS is mainly composed of electrolyte solutions although non-electrolyte solutions could also be possible.

The most recent and comprehensive studies of inorganic DS are made by Phuntsho et al. [17], Achilli et al. [18] and Tan and Ng [25]. Achilli and co-workers tested and compared 14 inorganic-based compounds as DS for FO process. These solutes were chosen from among more than 500 inorganic compounds because of their higher water solubility, osmotic pressure, lower specific cost and toxicity, which are crucial criteria that can impact greatly on FO performance and their end use. Tan and Ng [25] proposed a novel hybrid concept by combining FO and nanofiltration (NF) for seawater desalination; seven potential DS were tested at laboratory scale, including six inorganic-based compounds. Finally, Phuntsho et al. [17] evaluated the performance of nine commonly used inorganic fertilisers as possible DS candidates for fertigation. The selected DS exhibit different physical and chemical properties as displayed in Table 2. This table also includes the experimental water flux data for comparison.

Numerous studies have used sodium chloride as DS in a wide range of applications. For instance, it has been applied in food production [26,27] and water

Table 2
Physicochemical properties and experimental water fluxes of inorganic compounds tested as DS

| DS tested | MW | Osmotic pressure[a] at 2.0 M (atm) | pH[a] at 2.0 M | Max. solubility[a] (M) | Scale precursor ions | Experimental water flux[b] (μm/s) | References |
|---|---|---|---|---|---|---|---|
| $CaCl_2$ | 111.00 | 217.60 | 6.29 | 7.4 | Yes ($Ca^{2+}$) | 2.64 | [18,25] |
| KBr | 119.00 | 89.70 | 6.92 | 4.5 | No | 2.84 | [18] |
| $KHCO_3$ | 100.10 | 79.30 | 7.84 | 2.0 | Yes ($CO_3^{2-}$) | 2.25 | [18] |
| $K_2SO_4$ | 174.20 | 32.40 | 7.33 | 0.6 | Yes ($SO_4^{2-}$) | 2.52 | [18] |
| $MgCl_2$ | 95.20 | 256.50 | 5.64 | 4.9 | Yes ($Mg^{2+}$) | 2.33 | [18,25] |
| $MgSO_4$ | 120.40 | 54.80 | 6.70 | 2.8 | Yes ($Mg^{2+}$) | 1.54 | [18,25] |
| NaCl | 58.40 | 100.40 | 6.98 | 5.4 | No | 2.68 | [18,25] |
| $NaHCO_3$ | 84.00 | 46.70 | 7.74 | 1.2 | Yes ($CO_3^{2-}$) | 2.47 | [18] |
| $Na_2SO_4$ | 142.00 | 95.20 | 7.44 | 1.8 | Yes ($SO_4^{2-}$) | 2.14 | [18,25] |
| $NH_4HCO_3$ | 79.10 | 66.40 | 7.69 | 2.9 | Yes ($CO_3^{2-}$) | 2.04 | [18] |
| $NH_4NO_3$ | 80.04 | 64.90 | 4.87 | 84.0 | Yes ($CO_3^{2-}$) | 4.177 | [17] |
| $(NH_4)_2SO_4$ | 132.10 | 92.10 | 5.46 | 5.7 | Yes ($SO_4^{2-}$) | 5.391 | [17,18] |
| $NH_4Cl$ | 53.50 | 87.70 | 4.76 | 7.4 | No | 5.348 | [17,18] |
| $Ca(NO_3)_2$ | 164.10 | 108.50 | 4.68 | 7.9 | Yes ($Ca^{2+}$) | 5.022 | [17,18] |
| $NaNO_3$ | 85.00 | 81.10 | 5.98 | 10.5 | No | 5.706 | [17] |
| KCl | 74.60 | 89.30 | 6.80 | 4.6 | No | 6.337 | [17,18,25] |
| $NH_4H_2PO_4$ | 115.00 | 86.30 | 3.93 | 3.7 | No | 4.349 | [17] |
| $(NH_4)_2HPO_4$ | 132.10 | 95.00 | 8.12 | 6.5 | No | 3.892 | [17] |
| $KNO_3$ | 101.10 | 64.90 | 5.99 | 3.3 | No | 4.429 | [17] |

[a] Osmotic pressure, pH and solubility data were calculated by OLI Stream Analyzer.
[b] Experimental water fluxes were taken from [14] for the first ten DS for an osmotic pressure of 2.8 MPa, and the other experimental fluxes were taken from [13] at 2.0 M concentration of DS.

and wastewater treatment [23,29–31]. The fact that NaCl is used as DS for many FO studies is mainly because saline water is abundant on earth making seawater a natural and cheap source of DS. NaCl is also often utilised, because it is relatively straightforward to reconcentrate with RO process without the risk of scaling and it has high water solubility and exhibits high osmotic pressure. Moreover, the thermodynamic properties of NaCl have been widely investigated making it easier for the study.

The other inorganic DS which are commonly studied include magnesium chloride [32,33] ammonium bicarbonate mainly as a thermolyte solution that can be recovered and reused [8,15,16,24] and calcium chloride [18,25,27,34]. Specific application of each of these DS is discussed in details in a later part of the review.

### 3.2. Organic-based DS

Over the past decades, organic compounds particularly fructose and glucose solutions have been tested as DS, especially for seawater desalination [16,35–37] and food production [27,38–40] applications. Although organic DS are usually non-electrolyte compounds, they have the potential to generate high osmotic pressure as they generally exhibit high solubility [16] as it is depicted in Table 3.

Other organic DS include polyethylene glycol 400 (PEG) to concentrate tomato juice [27], ethanol for the recovery of water from highly impaired sources [41], albumin for dewatering RO concentrate [42] and 2-methylimidazole-based compounds [19].

### 3.3. Other DS

#### 3.3.1. Magnetic nanoparticles as DS

Nanoparticle research is currently an area of intense scientific interest due to a wide variety of biomedical applications such as biocatalysis and drug delivery. However, some recent studies [43–45] have focused their works on hydrophilic magnetic nanoparticles (MNPs). Three different types of MNPs were investigated as potential DS: the polyacrylic acid magnetic nanoparticles (PAA MNPs), the 2-Pyrrolidone-magnetic nanoparticles (2-Pyrol MNPs) and the triethyleneglycol magnetic nanoparticles (TREG MNPs). Although they are non-electrolytes, the main advantage of MNPs is their extremely high surface-area-to-volume ratio and their bigger sizes compared to inorganic salts and organic molecules that facilitate recovery using magnetic fields and low pressure membrane processes such as microfiltration or NF. Moreover, they are capable of producing very high osmotic pressure, up to 70 atm (for PAA MNPs), which is far higher than the seawater osmotic pressure of 26 atm, which make them very attractive for desalination [44].

