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Downscaling reverse osmosis for single-household wastewater reuse: towards low-cost decentralised sanitation through a batch open-loop configuration

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ABSTRACT

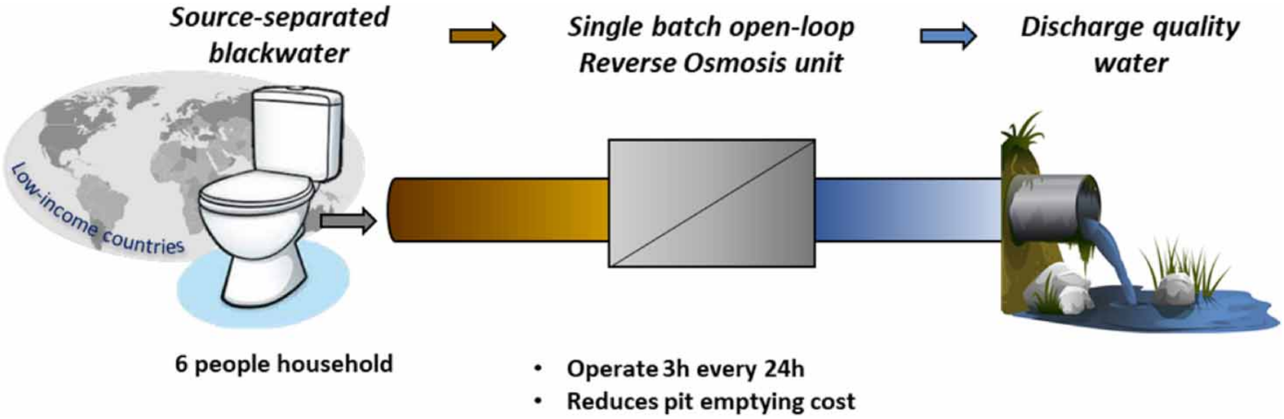
There is a significant demand for water recycling in low-income countries. However, wastewater infrastructure is primarily decentralised, necessitating the development of affordable household-scale reclamation technology. In this study, a batch open-loop reverse osmosis (RO) system is therefore investigated as a low-cost clean water reclamation route from highly saline concentrated blackwater. In a single-stage configuration, increasing feed pressure from 10 to 30 bars improved selective separation at water recovery exceeding 85%, whereas lower cross-flow velocity improved product recovery, reducing specific permeate energy demand from 21 to 4.8 kWh m^{-3}. Rejection achieved for total phosphorous (99%), chemical oxygen demand (COD, 96%), and final pH (8.7) of the RO permeate was compliant with the ISO30500 reuse standard for discharge. However, the rejection of total nitrogen in the RO permeate was non-compliant with the reuse standard due to the transmission of low-molecular weight (MW) uncharged organic compounds. It is suggested that rejection may be improved by increasing feed pressure to rebalance selectivity but may also be controlled by reducing fluid residence time (storage) to constrain the hydrolysis of urea. The economic analysis identified that a high-pressure 1812 element cost of ∼US$30 meets the sanitation affordability index of US$0.05 $capita^{-1}$ day^{-1}. However, the unit cost of a high-pressure feed pump must be reduced to ∼US$500 to obtain an affordable system cost. These unit costs can be achieved by manufacturing 1812 elements at economies of scale, and by adopting pumping solutions that have been developed for other applications requiring high pressures and low flows. Overall, our findings suggest that RO in the batch open-loop configuration has the potential to deliver affordable and safe water production from blackwater in a decentralised (single-household) context.

Key words: batch RO, blackwater, decentralised RO, urine and faeces, wastewater RO

