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Thin film composite hollow fibre forward osmosis membrane module for the desalination of brackish groundwater for fertigation

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HIGHLIGHTS

- Performance of PA hollow fibre FO membrane module was studied for FDFO process.
- Ion and membrane charge played a significant role in HFFO module performance.
- Membrane charge determined selective ion transfer sometimes resulting in scaling.
- Scaling occurred both on the active and support layer sides of the HFFO membrane.
- HFFO module with high packing density has high volumetric output per module.

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ABSTRACT

The performance of recently developed polyamide thin film composite hollow fibre forward osmosis (HFFO) membrane module was assessed for the desalination of brackish groundwater for fertigation. Four different fertilisers were used as draw solution (DS) with real BGW from the Murray–Darling Basin in Australia. Membrane charge and its electrostatic interactions with ions played a significant role in the performance of the HFFO module using fertiliser as DS. Negatively charged polyamide layer promotes sorption of multivalent cations such as Ca^{2+} enhancing ion flux and membrane scaling. Inorganic scaling occurred both on active layer and inside the support layer depending on the types of fertiliser DS used resulting in severe flux decline and this study therefore underscores the importance of selecting suitable fertilisers for the fertiliser drawn forward osmosis (FDFO) process. Water flux under active layer DS membrane orientation was about twice as high as the other orientation indicating the need to further optimise the membrane support structure formation. Water flux slightly improved at higher crossflow rates due to enhanced mass transfer on the fibre lumen side. At 45% packing density, HFFO could have three times more membrane area and four times more volumetric flux output for an equivalent 8040 cellulose triacetate flat-sheet FO membrane module.

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1. Introduction

Many countries are now facing acute water scarcity problems and the impact of climate change is further worsening the water crisis [1]. With the rapid increase in the world's population, the water demand is all set to increase further indicating that the water crisis is going to become even more severe in the future. Desalination is therefore going to play an increasingly significant role in solving the water crisis [2,3]. There are several state-of-the-art desalination technologies however, all these technologies are capital and energy intensive processes [4] making desalination either unaffordable or not a cost-effective option especially for large-scale irrigation purpose. Agriculture sector accounts for 70% of the world's total water consumption [5] and therefore water shortage could have a devastating consequence on the world's food security [1]. Reverse osmosis (RO) process is currently the most energy efficient desalination technology [6] however; it remains unaffordable to many societies in the world and certainly not for irrigation use. The high capital and operating costs associated with the RO technology are because of the need to operate the process at a high hydraulic pressure [7,8].

Recently, there have been efforts to develop alternative desalination technologies that operate at low or no hydraulic pressure and potentially reduce the capital and operation costs. Forward osmosis (FO) process has emerged as one of the most promising candidates for desalination with a potential to consume much lower energy than the conventional

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processes depending on the types of applications [9,10]. The FO process relies on the osmotic pressure difference across the semi-permeable membrane as the driving force to separate salt from the saline water sources instead of hydraulic pressure in the RO process. The osmotic driving force is generated by using a concentrated draw solution (DS) on one side of the osmotic membrane and feed solution (FS) or the impaired water such as saline water on the other side of the membrane. The water moves from the lower concentrated FS towards the higher concentrated DS by natural osmosis due to osmotic pressure difference without using any external energy. The DS finally becomes diluted but it cannot be used directly for potable purpose unless the draw solute is separated and removed from the pure water. A post-treatment process is essential for the FO process which could still require energy. Finding an ideal draw solute for FO process is therefore still a big challenge at the moment for potable water desalination.

FO is however found ideal when the presence of draw solutes adds value and as such the diluted DS can be applied directly without the need to separate the draw solutes from the water [11]. Fertiliser drawn forward osmosis (FDFO) process is one of such application in which saltwater is converted into nutrient rich water for fertigation using fertiliser solution as DS. The FDFO process has been recently recognised and studied as one of the most practical applications of FO process for irrigation [12,13]. Since the fertiliser is needed for the growth of the crops/plants, the question of separation of draw solutes from pure water does not arise unlike for the potable water purpose. The fertiliser concentration however must meet the nutrient standards for direct fertigation and this is challenging especially when feed water with a higher salinity is used. Few options have been explored to reduce the fertiliser concentration such as using blended fertiliser as DS [12], using nanofiltration (NF) as either pre-treatment to reduce feed TDS or as post-treatment process to reduce fertiliser concentration and recycle the excess fertiliser for further reuse and extraction of water [14].

Membrane properties play a major role in the performance of the FO process [9,15,16]. Following a renewed research interest in the FO process for various applications recently, many new high performing FO membranes have been reported [17–19]. Most efforts however focussed on developing polyamide (PA) based thin film composite (TFC) flat-sheet FO membranes with highly porous support layer to reduce the dilutive internal concentration polarisation (ICP), found mainly responsible for lower flux efficiency in the FO process. Although these efforts have helped improve the water flux by several factors however such membranes are also found to have low mechanical strength [20–22]. Although, the FO process does not use hydraulic pressure as the driving force nevertheless, membranes in general have to be robust to endure long-term operations.