#### 3.3.2. Concentrated RO brines as DS

The disposal of concentrated brines from a RO desalination plant is a significant environmental issue. RO concentrate is made up of waste flow with highly concentrated organic and inorganic compounds [46]. Hence, there is a need to sustainably manage the RO concentrate in order to avoid any adverse effects on the receiving environment. Recent studies have focused on the potential use of RO brines as DS to solve concentrate issues. Ling and Chung [43] designed a novel dual-stage FO process where MNPs were used as DS in an up-stage FO process to concentrate proteins and RO brine was used as DS in a down-stage FO process to reconcentrate MNPs. Bamaga et al. [47] designed a hybrid FO/RO process where the first FO process is used as a pre-treatment for RO desalination to minimise scaling risk during the desalination process. The second FO process, using the RO brine as DS, is utilised to concentrate the impaired water to minimise its volume for further treatments. Hence, in this application, the FO process

Table 3
Physico-chemical properties and experimental water fluxes of some organic compounds tested as DS

| DS tested | MW | Osmotic pressure[a] at 2.0 M (atm) | pH[a] at 2.0 M | Max. solubility[a] (M) | Experimental water flux[b] | References |
|---|---|---|---|---|---|---|
| Ethanol | 46.07 | 43.93 | 7.00 | Miscible | Not available | [41] |
| Sucrose | 342.30 | 56.81 | 6.18 | 6.1 | 0.35 LMH | [27] |
| Glucose | 180.16 | 55.03 | 7.01 | 800.0 | 0.24 LMH | [16,27,35] |
| Fructose | 180.16 | 55.02 | 7.01 | 22.4 | 7.5 LMH | [16,37,42] |

Note: MW, molecular weight; LMH, $L\,m^{-2}\,h^{-1}$.

[a] Osmotic pressure, pH and solubility data were calculated by OLI Stream Analyzer.

[b] Experimental fluxes were taken from [3] for fructose at 6 M fructose concentration and from [19] for sucrose and glucose at 58.29% (w/w) and 62.86% (w/w), respectively.

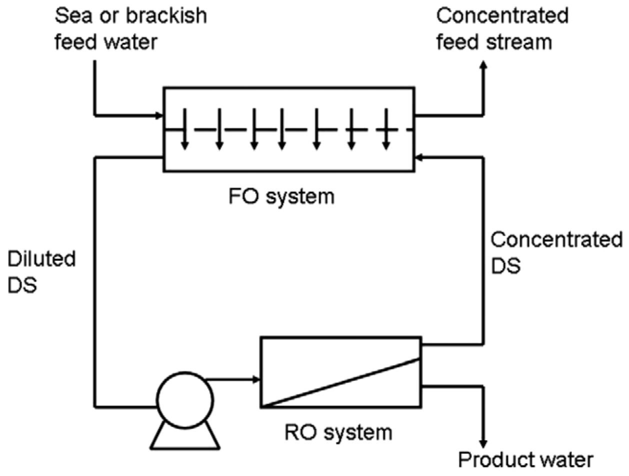

Fig. 2. Simplified FO/RO desalination process using RO brines as DS.

combining with RO brines as DS is used to lower energy requirement for desalination. Moreover, there are several benefits when coupling both FO and RO processes. In fact, the RO process was proved to be an efficient reconcentration and recovery process which is able to produce very high-quality product water. Using this concept of coupling RO and FO processes (Fig. 2), Modern Water [5] successfully designed and deployed the first commercial FO desalination plant with a capacity of $100\,m^3/d$ of produced water in Oman on the Arabian Sea.

### *3.3.4. Ionic polymer hydrogel particles as DS*

Li et al. [48] recently studied the development of a new class of DS, the polymer hydrogel particles for FO desalination. Hydrogels are three-dimensional networks of polymer chains that are linked by either physical or chemical bonds and are able to catch large volumes of water attracted by the highly concentrated hydrophilic groups. Their sizes generally range between 50 and 150 μm. Hydrogels with ionic groups are able to attract even more amount of water which increases their osmotic pressures and make them attractive for desalination applications. One important and advantageous aspect of polymer hydrogels is that they can undergo reversible volume change or solution–gel phase transitions in response to environmental stimuli including temperature, light, pressure or even pH. One particular interesting response to these stimuli is the change from hydrophilic to hydrophobic (generated by heating or pressure stimuli), which induces hydrogel particles to release water. This unique characteristic makes also the recovery of this novel DS very easy and at lower energy cost (compared to thermal or membrane processes). In a more recent study [49], they demonstrated that combining the polymer hydrogel particles with light-absorbing carbon particles enhances heating and dewatering of the particles. In both studies, the polymer hydrogel particles were able to deliver high osmotic pressure of about 2.7 MPa at 27 °C. Water fluxes ranged from 0.55 LMH to 1.1 LMH depending on the polymer used.

### *3.3.5. Micelles close to the Krafft point as DS*

Gadêlha and Hankins [50] introduced the concept of using colloidal systems such as micellar solutions as DS. This new potential DS presents interesting characteristics; it exhibits almost constant osmotic pressure above the critical micelle concentration which allows many dilutions prior to regeneration. Moreover, its solubility is highly temperature sensitive around the Krafft point, which is the critical minimum temperature under which micelles cannot form. This property of micellar solutions enables regeneration with small temperature fluctuations using for instance low-grade heating and cooling. The surfactant is then in crystalline form and can be readily separated from the product water. Another benefit of micelles is that they can act as monomeric concentration buffers which minimise the internal concentration polarisation (ICP) effects.

### *3.3.6. Dendrimers as DS*

Adham et al. [42] proposed the use of dendrimers as a novel DS for dewatering RO concentrate. Dendrimers are symmetrical spheroid or globular nanostructures that are precisely engineered to carry molecules. These macromolecules consist of a highly branched tree-like structure linked to a central core through covalent bonds. Because they are macromolecules, they can provide a high osmotic pressure up to 330 psi, much higher than RO concentrate. Moreover, they can be readily regenerated by conventional membrane processes such as UF. In this study, two types of dendrimers were tested: ethylenediaminecore dendrimers with sodium succinamate terminal groups and pentaerythrityl core dendrimer with sodium carboxylate terminal groups.