HIGHLIGHTS

- RO for decentralised blackwater treatment is investigated.
- For blackwater, a single-element batch RO system is proposed.
- RO delivers permeate quality to ISO30500 sanitation standard.
- The potential of RO to deliver sanitation with the low-income countries (LIC) affordability index is shown.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Recycling water from municipal wastewater is critical for water-scarce regions and is reliant upon reverse osmosis (RO) for producing high-purity recycled water (Bartels *et al.* 2005; Malaeb & Ayoub 2011). To date, water recycling has been implemented through large-scale, centralised infrastructure within high-income countries. However, there is a significant demand for water recycling in low-income countries, where infrastructure is primarily decentralised, with an emphasis on pit latrines that serve as intermediate storage facilities and are prone to flooding and leaching into local groundwater resources (Mercer *et al.* 2021). Due to the significant costs associated with pit emptying, unregulated discharge of untreated wastewater is prevalent, resulting in increased enteric pathogen contamination of local water resources and high morbidity rates worldwide (WHO/UNICEF Joint Water Supply, and Sanitation Monitoring Programme 2015). Enabling water recycling from wastewater at the single-household scale in low-income countries, therefore, provides the following three benefits: (i) improving local water resources through reducing enteric pathogen contamination; (ii) reducing pit latrine emptying costs, by reducing frequency and volume of pit latrine emptying; and (iii) creating a higher quality water product than is afforded from local sources of unknown provenance (Kamranvand *et al.* 2018).

RO has been successfully scaled down to a single-household application for drinking water, where the feed pressure provided by the mains supply typically offsets the need for a feed pump, while the relative low salinity of the feedwater imparts a negligible osmotic pressure, resulting in high-quality water production, and a good recovery ratio (RR) from a single element configuration. The blackwater produced prior to discharge into a pit latrine is typically concentrated due to the use of low flush volumes, or the adoption of dry toilet systems, which is increasingly popular due to water scarcity (Mkhize *et al.* 2017) and ethical considerations. Consequently, urine is the dominant liquid fraction, creating a saline wastewater matrix, comprising a broad range of inorganic and organic salts, low-MW organic compounds such as urea, and higher MW organics including secreted proteins and sugars (Kamranvand *et al.* 2020). The separation mechanisms imposed by the dense semi-permeable RO membrane (e.g., size-exclusion, charge exclusion, and other physico-chemical interactions) have been demonstrated to reject a range of nutrients and micropollutants present in household wastewater (Van Voorthuizen *et al.* 2005; Yoon & Lueptow 2005; Garcia *et al.* 2013) and urine (Ek *et al.* 2006), however, concentrated blackwater (or faecally contaminated urine) increases complexity as water quality can vary temporally, through dynamic hydrolysis reactions (Kamranvand *et al.* 2020). Concentrated blackwater also raises the osmotic pressure, where a transmembrane pressure (TMP) of 50 bar has been estimated to achieve an 80% RR from urine (Maurer *et al.* 2006). The membrane element configuration, and pump duty required to deliver high water recoveries from blackwater at a competitive cost are therefore considerably more challenging than for drinking water at a single-household scale.

Large-scale RO water recovery facilities are designed in a 'single-pass' plug flow arrangement (Figure 1), where a stage, comprising multiple RO elements, each with a conversion efficiency of ~15%, are arranged in series, while multiple stages with intermediate pumping are used to increase water recovery from the concentrate (Elimelech & Phillip 2011). However, several practical limitations exist for this configuration to recover water at a single-household scale: (i) significant variability in feed composition, will introduce a considerable inconsistency in product recovery; (ii) high RRs in single-pass will expose specific