Hollow fibre FO (HFFO) membranes could offer several advantages compared to flat sheet FO membranes [23]. Hollow fibre module have much higher membrane area to volume ratio than flat sheets so that large membrane area can be packaged into a small volume (high packing density) thereby decreasing the footprint and capital cost. For thin membranes without a fabric backing, fibres are self-supporting and less susceptible to damage during operational process [24]. As a result of their rugged self-supporting geometry, HFFO membranes can be made with thinner substrates without fabric backing thereby not only reducing the material cost but also in reducing the ICP effects. Lab-scale HFFO investigation during our recent study [25] concluded that water flux during HFFO comparatively gave up to 66% higher flux outcome in comparison of flat sheet membrane using fertilisers as DS. Most studies on the FO process including the FDFO process were however conducted at a lab-scale level with a very small membrane area, mostly less than 0.05 m^2 using the only commercialised cellulose triacetate (CTA) FO membrane and hence the study using hollow fibre FO membrane module at a larger-scale level are still very limited.

This study investigates the performance of the recently developed PA TFC HFFO membrane module for the desalination of real brackish groundwater (BGW) for irrigation using fertiliser as DS. This is the first study on the FDFO desalination process using PA HFFO membrane module at a much larger scale level than the lab-scale level reported in many earlier studies. The other specific objectives are to evaluate how the solution properties such as FS and DS properties and operational conditions such as crossflow rates, membrane orientation influence the performance of the HFFO when operated at a larger-scale module level. The study also investigated the impact of scaling on the HFFO membrane when fertilisers are used as DS with the real BGW for desalination. It is important to note here that, the scope of this study is limited to evaluating the performance of the newly developed HFFO membrane module for the FDFO desalination process. The post-treatment system to meet the water quality standard in terms of nutrient concentration required for fertigation of crops is not included in this study as it has been separately studied earlier [13,26,27].

2. Materials and methods

2.1. Draw solution and feed solution

The saline FS was prepared by dissolving the actual BGW salt in the tap water (TW). The BGW salt supplied by Pyramid salt Pty. Ltd Australia is collected from some of the evaporation ponds that are part of the salt interception scheme located within the Murray–Darling Basin in Australia [13]. The detailed composition of the BGW salt is presented in Table 1. To simulate the variation of BGW salinity within the basin [26,28], feed water containing different levels of salt concentrations or total dissolved solids (TDS) were prepared and used in this study. BGW5, BGW10, BGW20 and BGW35 therefore represent the feed water with TDS of 5, 10, 20 and 35 g L^{-1} respectively.

Four different fertilisers were used as draw solutes which included monoammonium phosphate or $NH_4H_2PO_4$ (MAP), diammonium phosphate or $(NH_4)_2HPO_4$ (DAP), ammonium sulphate or $(NH_4)_2SO_4$ (SOA) and calcium nitrate or $Ca(NO_3)_2 \cdot 4H_2O$. The selection of the fertilisers was based on the earlier studies in which these fertilisers were found to be suitable for use as DS [12,13]. NaCl was also used as reference draw solutes to compare the performance of the HFFO membrane module with available literatures on the HFFO membranes. All chemicals used in this study were of technical grade (Chem Supplies, Australia). All the initial fertiliser DS were prepared by dissolving the fertiliser salts in distilled water. Table 2 shows some of the essential properties for the five selected fertiliser DS in solution.

2.2. HFFO module experimental setup and operating procedures

The process layout diagram of the semi-pilot scale FO unit is presented in Fig. 1 along with the picture of the setup used in the lab. The housing of the HFFO element had an internal diameter of 7.5 cm and length of 50 cm. The element was composed of 790 individual fibres with an effective length of 45 cm and a total membrane area of 1 m^2 supplied by Samsung Cheil Industry, South Korea. The fibres were glued together at each end of the housing element to provide a perfect sealing and to prevent the leakage of solutions. The lumen side of the fibre was composed of PA TFC active layer supported on the porous polyethersulfone (PES) hollow fibre substrate on the outer shell of the fibre. The inner and

Table 1
Composition of raw BGW salt (1 g dissolved in clean water) obtained from the evaporation ponds of the salt interception scheme within the MDB. This same salt was used to prepare FS of different concentrations by dissolving in the distilled water. The list provides only those major elements.

Composition	Concentrations in 1 g L^{-1} salt solution (mg L^{-1})	Composition	Concentrations in 1 g L^{-1} salt solution (mg L^{-1})
Calcium	32	Chloride	558
Magnesium	13	Sulphate	52
Potassium	3	CO_3	2
Sodium	340	Total (TDS)	1000

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