## 4. Reconcentration and recovery processes for DS

Separation of the DS after it has been diluted for recovery, regeneration and recycling is one of the biggest challenges facing the FO process, especially for

Table 4
Summary of tested DS and regeneration methods for FO process. Modified from Gadêlha and Hankins [50]

| DS tested | Reconcentration and regeneration methods | References |
|---|---|---|
| Volatile solutes ($SO_2$) | Heating or air stripping | [51] |
| Alcohol, $SO_2$ | Distillation | [58] |
| $Al_2SO_4$ | Doped $Ca(OH)_2$ to precipitate $CaSO_4$ and $Al(OH)_2$ | [59] |
| Glucose | Direct application | [35] |
| Glucose and fructose | Direct application | [36] |
| Fructose | Direct application | [37] |
| Glucose/fructose | RO process | [60] |
| $MgCl_2$ | Direct application | [10] |
| | NF process | [25,32] |
| $KNO_3$ and $SO_2$ | $SO_2$ is removed through standard means | [61] |
| $NH_4HCO_3$ | Heating—decomposition into $NH_3$ and $CO_2$ | [24] |
| MNPs | Magnetic field separators | [42,45] |
| | FO process using RO brines as DS | [43] |
| | UF process | [44] |
| Albumin | Denatured and solidified upon heating | [42] |
| Dendrimers | Wide range of pH values and UF | [42] |
| 2-methylimidazole-based compounds | FO-MD | [19] |
| NaCl | RO process | [31] |
| | Distillation/RO process | [53] |
| | Direct application | [57] |
| $MgSO_4$ and $Na_2SO_4$ | NF process | [25] |
| Micelles close to the Krafft point | Temperature swing with low-grade heat and crystallisation | [50] |
| RO brines | RO process | [5] |
| Ionic polymer hydrogel particles | Direct application | [47] |
| | Heating or pressure stimuli | [49] |
| Fertilisers | Direct application | [17] |

drinking water production when high-quality water is required. In order for FO process to compete with other membrane processes, the DS reconcentration and recovery should operate at low-cost energy. This process should also provide high recovery of the DS while producing high-quality product water. Therefore, attention is now given to find easy and efficient reconcentration and recovery processes for selected DS.

Table 4 summarises some tested DS and their proposed reconcentration and recovery methods. Since the mid-1960s, attempts have been made to find a DS that can be easily separated, recovered and regenerated. For instance, Batchelder [51] was the first to test volatile solutes ($SO_2$) as DS and recovery was made by heating and air stripping process. Later, thermolytic solutions such as carbonates of ammonia were found to be readily recovered through distillation process using low heat energy as this DS can decompose into $NH_3$ and $CO_2$ by heating up to only 60 °C [24]. However, the proximity of low-grade heat from thermal power plants for instance is required to ensure that the recovery process is economically viable.

The regeneration of MNPs has also been investigated in many studies. Adham et al. [42] proposed the regeneration of MNPs by magnetic field separators, but this method caused agglomeration of MNPs which decreased their osmotic pressures and therefore the water flux. Ultrasonication was suggested to prevent this issue, but this potentially weakens the magnetic properties of MNPs and thus reduces the regeneration efficiency [43,45]. Recently, Ling and Chung [44] used UF for the recovery of MNPs and demonstrated that PAA-MNPs can be recycled up to five times only using UF without increasing their sizes or reducing their osmotic pressures while delivering reasonable water flux and salt rejection.

For some specific applications, however, the diluted DS can be used directly without the need for separation processes which considerably reduce the energy cost of the process [52]. Such applications include emergency water supply [35,37], dilution of input stream to RO desalination plant [47,53], dilution of RO brine before discharging into the environment [29,30], osmotic cleaning of fouled RO membranes

[54,55], production of biofuel from algae [32,56,57] and direct irrigation [17].

## 5. DS for modern applications

Many studies on the potential use of FO process for both industrial and domestic applications appear in the literature. The following section reviews the use of different types of DS for various FO applications such as desalination, water purification, wastewater treatment, energy production, biomedical applications and food processing.

### *5.1. DS for potable water production*

For the production of potable water by FO desalination process, the DS must have special properties. Besides meeting the general criteria such as high solubility, high osmotic pressure and pH compatible with the FO membrane, the DS for potable water should have a low reverse salt flux and be easily separated, recovered and regenerated for reuse with minimum efforts. In fact, any trace concentration of the DS in the final desalted water should not cause any health hazard and hence must meet the World Health Organisation (WHO) guidelines for drinking water quality standards [62]. Although FO process can extract water from any saline water sources as long as the DS can generate osmotic pressure much higher than the feed water, finding ideal DS meeting all these properties for potable water is still a challenge.

Initial works on FO desalination for drinking water production focused on applications where the diluted DS can be used directly for drinking water without the need for separation process. Such applications include production of nutrient drinks, emergency water supply in life boats and emergency relief situations during natural disasters. For these particular applications, glucose and fructose were used as DS [35–37]. Glycine was also suggested as DS for this purpose as it is more efficient in osmosis than fructose; however, it can be toxic for human at high concentrations. Stache [37] showed that fructose content must be at least 90% (w/w) which otherwise, the water flux rapidly decreases and for concentration below 74% (w/w), the water flow may be reversed from fructose DS to the saline solution. This also suggests that the final nutrient drink shall still contain high concentration of fructose solution. More lately, Wallace et al. [34] developed a thermodynamic benchmark for assessing an emergency drinking water device driven by FO process using brackish water as feed solution and mixtures of salt ($MgCl_2$, $CaCl_2$ and NaCl) and sugar (sucrose and glucose) as DS. HTI has recently developed and manufactured the first commercial FO membrane material and hydration bags for emergency water supply where sugar or beverage powder are used as DS [3,4]. However, these studies only developed batch desalination processes for emergency relief situations and not for continuous drinking water supply.

In an attempt to develop a continuous FO process involving reconcentration and recovery of the DS as shown in Fig. 3, McGinnis [61] suggested the use of potassium nitrate ($KNO_3$) and sulphur dioxide ($SO_2$) as DS for seawater desalination. This concept involved two-stage FO process for recovering water from aqueous solutions by taking advantage of highly tempera-

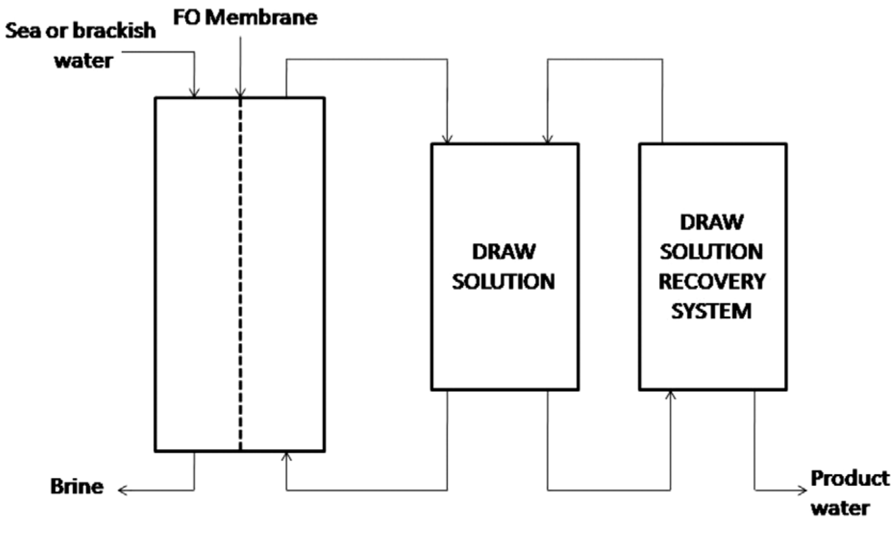

Fig. 3. Schematic diagram of FO desalination process for potable water with DS recovery system.

