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Evaluation of draw solutions and commercially available forward osmosis membrane modules for wastewater reclamation at pilot scale

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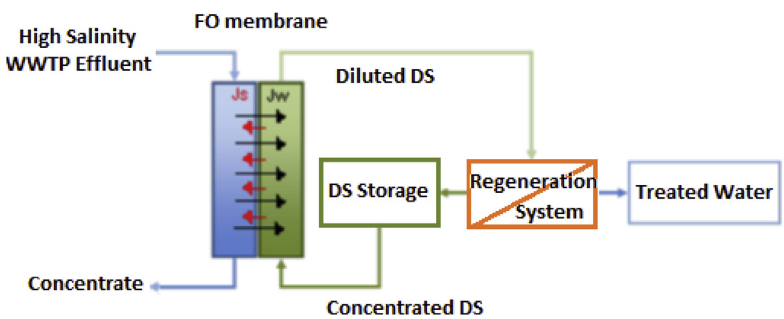
HIGHLIGHTS

- An intensive evaluation of DS for hybrid FO systems for WWTP effluent is presented.
- An osmotic pressure of max. 10 bars was selected as the optimal operating pressure for the DS.
- Replacement price, pH and toxicity were the most relevant properties for a DS.
- The selected DS were $MgSO_4$, Sodium Polyacrylate and $K_4P_2O_7$.
- Commercially available FO TFC flat sheet membranes obtained the best operational performance.

GRAPHICAL ABSTRACT



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ABSTRACT

An intensive evaluation of draw solutions (DS) was performed by focusing on the wastewater reuse applications of hybrid forward osmosis (FO) processes. The substances studied were potassium formate, potassium phosphate, magnesium sulphate, sodium chloride, sodium polyacrylate and polyethylene glycol, and their osmotic pressure, conductivity, pH, thermostability, sunlight exposure, toxicity, FO filtration performance and replenishment costs were determined. Additionally, commercially available FO membrane modules were evaluated at pilot scale. The results revealed that the most relevant DS properties for wastewater reuse under the studied conditions were the DS regeneration method, DS replacement price, pH adjustment and toxicity. These properties were shown to be more relevant than filtration flux when a maximum DS osmotic pressure value of 10 bar was used. This was the limit for efficient DS recovery. When the different FO membranes were compared, thin-film composite (TFC) flat-sheet membranes showed the highest flux and the highest salt rejection, and the lowest permeability and salt rejection values were presented by cellulose triacetate (CTA) hollow fibre membranes. Based on the information obtained, a TFC-FO/nanofiltration (NF) demonstration plant will be constructed next to the wastewater treatment plant (WWTP) in San Pedro del Pinatar, in the region of Murcia (Spain). This represents the world's first FO demonstration plant for municipal wastewater reclamation and its results will allow this technology to be evaluated for wastewater reuse for agricultural purposes.

1. Introduction

The total volume of treated wastewater reused in Europe by 2025 will be 3222 Mm^3/yr. Spain shows the greatest reuse potential at over 1200 Mm^3/year, which represents around a third of the

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potential water reuse in Europe and will be used primarily for agricultural purposes [1]. The region of Murcia in southeastern Spain faces high water stress and claims to reuse 95% of its wastewater indirectly or directly [2]. Only high-salinity water, which cannot be directly reused in agriculture, is discharged into the sea. In order to minimize water loss and reuse this high-salinity water, reverse osmosis (RO) is commonly used.

FO has been evaluated in recent years as an alternative to RO [3]. Nevertheless, further research into FO systems is required in order to determine their real applicability. The FO process uses a semi-permeable membrane to effectively separate water from the solutes it contains. This separation is driven by an osmotic pressure gradient, such that a solution of high concentration (relative to that of the feed solution) called a draw solution (DS) is used to induce a net flow of water through the membrane into the DS stream, thus effectively separating the feed water from its solutes. After that, an efficient separation system between the DS and the product water is required, and this is highly dependent on the final water use; this step is avoidable only if fertigation is applied [4]. This fact makes the installation of a hybrid FO system essential. The study also revealed that, although hybrid technologies like FO combined with membrane bioreactors (FO-MBR) or FO-RO have been proposed as promising technologies, there is still a lack of overall energy balance for these integrated and alternative systems that would allow them to be compared with conventional technology. In this regard, other recent reviews [5–7] have compared energy usage by FO-RO and RO alone (including adequate pretreatment) and concluded that reverse osmosis is more energy efficient due to the DS recovery step, which implies a high energy input. Moreover, with the commercial technology currently available, FO systems for wastewater treatment seem to involve higher capital costs than conventional technologies [8]. However, a hybrid process like FO-RO may be advantageous if all costs incurred are considered, rather than only energy and capital costs. The reason for this is basically the lower fouling propensity reported for the FO process [9–11] compared to conventional membrane technologies applied to wastewater treatment, which would theoretically reduce the need for chemicals throughout the whole process. This is due to a lack of pH adjustment and antiscalant in the pretreatment and reduced chemical cleaning frequency [12–14]. This is important not only because of the reduction in chemicals used, but also because of the corresponding reduction in plant shutdowns. This advantage means that the FO process is not intended to replace RO, but is rather proposed as a way to process feed waters that cannot be treated by RO [12]. Moreover, FO systems present a greater rejection of contaminants than UF and MF membranes [15,16]. Therefore, another important benefit of hybrid FO processes is their high rejection due to the dual barrier (FO and NF or RO), which may solve rejection problems if the system is adequately customized for the targeted compounds.

