A NOVEL FERTILISER DRAWN FORWARD OSMOSIS DESALINATION FOR FERTIGATION

by

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Doctoral of Philosophy

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of candidate

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1. ***S. Phuntsho**, H. K. Shon, S. Vigneswaran, J. Kandasamy, S. K. Hong and S. Y. Lee. (2012). Influence of temperature and temperature difference in the performance of forward osmosis desalination process. Journal of Membrane Science 415-416 (2012): 734-744.

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Conference papers and presentations

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3. Laura Chekli, **Sherub Phuntsho** and Ho Kyong Shon. Assessing the aggregation behaviour of Iron Oxide Nanoparticles by Flow Field-Flow Fractionation. CESE 2012 Sep 9-13, 2012 Melbourne.
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8. ***Sherub Phuntsho**, Amit Chanan and Ho Kyong Shon. Fertilised irrigation using energy-efficient forward osmosis for saline groundwater desalination in the Murray Darling Basin. IAL 2012. Adelaide, Australia. 24-29 June 2012.
9. *Tahir Majeed, Ho Kyong Shon, **Sherub Phuntsho**, and Roger Ben Aim. Fertilizer Drawn Forward Osmosis (FDFO) for Fertigation to Tomato. IWA LET 2012, Brisbane, 3-7 June 2012.
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1. **S. Phuntsho**, H. K. Shon, S. Vigneswaran, and J. Kandasamy, Wastewater Stabilization Ponds (WSP) For Wastewater Treatment, in Water and Wastewater Treatment Technologies, S. Vigneswaran, Editor. 2009, Encyclopedia of Life Support Systems (EOLSS).

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LIST OF ABBREVIATIONS

FO : Forward osmosis
FDFO : Fertiliser drawn forward osmosis
RO : Reverse osmosis
SWRO : Seawater reverse osmosis
PRO : Pressure retarded osmosis
BW : Brackish water
BGW : Brackish groundwater
RSF : Reverse solute flux
SRSF : Specific reverse solute flux
DS : Draw solution
FS : Feed solution
SIS : Salt interception scheme
MDB : Murray-Darling Basin
MDBA : Murray-Darling Basin Authority
CP : Concentration polarisation
ICP : Internal concentration polarisation
ECP : External concentration polarisation
GL : Giga litre
CTA : Cellulose triacetate
TFC : Thin film composite
CA : Cellulose acetate
PWP : Pure water permeability
HTI : Hydration Technology Innovations
NF : Nanofiltration
TDS : Total dissolved solids
DI water: Deionised water
NPK : Nitrogen Phosphorous Potassium
PR : Performance ratio
EC : Electrical conductivity
MSF : Multi stage flash
MED : Multi effect distillation
DAP : Diamminium phosphate or $(NH_4)_2HPO_4$
MAP : Monoammonium phosphate or $NH_4H_2PO_4$
SOA : Sulphate of ammonia or $(NH_4)_2SO_4$
MW : Molecular weight
PAO : Pressure assisted osmosis

List of Symbols

A	: Pure water permeability coefficient ($Lm^{-2}h^{-1}bar^{-1}$)
B	: Salt permeability coefficient ($m.s^{-1}$)
C	: Solute concentration (mg/L or Moles or M)
D	: Diffusion coefficient ($m^2\ s^{-1}$)
d_h	: Hydraulic diameter (m)
J_s	: Solute flux ($mmoles.m^{-2}.h^{-1}$ or $g.m^{-2}.h^{-1}$)
J_w	: Water flux ($Lm^{-2}h^{-1}$)
k	: Mass transfer coefficient
K	: Resistance of solute diffusion within the membrane support layer (s/m)
L	: Length of the channel (m)
M	: Molar concentration of the solution (M)
M_w	: Molecular weight (mol/g)
n	: Van't Hoff factor
P	: Applied hydraulic pressure (bar)
R	: Universal gas constant (0.0821 $L.atm.mol^{-1}\ K^{-1}$)
Re	: Reynolds number
R_s	: Salt rejection (%)
Sc	: Schmidt number
Sh	: Sherwood number
T	: Absolute temperature (in K)
π	: Osmotic pressure (atm or bar)
σ	: Reflection coefficient

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ABSTRACT

Agriculture consumes maximum water of up to 70% of the total fresh water withdrawn in the world for consumptive purposes. Rapid population growth is further driving fresh water demand and putting tremendous stress on limited fresh water resources. This increasing demand can only be met by improving the current water use efficiency and by creating new water sources. Desalination could therefore play a significant role in creating a new water source by using unlimited saline water sources. However, current desalination technologies are energy intensive and energy has a significant impact on climate change. If low cost desalination technologies were made available, their impact on agriculture sector would be significant for many water stressed regions of the world.

Recently, forward osmosis (FO) has been recognised as one of the most promising low energy processes for desalination. The FO process is based on the principle of natural osmotic process driven by the concentration gradient and not by hydraulic pressure like the reverse osmosis (RO) process and hence requires significantly lower energy. In the FO process, a concentrated draw solution (DS) extracts fresh water from the saline water using special membranes. The issue of membrane fouling in FO process is less challenging than the RO process where fouling constitutes a major operating issue. However, the lack of a suitable DS has limited the application of FO desalination for potable water. The separation of draw solutes from the diluted DS after desalination requires additional post-treatment processes that still consume energy, making FO uncompetitive with the already established RO desalination technology.