ture dependent solubility of $KNO_3$ and $SO_2$, as well as the relatively temperature independent solubility of NaCl, the primary solute present in seawater. However, performance data are not available till now. Later, McGinnis and co-workers [15,24] demonstrated a thermolyte solution using the mixture of ammonia and carbon dioxide gases in specific ratios that can generate high osmotic pressure of up to 238 bars. The most important feature of this DS is that the mixture can be easily recovered through distillation process. Water fluxes close to 25 LMH were achieved with a driving force of more than 200 bars using this mixture as DS. Similarly, Hancock and Cath [8] and Ng and Tang [16] tested $NH_4HCO_3$ as DS for FO seawater desalination. Although adequate water flux can be achieved using $NH_4HCO_3$ as DS, the solubility of $NH_4HCO_3$ was found to be one of the lowest in comparison with other DS tested, whereas its reverse salt diffusion was one of the highest due to its low MW [18]. DS with high reverse salt flux is not recommended for potable water production as discussed earlier since any trace of the DS in the final product may pose health hazards or result in the final product not meeting the WHO standards. Finally, Ng and Tang [16] found that this DS can also suffer from early decomposition if operated at temperature higher than 30 °C [2] and such temperature is the ambient temperature in regions such as in the Middle Eastern countries where desalination for drinking water production is operated.

Besides thermolytic solutions, other DS have been proposed for the production of potable water by FO desalination. Tan and Ng [25] tested seven potential DS on a new hybrid concept for seawater desalination by combining FO and NF processes. Their results on FO membrane showed that NaCl and KCl produce the highest flux of more than 25 LMH while $MgCl_2$ and $CaCl_2$ exhibited the largest osmotic pressure due to their high solubility in water. However, water fluxes were only comparable to those obtained with NaCl and KCl, and these lower-than-expected water fluxes were attributed to more severe CP effects. Experiments on FO membrane also demonstrated that solute rejection for all tested DS was always above 99.4% and could achieve 99.99% with $MgSO_4$. NaCl and KCl were not selected for tests on the hybrid FO/NF process as previous works demonstrated that both solutes exhibit low salt rejection (lower than 65%) with NF membrane. $CaCl_2$ was not selected as well for further tests with NF since at high concentration, when exposed to atmosphere, it could form precipitates with $CO_2$ and cause membrane fouling. The four last compounds (i.e. $MgCl_2$, $MgSO_4$, $Na_2SO_4$ and $C_6H_{12}O_6$) were tested on the coupled FO/NF process. $C_6H_{12}O_6$ was not recommended as DS for this process as it is susceptible to degradation by microorganisms rendering the regeneration of this compound difficult. Tan and Ng concluded that organic DS should be avoided for recycled usage. Results also showed that a single-pass NF used as regeneration process is not able to produce good quality product water in terms of total dissolved solid (TDS) concentration. Experiments using the second-pass NF process produced better results with permeate qualities having the recommended TDS concentration of 500 mg/L when using $MgSO_4$ and $Na_2SO_4$ as DS.

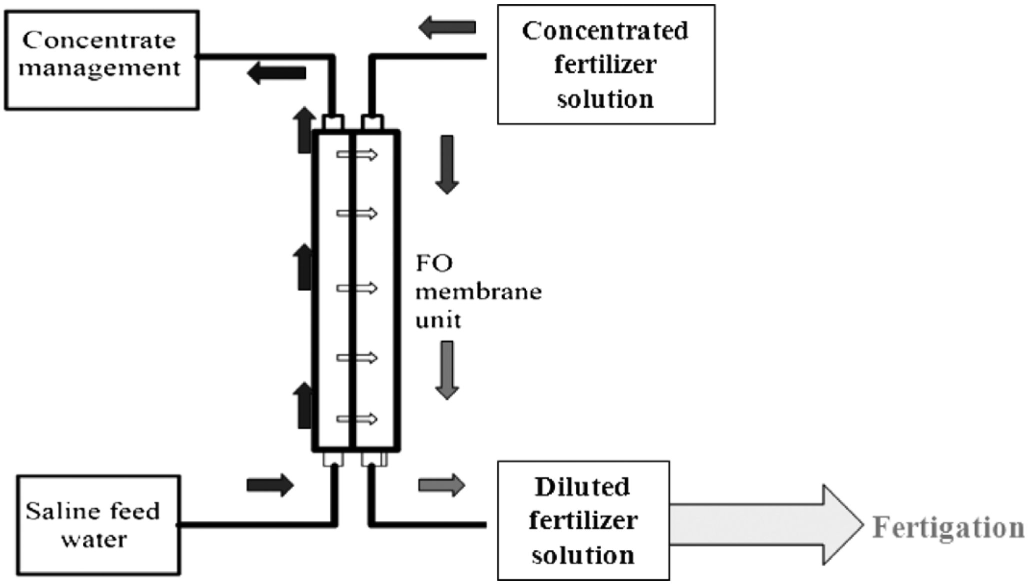

Fig. 4. Schematic diagram of the fertiliser drawn forward osmosis desalination for direct fertigation.

A novel innovation has been the use of MNPs for FO desalination by Ling and Chung [44]. They designed and tested a novel integrated FO-UF system for desalination using MNPs as DS. This system uses MNPs to induce water across the FO membranes while UF membrane was used to regenerate the MNPs DS. Among the MNPs tested, PAA-MNPs showed the best performance by producing an osmotic pressure of about 70 atm at a concentration of 0.08 mol/L and delivering a water flux of about 17 LMH. Moreover, these MNPs can be effectively recovered by several traditional processes as discussed in the previous part.

Another novelty has been the development of composite polymer hydrogel particles (PHP) with light-absorbing carbon particles for FO desalination by Li et al. [49]. The addition of carbon particles was proved to increase the swelling pressure of hydrogels resulting in higher fluxes. Sunlight irradiation was used as stimulus to separate the produced pure water from the swollen PHP. For some of the polymer hydrogels, more than 98% of water was recovered after 60-min exposure to the sunlight with an irradiation intensity of 1 kW/m$^2$. However, the use of such DS could prove a practical challenge especially if it exists in solid form.

