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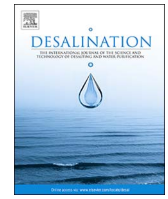

Environmental and economic impacts of fertilizer drawn forward osmosis and nanofiltration hybrid system

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ABSTRACT

Environmental and economic impacts of the fertilizer drawn forward osmosis (FDFO) and nanofiltration (NF) hybrid system were conducted and compared with conventional reverse osmosis (RO) hybrid scenarios using microfiltration (MF) or ultrafiltration (UF) as a pre-treatment process. The results showed that the FDFO-NF hybrid system using thin film composite forward osmosis (TFC) FO membrane has less environmental impact than conventional RO hybrid systems due to lower consumption of energy and cleaning chemicals. The energy requirement for the treatment of mine impaired water by the FDFO-NF hybrid system was 1.08 kWh/m^3, which is 13.6% less energy than an MF-RO and 21% less than UF-RO under similar initial feed solution. In a closed-loop system, the FDFO-NF hybrid system using a TFC FO membrane with an optimum NF recovery rate of 84% had the lowest unit operating expenditure of AUD \$0.41/m^3. Besides, given the current relatively high price and low flux performance of the cellulose triacetate and TFC FO membranes, the FDFO-NF hybrid system still holds opportunities to reduce operating expenditure further. Optimizing NF recovery rates and improving the water flux of the membrane would decrease the unit OPEX costs, although the TFC FO membrane would be less sensitive to this effect.

1. Introduction

Agricultural sectors consume up to 60–75% of Australia's total fresh water, mainly in the form of irrigation to grow food [1]. However, the scarcity of fresh water is a major issue in many regions. During drought, the limited available fresh water is prioritized for domestic consumption, leaving agriculture among the most affected sectors. Creating new water resources, by recycling, desalinating and reusing water, for example, should be one of the strategies in a sustainable integrated water management plan.

Coal seam gas and underground coal mining activities produce large volumes of saline groundwater. Despite meeting progressively more stringent discharge standards, proper treatment, management and disposal remain a significant challenge for the coal industry [2]. Currently, this water is simply treated and disposed into the environment; however, with better treatment, mine impaired water could become a valuable resource for irrigation in dry regions or during the drought seasons. Salinity is the biggest obstacle to make this idea a viable commercial reality. Reverse osmosis (RO) is currently the most efficient desalination technology, but it is expensive and highly energy intensive, and this makes desalination for irrigation commercially unviable [3–5].

Among several recent innovations in desalination technologies, forward osmosis (FO) has emerged as a promising candidate for various applications, including irrigation [6]. Fertilizer drawn forward osmosis (FDFO), which uses fertilizers as its draw solution (DS), has shown potentially lower additional energy consumption and the diluted DS, containing fertilizer nutrients, can be used as non-potable water for the irrigation of crops [7].

In a recent study, Phuntsho, et al. [7] reported that although using the FDFO process alone would be ideal, the final dilution of the fertilizer DS is limited by its osmotic equilibrium with the feed salinity or osmotic pressure. When the feed has higher salinity, the concentration of the final diluted fertilizer is also correspondingly higher, and is

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greater than the concentration level generally required for direct irrigation [8]. Among several options studied, nanofiltration (NF) has been suggested as one of the most suitable post-treatment processes to reduce fertilizer concentration for direct fertigation, and an FDFO-NF hybrid system has recently been studied both in the laboratory and at pilot scale [9,10].

The pilot study was carried out using a 1000–4000 L/d capacity FDFO-NF desalination system at Centennial Coal's Newstan colliery in Fassifern, New South Wales for six months [3]. The pilot-scale FDFO-NF process was composed of two spiral wound FO membrane modules and one spiral wound NF membrane module. Flow rates, pressures, and electrical conductivity meters were installed at both the inlet and outlet of the membrane module. All the sensors were connected to a computer and thus collecting the data automatically. Detailed information about the design and control of the FDFO-NF system are described in our previous studies [11,12]. This study revealed that the technology was robust with the potential to produce nutrient rich irrigation water to support the surrounding farming industry. However, FDFO-NF hybrid desalination is a new technology and, therefore environmental and economic life cycle assessment (LCA) is essential to understand its comparative advantages with existing desalination technologies such as RO hybrid systems.

The main objective of this work was, therefore, to conduct an environmental and economic LCA that compares the FDFO-NF hybrid system with two conventional RO hybrid systems in the desalination of mine impaired saline groundwater. It has to be acknowledged that for the economic life cycle assessment of the FDFO-NF hybrid process only operating expenditure (OPEX) was considered due to the system boundary limitation of the current LCA study. Conventional RO hybrid systems use microfiltration (MF) and ultrafiltration (UF) as a pre-treatment process and are termed here as MF-RO and UF-RO hybrid systems, respectively. To authors' knowledge, this study is the first to undertake a detailed environmental and economic analysis of the FDFO-NF hybrid process for irrigation through reuse of coal mine impaired water.

