Economic, energy and carbon footprint assessment of integrated forward osmosis membrane bioreactor (FOMBR) process in urban wastewater treatment

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Supplementary information

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Summary: There are seven pages in the supporting information section (4 tables and 1 graph)

Appendix A: Mass balance, CAPEX and OPEX parameters and assumptions

Table A1. Characteristics of the influent wastewater

Parameters of the wastewater influent	Symbol	Values	Unit
Influent flow rate	Q_{Inf}	15 000	m^3 day^{-1}
Biosolids concentration in influent	$X_{S,Inf}$	100	mg-COD L^{-1}
COD concentration in influent	$S_{COD,Inf}$	400	mg-COD L^{-1}
NH_4^+ concentration in influent	$S_{NH,Inf}$	50	mg-N L^{-1}
NO_3^- concentration in influent	$S_{NO,Inf}$	0	mg-N L^{-1}

Other assumptions implemented for the mass balance calculations:

i. All of the units were operated with the steady-flow, therefore, there was no accumulation within the system.

ii. The density of the wastewater was assumed to be constant at 1000 kg m^{-3} (The contaminants in the influent were too small to be compared with the volume of wastewater to cause a significant change in the density).

iii. Constant influent characteristics, component conversion in the bioreactor, digester and AMOX reactor. Constant solid destruction in digester over variation of sludge age, stoichiometric ratio, kinetics and temperature of the process (Table A2, supplementary information).

iv. The fouling formation, propensity and characteristics were assumed to be constant, hence, the chemical cleaning frequency was expected to be consistent. However, it was expected the fouling on FO membrane was relatively loose and low in propensity, and therefore, FO required fewer cleaning regimes compared to MF and RO membranes. Intense chemical cleaning, using 3500 ppm sodium hypochlorite (NaOCl) and 2500 ppm citric acid, was conducted 4 times per year for MF and RO, but only twice per year for the FO.

v. The flow of the recycle stream from the sludge handling units to the bioreactors were assumed to be insignificant to affect the characteristics of the influent wastewater.

Table A2. Parameters of the mass balance calculations

Scenario	Unit	Operation Conditions/ Assumptions
All scenarios	Primary Treatment	**Primary Settler** All COD solids is removed and transported to digestion (sludge treatment) at 1%
	Sludge treatment	**Thickener** Biosolids dewatered to a concentration of 5%
		Anaerobic digester Retention time in digester: 16 days Conversion to electricity: 40% Temperature of vessel: 40% Safety margin 1%
		Belt press Biosolids dewatered to a concentration of 15%
A and B	MFAeMBR and FOAeMBR	**MBR** COD conversion: 0.99 NH_4^+ conversion: 0.99 NO_3^- conversion 0.7 - 0.99 Biomass retention time: 30 days Autotrophs decay rate: 0.1 per day Heterotrophs decay rate: 0.2 per day Autotrophs yield rate: 0.24 g cell COD formed/ g NH_4^+-N oxidized Heterotrophs yield rate: 0.67 g cell COD formed/ g COD removed (oxidized+assimilated)
All scenarios with MF application	MFAeMBR and MFAnMBR	**MF unit** Water flux recovery: 95% Rejection performance: COD = 50% Intense chemical cleaning: 4 times per year Concentration of chemicals used for cleaning: 3500 ppm NaOCl, 2500 ppm citric acid
Scenario B: MFAeMBR-RO	RO	**RO unit** Water flux recovery: 75% Rejection performance: COD = 100%, NH_4 = 98%; NO_3= 95% Intense chemical cleaning: 4 times per year Concentration of chemicals used for cleaning: 3500 ppm NaOCl, 2500 ppm citric acid
All scenarios with FO application	FOAeMBR and FOAnMBR	**FO unit** Water flux recovery: 80% Rejection performance: COD = 99%, NH_4^+ = 93%; NO_3^-= 85% (experimental results) Intense chemical cleaning: 2 times per year Concentration of chemicals used for cleaning: 3500 ppm NaOCl, 2500 ppm citric acid
Scenario B: FOAeMBR-RO	RO	**RO unit** Water flux recovery: 50% Rejection performance: COD = 100%, NH_4^+ = 98%; NO_3^-= 95%

		Intense chemical cleaning: 4 times per year Concentration of chemicals used for cleaning: 3500 ppm NaOCl, 2500 ppm citric acid
Scenario C	MFAnMBR and FOAnMBR	**AnMBR** ***Remarks****: Due to the complexity of the anaerobic reactions; it has been simplified to acidogenesis and methanogenesis. The COD in the wastewater is assumed to be fully degradable.* Conversion by acidogenesis: 1 Conversion by methanogenesis: 0.99 Biomass retention time: 40 days Acidogenesis decay rate: 0.02 per day Methanogenesis decay rate: 0.036 per day Acidogenesis yield rate: 0.07 g COD formed/ g COD removed Methanogenesis 0.076 g COD formed/ g COD removed **PN/Anammox** Conversion by autotrophs: 0.57 Conversion by anammox (MF): 0.26 Conversion by anammox (FO): 0.40 Biomass retention time: Indefinite Autotrophs decay rate: 0.2 per day Anammox decay rate: 0.00384 per day Autotrophs yield rate: 0.24 g COD formed/ g COD removed Anammox 0.164 g COD formed/ g COD removed

Other assumptions implemented for CAPEX and OPEX calculations:

i. Other values or costs provided in $USD by the suppliers were converted by assuming constant exchange rate of $USD 1.00 = $AUD 1.33.

ii. The detailed calculation of the pump installation (except for the membrane units; MF, FO and RO) in the wastewater treatment plants were not considered, therefore, a higher contingency value (50%) was applied to cover for the pump installation and operation.

iii. The cost of the gas purging in the anaerobic membrane bioreactor (AnMBR) was not significant to be compared to the other OPEX (e.g. aeration and mixing) hence, purging cost was not included in the calculations.

iv. The energy consumed for the anaerobic digester unit included the energy required for stirring and pre-heating of the influent.

v. Membrane cost was assumed to be constant throughout the operation. The installation and membrane replacement costs are as shown in Table 3 in the main manuscript.

vi. The earnings of the wastewater treatment plant depending on the quality of the effluent or product water produced (Table A3, supplementary information).