### *5.2. DS for non-potable water production*

#### *5.2.1. Fertigation*

Due to the limited availability of freshwater, desalination of seawater and brackish water could be a reliable source for irrigation. Since FO was proved to be more energy-efficient over conventional desalination processes such as RO, this process can be used to desalinate locally available saline water to replace long-distance diversion of freshwater for irrigation. A recent study by Phuntsho et al. [17] investigated the use of fertilisers as DS driven by FO process to extract water from brackish sources for direct irrigation. There are plenty of advantages when fertilisers are used as DS in FO process and the detail review on this particular concept can be found in the recent review by Phuntsho et al. [63]. In fact, the fertiliser DS does not require an additional separation process as it can be directly used for fertigation or fertilised irrigation as it is displayed in Fig. 5. The diluted DS is a nutrient-rich solution required for the crops, and the FO process has a high salt rejection rate which is also good for plants.

Phuntsho et al. [17] studied nine different commonly used fertilisers as potential DS and evaluated their performance in terms of pure water flux and reverse solute flux. KCl, $KNO_3$ and $NaNO_3$ showed the highest water flux while $NH_4H_2PO_4$ and $(NH_4)_2HPO_4$ exhibited the lowest performance in terms of water flux among the selected DS. The ammonium compounds of phosphate and sulphate (i. e. $(NH_4)_2SO_4$, $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$ and $Ca(NO_3)_2$) displayed the best performance in terms of reverse salt diffusion as they have ionic species with large hydrated diameter compared to other fertilisers which have ionic species with small hydrated diameter such as $Cl^-$, $K^+$, $Na^+$, $NO_3^-$ and $NH_4^+$. They also estimated the theoretical quantity of water that a kilo-

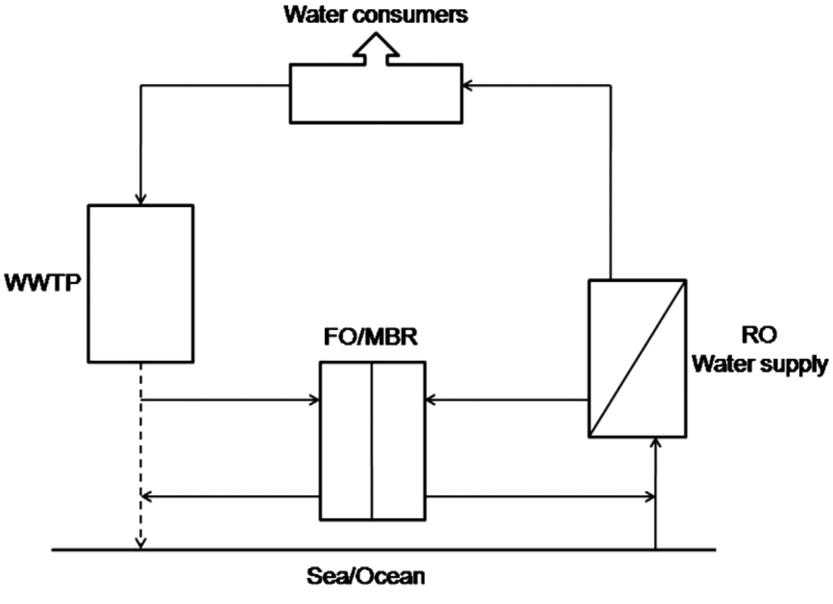

Fig. 5. Schematic diagram of FO/MBR hybrid system (WWTP: wastewater treatment plant; MBR: membrane bioreactor).

Table 5
Performance of the fertiliser DS in terms of water flux, reverse salt flux and water extraction capacity [17]

| Fertilisers | Water flux | | | Reverse water flux | Water extraction capacity | |
|---|---|---|---|---|---|---|
| | Experimental $J_w$ (μm/s) | Estimated theoretical $J_w$ (μm/s) | Performance ratio (%) | $J_s$ (mmoles/m$^2$ s) | From brackish water (L/kg fertilisers) | From seawater (L/kg fertilisers) |
| $NH_4NO_3$ | 4.2 | 27.9 | 14.9 | 0.791 | 32.4 | 15.2 |
| $(NH_4)_2SO_4$ | 5.4 | 39.7 | 13.6 | 0.006 | 26.3 | 12.7 |
| $NH_4Cl$ | 5.3 | 37.8 | 14.2 | 0.333 | 58.8 | 29.1 |
| Ca $(NO_3)_2$ | 5.0 | 46.7 | 10.8 | 0.009 | 23.7 | 11.5 |
| $NaNO_3$ | 5.7 | 34.9 | 16.3 | 0.278 | 34.8 | 17.7 |
| KCl | 6.3 | 38.4 | 16.5 | 0.222 | 42.4 | 21.0 |
| $NH_4H_2PO_4$ | 4.3 | 37.2 | 11.7 | 0.069 | 27.6 | 13.7 |
| $(NH_4)_2HPO_4$ | 3.9 | 40.9 | 9.5 | 0.010 | 30.2 | 14.4 |
| $KNO_3$ | 4.4 | 27.9 | 15.9 | 0.486 | 30.5 | 13.7 |

gram of fertiliser mass can extract from sea and brackish water. $NH_4Cl$, KCl and $NaNO_3$ were able to extract higher amount of water than other DS tested, while $Ca(NO_3)_2$ with largest MW has much lower water extraction capacity. All the results discussed previously are gathered in Table 5. They concluded that any soluble fertilisers can be used as DS and their choice of the DS will depend on compatibility with the FO membrane (physical and chemical parameters) and plant nutrient requirements.

### 5.2.2. RO concentrate management

Past studies have demonstrated that FO can be effectively used for the treatment of a wide range of highly concentrated feed solutions. Martinetti et al. [29] studied the desalination of two RO brine streams with TDS concentrations of about 7,500 and 17,500 mg/L using NaCl as DS. The FO process achieved high water recoveries, up to 90% from the RO brines. They found that water recoveries were limited by the precipitation of organic salts on the membrane surface. However, after cleaning with $Na_2EDTA$ and osmotic backwashes, water fluxes were almost restored at initial levels.

Adham et al. [42] evaluated the treatment of RO concentrate using FO with a wide range of DS including MNPs, albumin and dendrimers. MNPs were able to generate osmotic pressures ranging from 3 to 25 psi which were not adequate for dewatering of RO concentrate. They explained this due to their high MW and low solubility. However, the authors contemplated that MNPs may enhance its performance as DS if they can be properly synthesised with a smaller size and a more hydrophilic surface. They also observed that dendrimers could generate osmotic pressure of 330 psi which is adequate to dewater RO concentrate. More specifically, it was 20% of a G2-pentaearythirityl sodium carboxylate dendrimer solution which produced this high osmotic pressure. UF was proved to be an efficient recovery system for this DS with more than 85% rejection.