Different authors have reviewed the application of forward osmosis for wastewater reclamation [12,17–19]. The FO membrane flux and the selection of the DS were identified as the main problems to be solved in this application [20]. It is necessary to identify a low cost DS that can generate high osmotic pressures, and is non-toxic and economically separable [3]. The ideal DS allows high flux with low salt diffusion to the feed side and is easy to separate in order to recover the water from the diluted DS. In addition to these requirements, the DS has to meet maximum diffusion through the porous membrane support in order to avoid osmotic pressure and flux decline [21,22]. The lack of diffusion through the porous support is known as internal concentration polarization (ICP) and causes either dilution of the DS or concentration of the feed solution, depending on whether the DS or the feed is being run along the active membrane layer [23,24]. For the specific application of wastewater reuse, DS concentration in the final product water must be below the standards reflected in the corresponding wastewater reuse regulations.

A demonstration plant will be constructed in order to evaluate the hybrid FO technology applied to high-salinity wastewater treatment plant (WWTP) effluent for irrigation purposes. This paper describes the preliminary studies that were carried out prior to the final design of the plant. Accordingly, a systematic assessment of the effect of DS on FO performance was carried out using experimental filtration data. The chemical properties of the DS, their cost and the potential for economic recovery were evaluated. Finally, several commercial FO membranes were evaluated in terms of water permeability and salt rejection.

2. Materials and methods

2.1. Feed water

Synthetic feed water was prepared with deionized water (DI) adjusted with NaCl to 5 mS/cm of conductivity (concentration and osmotic pressure of 2.72 g L^{-1} and 2 bar, respectively), to make it similar to the feed water coming from the WWTP effluent at San Pedro del Pinatar.

2.2. FO membranes

Five commercial FO modules were used for the performance tests: two FO 4040 spiral wound (SW) membranes with an area of 3 m^2 made of cellulose triacetate (CTA) and thin-film composite (TFC), respectively, one FO 4040 spiral wound membrane with an area of 4.12 m^2 made of TFC, one FO flat-sheet (FS) membrane with an area of 1.3 m^2 made of TFC, and one FO hollow fibre (HF) with an area of 25 m^2 made of CTA. In all membranes, the active layer faced the feed solution.

2.3. Chemicals

The different DSs (potassium formate, potassium phosphate, magnesium sulphate and sodium chloride, all with >98% purity) were purchased from Barcelonesa de Drogas y Productos Químicos (Spain). Sodium polyacrylate 6500 Da (previously diluted: 43% w/w) and polyethylene glycol 10,000 Da were bought from Kemira Ibérica (Spain) and Sigma Aldrich, respectively. The pH was adjusted with HCl 1 M or NaOH 1 M solutions from Panreac.

2.4. DS performance tests: water flux (Jw) and reverse salt diffusion (Js)

The FO filtration tests were performed with the 4.12 m^2 spiral wound (SW) membrane. Two kinds of experiment were carried out. First, the initial DS concentration in every FO run was set to 40 bar of osmotic pressure and the synthetic feed water was prepared as described in Section 2.1. The synthetic feed water (FW) concentration (2.72 g L^{-1} of NaCl) and temperature (25 °C) were kept constant throughout the whole test. The water passing through the membrane progressively diluted the DS, thereby covering a wide range of osmotic pressure values. This made it possible to obtain a wide range of operational point data in a single experiment, in which different normalized water fluxes (Jw) were tested.

In addition, for every DS selected, the osmotic pressure of both the synthetic feed water and the DS were kept constant at 2 bar and 10 bar, respectively, for 2 h at 25 °C. The DS concentration in the synthetic feed water tank was therefore monitored to check the normalized reverse salt diffusion (Js) from the DS side to the feed water side.