Table A3. Specific earnings of wastewater treatment

Earnings		**Values**	**Unit**
Biological treatment	Carbon-based compounds removal	5	$/ kg-chemical oxygen demand (COD)
	Nitrogen-based compounds removal	15	$/kg-N
Electricity produced from methane		0.12	$/kWh
Water sale		1.70	$/m^3

Appendix B: Sensitivity analysis – carbon footprint

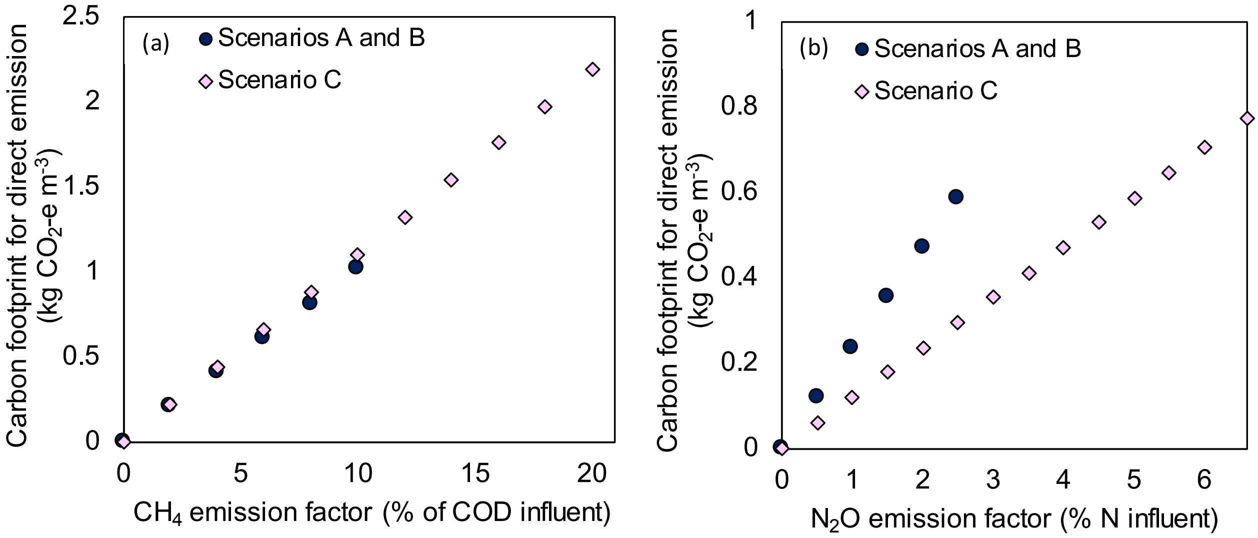

Fig. B1: Sensitivity analysis of carbon footprint for direct emission due to the variation of GHG emit/mass influent ratio (a) CH_4 emission factor in scenarios A, B and C; (b) N_2O emission factor in scenarios A, B and C

Based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories[1], the CH_4 emission factor $(B_O \times MCF)$ may vary from 5 – 10% and 5 – 20% of COD influent for aerobic-anoxic and anaerobic+PN/AMOX operations respectively under a sub-optimal operation. As for N_2O emissions, a review done by Law (2012) shows that the aerobic-anoxic may vary from from 0.035 –2.59 % of N-influent for aerobic-anoxic process and 0.4 – 6.6 % of N-influent for anaerobic+PN/AMOX process.[2]

Appendix C: Reverse salt diffusion baseline calculation

Table C1. Methodologies of reverse salt diffusion in FOMBR operation

Parameters	Equation/ Justification	Value	Unit
Volume of MBR (V_{MBR})	$\frac{Mass\ biosolid\ in\ bioreactor}{Biosolid\ concentration}$	896	m^3
Maximum salt concentration in MBR ($C_{salt\text{-}max}$)	Assumption	3	kg NaCl m^{-3}
Reverse salt flux (RSD_{flux})	Assumption	0.01	kg $m^{-2}.hour^{-1}$
Area of MF required (A_{MF})	-	2776	m^2
Rate of salt diffuse (RSD_{rate})	$RSD_{flux} \times A_{MF}$	416	kg $hour^{-1}$
MF water flux (MF_{flux})	Assume the MF is operated at 2 bar	0.05	$m^3\ m^{-2}\ hour^{-1}$

The CAPEX and OPEX of MF in controlling salinity in FOMBR were referred to Choi's work (2015)[3]. The CAPEX of MF installation was \$119 944 meanwhile the CAPEX for the FO operation was \$31 504 year^{-1}. These values were equivalent to 5 % and 7 % of FO CAPEX cost and FO OPEX in scenario A respectively.

References:

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