### 5.2.3. Wastewater treatment

FO process is characterised by low fouling potential and therefore a number of studies have been recently reported for its potential application in wastewater treatment. Applications of FO process for wastewater treatment include mainly osmotic membrane bioreactor (OSMBR) [23,64,65], anaerobic digester concentrate [30] and treatment of TDS from landfill leachate [31].

As with many other applications, all the studies reported on OSMBR so far have been limited to using NaCl as DS [23,64,65]. This in fact opens up the potential for using seaweater and concentrated brine from a nearby RO desalination plants for OSMBR as it is displayed in Fig. 5. The different studies with NaCl DS indicate that the FO membrane in MBRs could offer the advantage of higher pollutant rejection with lower hydraulic pressure in comparison with conventional MBR. Achilli et al. [23] showed that total organic carbon (TOC) and $NH_4^+$–N removals were much higher than those obtained with conventional MBRs with removals greater than 99% compared to 95% with traditional processes. Although reverse salt diffusion of DS caused initial flux decline in OSMBR process, salt concentration in the bioreactor stabilised after certain period of operation and then flux decline was only caused by membrane fouling. Besides, the level of salinity observed in the bioreactor did not present toxic effects on the biological process indicating that NaCl is a suitable DS for this application.

The sludge produced in the effluent from wastewater treatment facilities is generally treated in anaerobic digesters. After treatment, the sludge is dewatered which produces a centrate (liquid stream) and concentrated solids. The centrate holds high concentrated nutrients, TDS, TOC, heavy metals, colour and TSS. Sometimes this centrate is used as a soil fertiliser, but it is commonly returned to the wastewater treatment facilities for further treatments. Holloway et al. [30] investigated the use of FO for the concentration of centrate using NaCl as DS. Although flux decline was observed for each trial, due to the decrease in driving force and membrane fouling; almost complete restoration was obtained after cleaning. Colour and odour were highly rejected with almost 100% rejection. Phosphorus rejection exceeded 99%, and total Kjeldahl nitrogen and ammonia rejections were about 92 and 87%, respectively. They concluded that if a RO process is combined for DS reconcentration, higher rejection is expected.

Landfill leachate is a complex solution, generally composed of organic compounds, nitrogen, TDS and heavy metals. Nowadays, landfill leachates are treated in wastewater treatment facilities which mainly are focused on the removal of organic compounds, nutrients and heavy metals. TDS is not often treated and sometimes effluents are highly concentrated in TDS. York et al. [31] studied the possibility of using FO as a potential process for treating landfill leachates and especially TDS. A full-scale system was designed using a solution of 75 g NaCl/L as DS. In this system, the FO process was used to draw water from the leachate into the DS. The diluted DS was then treated by a RO process to produce freshwater and reconcentrate the DS. The combined FO/RO process was proved to be more efficient than the RO process alone as RO is less resistant to fouling than the FO process. This system was able to remove the vast majority of contaminants present in the feed solution. TDS rejection was almost 98% and most contaminants had more than 99% rejection.

Although, in the real application, the selection of DS would depend on the end use of the final product water after treatment of wastewater by FO process, the studies above on wastewater treatment using NaCl as DS indicate the possibilities of using seawater which exists in abundance or RO concentrate as suitable DS for the treatment of impaired water. Phuntsho et al. [17,63] suggested that fertilisers can also be used as DS for treating wastewater by FO process and diluted DS can then be used directly for irrigation purpose. If recovery, regeneration and recycling of DS are necessary, a more suitable DS could be electrolytes containing multivalent ions which can be easily reconcentrated and recycled using NF or other suitable process.

### *5.3. DS for other applications*

#### *5.3.1. Energy production*

Since the concept of osmotic power generation was first reported by Pattle [66], there is a growing research interests in power generation by taking advantage of the osmotic pressure difference between two streams of different salinity specifically at the point where freshwater meets the saline water such as sea [67–70]. The most recent comprehensive review of the pressure-retarded osmosis (PRO) for osmotic power generation can be found in the article by Achilli et al. [71]. In a PRO process, a hydraulic pressure is applied on the opposite direction of the osmotic gradient similarly to RO process, but the water flow is in the direction of the concentrated DS like in the FO process. Generally, seawater is used as DS by taking advantage of the salinity gradient that exists in nature. The osmotic pressure gradient between the freshwater from rivers and the highly saline seawater is converted into a hydrostatic pressure that can run a turbine to generate electricity as it is depicted in Fig. 6. The production of renewable energy by PRO from seawater is becoming more and more attractive and in fact seawater is an unexploited and large resource and its use has very small effect on the environment [66]. Aaberg [67] estimated that the overall power production potential from PRO is in the order of 2000TWh per year.

Although the power generation takes advantage of the salinity gradient that exists in nature, there is also a potential for generating power by PRO using RO concentrate as a DS. RO concentrate is one of the most significant issues in a RO desalination plant. The osmotic gradient between the RO concentrate and the seawater could be significant, and this can be used advantageously to generate power which can then be used further for desalination process in the process making the desalination plant more energy efficient.

#### *5.3.2. Biomedical applications*

Proteins have a wide range of commercial applications, particularly in the pharmaceutical market, but enriching and separating protein is technically and economically challenging as most proteins are chemically unstable and heat sensitive. Some studies have

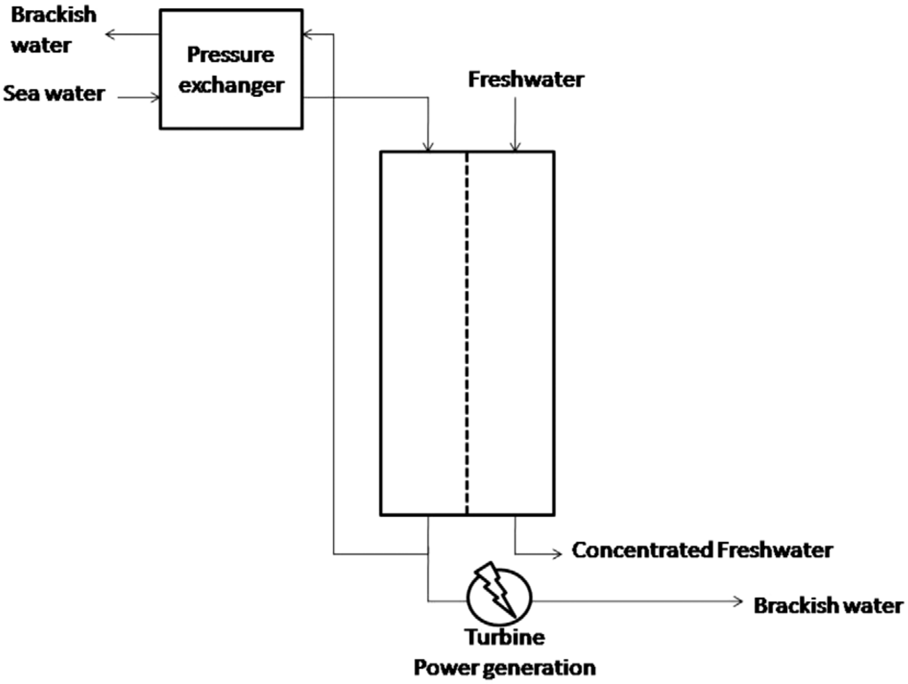

Fig. 6. Schematic diagram of osmotic power generated by PRO process.

recently proposed the use of FO process to concentrate proteins. For this specific application, the choice of a suitable DS is crucial since the appropriate DS must be easy to recover without denaturing the protein.