The FO process offers novelty for those applications where the complete separation of draw solutes is not necessary and where the final diluted DS can be used directly if the presence of draw solutes adds value to the end use. Fertiliser drawn forward osmosis (FDFO) desalination for fertigation is therefore proposed based on this concept. When fertilisers are used as the draw solutes in the FDFO desalination process, the diluted fertiliser solution after desalination can be directly applied for fertigation because fertilisers are essential for plants. This concept avoids the need for an additional post-treatment process for the separation and recovery of draw solutes. The objective of this study is therefore to investigate the performance of the FDFO desalination process for fertigation, identify its limitations and investigate options to overcome these limitations. The study has been presented in eleven chapters that include a definition of the detailed

concept and an assessment of the performance of eleven selected fertilisers as the DS under various conditions, through both simulation and bench-scale experiments.

The energy required for FDFO for direct fertigation was estimated to be less than 0.24 kW/m^3 of fertigation water, which is comparatively lower than the most efficient current desalination technologies. As such, FDFO can also be easily powered using renewable energy sources, such as solar and wind. Since fertilisers are extensively used for agriculture, FDFO desalination does not create additional environmental issues related to fertiliser usage. In fact, FDFO desalination could add more value to irrigation water, thereby providing opportunities for improving the efficiency of water and fertiliser uses. FDFO desalination can be operated at very high feed recovery rates: higher than 80% using a feed of seawater quality. However, FDFO desalination has its own process limitation. Based on the principles of natural osmosis, the net movement of water across the membrane towards the DS cannot theoretically extend beyond osmotic equilibrium, which in turn is limited by the total dissolved solids (TDS) content of the feed solution (FS). Therefore, it is not possible to achieve a concentration of the diluted DS that is lower than the equivalent concentration of the FS without external influence.

Based on the models for osmotic equilibrium, the water extraction capacities of eleven selected fertiliser DS were calculated for FS, simulated for different ranges of TDS. The water extraction capacities of the fertilisers were observed to depend on the molecular weight and osmotic pressure of the draw solutes, as well as on feed concentration. Based on the water extraction capacity, the expected fertiliser nutrient concentrations in the final FDFO product water was estimated in terms of nitrogen phosphorous potassium (NPK) concentrations. The expected final nutrient concentrations for simulated brackish water (BW) feed (TDS 5,000–35,000 mg/L) failed to meet acceptable NPK concentrations for direct fertigation of crops. Hence, achieving acceptable nutrient concentrations for direct fertigation will be a major challenge for the FDFO desalination process. The rest of the study therefore focussed on investigating processes and options that would help reduce the nutrient concentrations in the final FDFO product so that the final FDFO product water could be used for direct fertigation.

Before the experimental investigation on the FDFO desalination, the influence of major parameters on the performance of FO desalination process was investigated. The thermodynamic properties of the DS play a more influential role on water flux than the thermodynamic properties of the FS at higher temperature. Although water flux comparable to the RO desalination process was obtained by increasing the fertiliser DS concentrations, the internal concentration polarisation effects played a significant role in the performance of the FDFO desalination process. It was observed that any soluble fertilisers with osmotic pressure in excess of the FS can draw water in FO process; however, only eleven different chemical fertilisers commonly used for agriculture worldwide were selected and their performances studied. The performance of the fertiliser solutions as DS were assessed in terms of water flux, reverse draw solute flux, water extraction capacity and nutrient concentrations in the final product water.

Blended fertilisers as the DS were able to achieved significantly lower NPK concentrations by FDFO desalination than the straight/single fertiliser as DS. However, it was observed that blending fertilisers generally resulted in a slightly reduced bulk osmotic pressure and water flux compared to the sum of the osmotic pressures and water fluxes of the two individual fertilisers when used as DS alone. An integrated FDFO-NF desalination process was investigated to reduce the nutrient concentrations in the final product water. Nanofiltration (NF) as pre-treatment or post-treatment was found to be effective in reducing the final NPK concentrations to acceptable limits for direct fertigation although it required second NF pass, especially when monovalent fertiliser was used as the DS or when a high TDS feed was used. NF as post-treatment was more advantageous in terms of both nutrient reduction and energy consumption because high quality, diluted DS was used as feed.

Finally, this study has recommended a pilot test of the integrated FDFO-NF desalination process in the Murray-Darling basin. Recommendations for further investigations on reducing nutrient concentrations include pressure assisted FDFO desalination and the concept of using osmotic fillers as the DS with fertilisers. The study also recommended evaluating the potential for fertiliser drawn pressure retarded osmosis (FD-PRO) desalination for simultaneous desalination and power generation, and for self-powering the FO desalination process. The other recommendations include a study on membrane fouling and scaling issues for FDFO desalination operated at high recovery rates, boron rejection and, finally, a life cycle analysis of the FDFO desalination process.