2. Materials and methods

2.1. Life cycle assessment of hybrid desalination systems

The LCA framework used for this study is described elsewhere [13–15]. A standard LCA generally consists of four stages; goal and scope definitions, life cycle inventory analysis (LCI), life cycle impact assessment, and interpretation. The first three stages are briefly described in this section. The last stage, interpretation, is discussed in Section 3.

Three hybrid desalination systems were chosen for comparison: MF-RO, UF-RO, and FDFO-NF. FDFO-NF is further divided into two groups, namely FDFO-NF (CTA) which uses cellulose triacetate (CTA) membrane and FDFO-NF (TFC) which uses a thin film composite (TFC) membrane for the forward osmosis process. Fig. 1 shows the system boundaries under which the LCA was carried out for the desalination of coal mine impaired water. It has to be acknowledged that the data obtained in our previous pilot-scale FDFO-NF hybrid system study was used as the basis for this LCA study. Nevertheless, there were some challenges to incorporate all the operating data for this LCA study. In fact, the main objective of the previous study was to prove technical feasibility of the FDFO-NF process including cleaning strategies for the desalination of saline water produced during coal mining activities. Therefore, the life cycle analysis of all the hybrid system was conducted by assuming and adopting full-scale operating conditions from the previous LCA studies [13,14,16–18]. The details will be discussed in Section 2.3.

2.1.1. Life cycle inventory (LCI) analysis

To collect the primary data for each hybrid system, an inventory analysis was carried out using the Ecoinvent LCA database version 3.0 and the Australian LCA database, Simapro version 8.1 [19–21]. Simapro LCA is one of the most widely used software tools. It includes impact assessment methods and several representative databases such as the Australian LCA database. Several common considerations for LCA for all hybrid systems are summarized as follows:

- In cases where no specific database for the production of materials and their quantities could be found in the Australian LCA database, information from the closest found database, Eco-invent, was used for the LCI.
- The types of materials used for MF, UF, NF and RO membranes applicable to this study and the total weight of materials for each membrane module were adopted from published literature [14,22,23].
- One of the most challenging parts of the operation phase is simplifying the membrane manufacturing procedure, including the consumption and production of the specific resources. All process data related to this procedure, including the covering membrane, spacer, membrane housing, collection tube, and glue, were available in previous studies [13,14,17].
- The electricity production model is based on the Australian mix electricity data in the Simapro Australian LCI database. It consists of approximately 70% coal, 14% natural gas with remaining 16% derived from several sources, including renewable energy sources [18]. The cost of electricity was calculated at AUD $0.29/kWh in New South Wales, Australia [24].
- The LCA in the chemical phase is based on previous studies which include the most commonly used cleaning chemicals and scale inhibitors for each membrane process (UF, MF, RO, FO and NF). However the chemical transport component has been excluded, since transportation conditions are the same in all cases [25].
- It has to be noted that the feed water quality influences the fouling propensity. In this study, as shown in Table S1 in the Supplementary Information (SI), the concentration of the feed water was assumed to be 2491 mg/L total dissolved solids ($\approx$ 2500 mg/L TDS). Based on this feed water quality, the frequency of chemical cleaning for RO hybrid systems for this study was adopted from [13,26].
- Economic and environmental impacts of brine disposal may lead to different LCA results. However, as mentioned earlier, we conducted the pilot-scale FDFO-NF study at one of the coal mine site in Australia [3]. Since there is an available wastewater treatment plant (WTP) to treat mine impaired water, FO and RO brines as well as chemical cleaning wastewater can be directly transported to the WTP. For this reason, the current study did not consider the impacts of the brine and/or waste disposal on the LCA results.
- The issues on forward and reverse salt flux and thus accumulation of ammonia and feed water constituents in the feed and draw solutions, respectively, could have significant environmental and economic impacts [3]. However, such issues were not considered in the current study as the scope of this study was first to evaluate comparative advantages of the FDFO-NF system, but the results obtained through the current study will be used as the basis for future comprehensive analyses.
- The construction and decommissioning phases of the plant were not accounted for this study due to its long life span, and given that similar conditions apply to all the three hybrid systems [25].
- The water quality for all hybrid systems was assumed based on the characterization of feed, diluted fertilizer, and final product water as shown in Table S1 in the SI, which was around 2500 mg/L TDS, 7600 mg/L TDS, and less than 1000 mg/L TDS (irrigation purpose [3]), respectively.
- Plant capacity in the LCA was set for the production of 100,000 m^3 of reusable water, and this figure was used for all hybrid systems. All materials and energy inputs were determined and normalized based on the functional unit [14]. Operational phase of life cycle