Yang et al. [33] studied the potential use of $MgCl_2$ as DS for protein enrichment by FO process using a dual-layer hollow fibre NF membrane. They found that $MgCl_2$ can enrich lysozyme product to high purity without changing the conformation or denaturing the protein due to low reverse solute flux. In a more recent study, Ling and Chung [43] developed a dual-stage FO system using MNPs as DS to concentrate proteins in an up-stage FO process and RO brines as DS to reconcentrate the MNPs in a down-stage FO process as shown in Fig. 7. In their study, they synthesised hydrophilic MNPs as DS which can exhibit high osmotic pressure and can be easily recycled either by membrane process or magnetic fields [45,72]. Moreover, their reverse salt flux was found to be very low as they are too large to pass across the membrane pores which keep proteins intact and stable during their enrichment. They also demonstrated that the use of concentrated salts as DS (e.g. NaCl) may denature proteins since they will exhibit much reverse salt diffusion and inevitable salt leakage will alter protein intrinsic characteristics.

For long-term treatment of chronic illness, patients require continuous, controlled and targeted release of drug for longer period of time (i.e. up to a year). DUROS® [7] has successfully developed and commercialised the first osmotic pumps for this purpose.

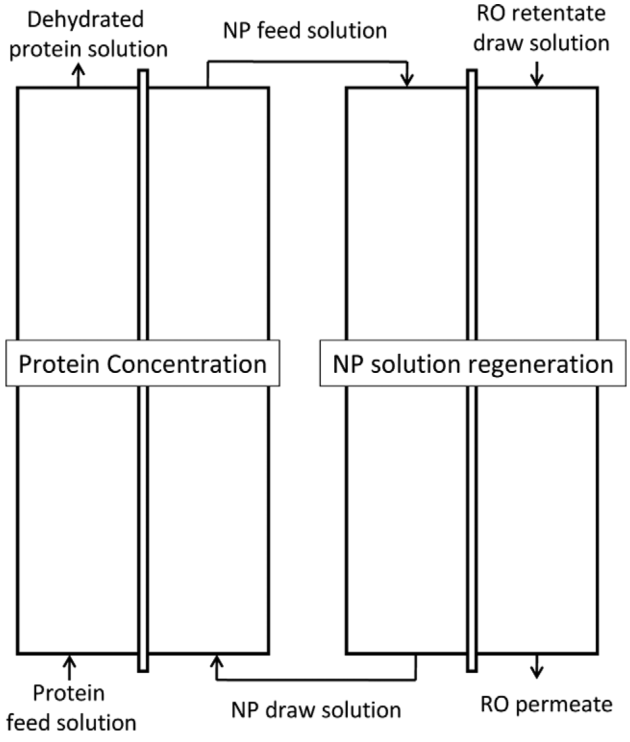

Fig. 7. Schematic diagram of the laboratory-scale dual FO system (adapted from [43]).

Osmotic pump system is made up of a titanium cylindrical reservoir that protects the drug from body moisture, cellular components or enzymes that may affect the drug before it has been delivered to the body. A semi-permeable membrane covers one side of the cylinder and the DS is stocked in a small portion of the cylinder, behind the membrane, and separated from the drug compartment by a piston. Generally, the DS is a mixture of NaCl and pharmaceutical excipients. The drug outlet is a small orifice located on the other side of the cylinder. When implemented, an osmotic gradient is set up between the tissue water and the DS which induces water to flow across the membrane. The pressure inside the DS compartment is then continuously increasing which pushes the piston and increases the pressure in the drug reservoir which leads to the delivery of the drug into the body.

### *5.3.3. Food industry*

FO process has significant application potential for concentrating beverages and liquid foods. FO process can operate at low temperatures and low pressures which prevent final products from sensory (i.e. taste, aroma and colour) and nutritional (i.e. vitamins) degradation.

In 1966, Popper et al. [73] were the first to use the FO process to concentrate fruit juices. They used saturated NaCl as DS and achieved water flux of 2.5 kg/$m^2$h. Although highly concentrated fruit juices were produced, salt was observed in the feed solution due to reverse diffusion of NaCl. Herron et al. [40] developed a membrane module and a method to concentrate juices and wines. High water fluxes were achieved for orange juice and coffee feed solution, probably due to the high turbulence in the FO membrane module using 50–85 wt.% sugar solution as DS. Adopting the method of Herron et al. [40], Petrotos et al. [27] studied the concentration of tomato juice and tested six different compounds (i.e. calcium chloride, calcium nitrate, glucose, sucrose and polyethylene glycol 400 or PEG400) as potential DS. Their experiments showed that the choice of a suitable DS depends greatly on its mass transport characteristics (i.e. viscosity and diffusivity). Based on this result, NaCl and $CaCl_2$ showed the best FO performance as they exhibit the highest water flux due to their lower viscosity. In a further study, Garcia-Castello et al. [26] focused on the performance of the FO process in sucrose concentration using NaCl as a surrogate DS. They have found that much higher sucrose concentration factors can be obtained in comparison with RO process. However, water fluxes were found to be low compared to those obtained with RO which is mainly the consequence of higher concentration factors combined with ICP effects.

From the above studies, it appears that FO offers plenty of advantages over conventional processes for the concentration of liquid foods. However, the lack of suitable membranes as well as the development of an efficient reconcentration and recovery process for the DS is the major limitation that prevents FO to be implemented at a full-scale process in the food industry.

## 6. Criteria for the selection of suitable DS

Based on the past and current studies on FO process, it is clear that the selection of a suitable DS depends on many criteria. In the following paragraph, useful information for the selection of suitable DS is provided. The information provided is general to any FO applications, so it is important to understand that for some specific applications, further criteria need to be evaluated before an appropriate selection of the DS.

Before running any bench-scale experiments, an initial screening of DS can be carried out. Thermodynamic modelling softwares can be handy in determining some basic properties such as water solubility, pH, speciation and osmotic pressure, which are important criteria that can affect greatly the FO process performance as discussed earlier. Then, it is important to ensure that the DS is inert, of near neutral pH, stable and non-toxic, especially when FO is used for drinking water production as mentioned previously. Another important factor that has to be assessed is that DS should not alter chemically or physically the membrane through reaction, adsorption, dissolution or fouling. Finally, to ensure the economic viability of the process, the DS should not be expensive.

Once this preliminary screening has been carried out, experiments can be conducted to assess DS performance in terms of water flux, reverse salt transport and water recovery, which are the three main parameters used for assessing the performance of FO process. Another important criterion in most FO applications is the separation and recovery of the DS after it has been diluted. This process should be able to reconcentrate and recover the DS at low-cost energy, otherwise full-scale implementation will not be financially viable compared to other pressure-driven processes that are already commercialised.

Finally, the FO process should be tested at full-scale with the selected DS and life cycle assessment

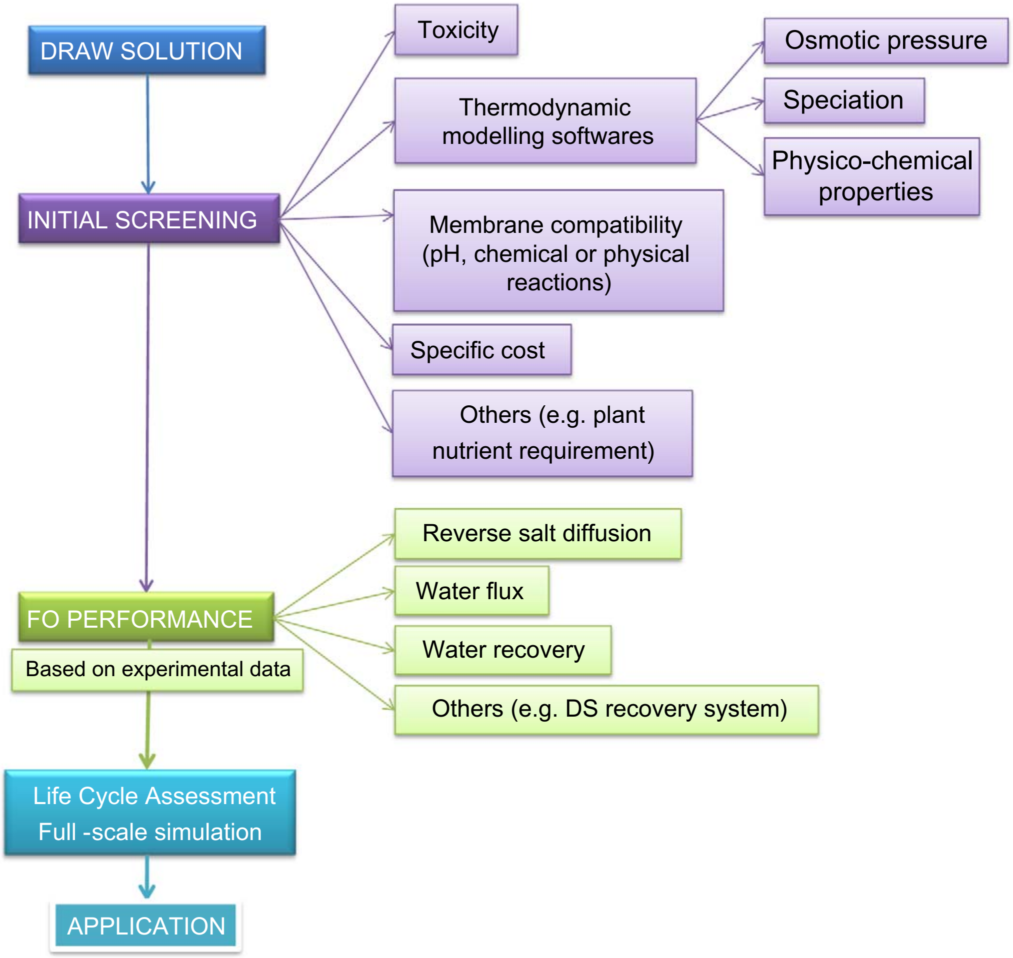

Fig. 8. DS selection criteria flow diagram.

should be conducted in order to ensure that each stage of the process (from the production of raw materials to the treatment of waste) has no or few impacts on the environment. A flow diagram that displays the DS selection criteria, as described above, is illustrated in Fig. 8.

## 7. Concluding remarks

FO is a novel and emerging low energy technology for desalination. Its performance relies on the selection of suitable membrane and DS. In fact, to further improve the FO process performance, efforts have to be made on the development of new membranes for reducing ICP effects as well as the development of methods for the selection of suitable DS. A wide range of DS that are used for different applications have been reviewed in detail and their limitations are identified and discussed in this particular review. The following conclusions may be drawn from this review:

- As the main source of the driving force in FO process, the DS constitutes an integral part of the FO process and therefore careful selection of DS is essential as its properties can affect the process performance. Although any soluble compounds can generate osmotic pressure, the selection of suitable DS depends on the end-use application of the final product water. Besides high solubility and high osmotic pressure, other properties of the DS such as MW, diffusion coefficient and DS viscosity can affect the performance of FO process. The performance of each DS varies because they influence concentration polarisation effects to varying degree.
- Inorganic- and organic-based DS are most commonly used in the lab-scale FO studies, either because of their specific application or because their thermodynamic properties are well understood. However, most candidates have issues related to the separation of draw solutes from the water for regeneration and further reuse. Separation and regenera-

tion of DS remain a contentious issue as additional process and energy are required, and this process is also essential especially for FO process for potable water application. Few emerging DS such as ammonia-carbon dioxide, MNPs and hydrogels are considered promising candidates for potable water applications and therefore worth further studies.

- Because of the issues of energy with the DS separation and regeneration process, FO applications find suitable for non-potable applications. NaCl or seawater has been widely used as DS for the wastewater treatment and the diluted DS is either discharged to the sea or, used as RO feed for potable application. RO concentrate has been used as DS for similar applications and recently commercialised. Fertilisers are another promising DS candidates both for desalination and for treating impaired water by FO process where the diluted DS can be used directly for fertigation.
- This review also proposed and discussed the criteria for selecting a suitable DS candidate for specific application. There is no particular DS that can be considered as the most suitable candidate, and the suitability depends on the types of application intended. The success of FO desalination for potable water will depend on how easily the draw solute can be separated from the freshwater. Therefore, FO technology still requires extensive research in the future particularly related to the development of more suitable draw solutes. This also includes how the influence of concentration polarisation effects can be reduced through process optimisation and improved membrane design.

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