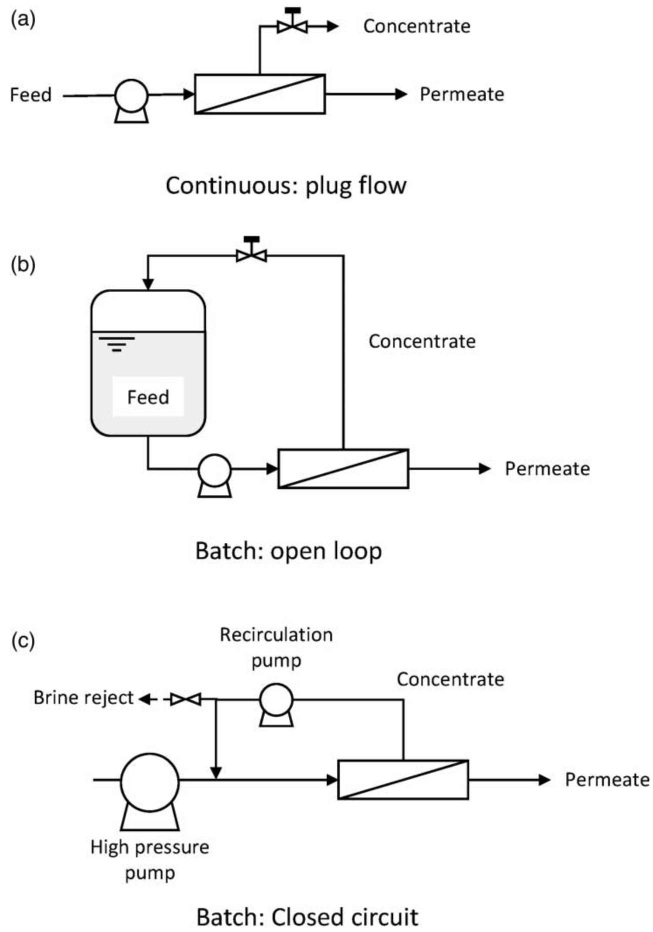


Figure 1 | Schematics of the various process designs of RO showing (a) a once through plug flow system typically used for desalination; (b) a batch open-loop configuration generally used for small batch operation; and (c) a batch closed-circuit design for achieving greater energy efficiency.

elements to high solute concentrations, augmenting fouling; and (iii) the cross-flow and geometric restrictions of commercial RO element design yield around 9% product recovery per 100 cm element length (40″) (Singh 2015), making system scalability and cost practically unfeasible. A batch-configured RO instead comprises a single stage, as the required RR is achieved by recirculating the concentrate (Figure 1), which is advantageous in handling variation in feedwater composition, while the shorter element contact time with the final high-recovery concentrate has been shown to limit fouling, particularly when high RRs are sought within a low-volume process (Warsinger *et al.* 2016). A single-stage design can also improve the cost of an RO sanitation solution, which must meet an affordability index of US$0.03–0.05 person^{-1} day^{-1} to be considered economically viable (Tobias *et al.* 2017). However, repressurisation of the recirculating concentrate is energetically costly, and while a few process designs have been proposed to recover or maintain pressure in the recirculation loop (e.g., closed circuit RO) (Gray 2002; Qiu & Davies 2012; Warsinger *et al.* 2016; Werber *et al.* 2017), such interventions necessarily increase capital cost for pumping which are already sensitive due to the osmotic pressure of blackwater and the scale of implementation.

This study, therefore, seeks to explore the technical and economic feasibility of a batch open-loop RO configuration for single-household scale water recycling from blackwater. The system analysis is conducted experimentally on incoming flow rates comparable to a full-scale system (approximately six people) with a critical focus on three key objectives: (i) evaluate a single-stage design to minimise depressurisation/repressurisation during recycling to reduce energy losses by increasing product recovery per pass through multi-element configuration and hydrodynamic conditions; (ii) characterise permeate to establish the influence of concentrated blackwater on water quality by operating in open-loop batch recycle at high RRs; and (iii) conduct cost analyses of the finalised batch open-loop configuration to determine key cost drivers, and feasibility of RO as a cost-effective sanitation solution for water recycling from blackwater at a single-household scale.

2. MATERIALS AND METHODS

2.1. Experimental setup

The batch open-loop RO system (Figure 2) comprised 1812 membrane elements between 1 and 3 (Table 1) configured in series or in parallel to evaluate product recovery and pressure drop within a single-stage design. A 19 L stainless steel vessel was used to retain the feed, with the concentrate recycled using a high-pressure diaphragm pump (M-03S, Hydracell, USA) controlled through a variable frequency drive (Control Techniques M200, Sterlitech, USA). The test setup was complemented with a pressure relief valve (200–1,500 psi, Swagelok, UK), pressure gauges (0–100 barg, Swagelok, UK), pressure regulators (Sterlitech, USA), and a variable area flow meter (0.5–7 L min^{-1}, Sterlitech, USA). A heater/chiller (Grant TC120-R4, Wolflabs, UK) connected to a stainless steel recirculation coil placed in the feed vessel maintained the feed temperature at 25 °C. Before first use, the 1812 elements were flushed with deionised (DI) water at 3 L min^{-1} for 30 min to remove the preservative solution and conditioned at 30 bar for 1 h with DI water. For a standard experiment, 10 L of feed solution was added to the feed vessel and allowed to equilibrate at 25 °C before initiating testing.

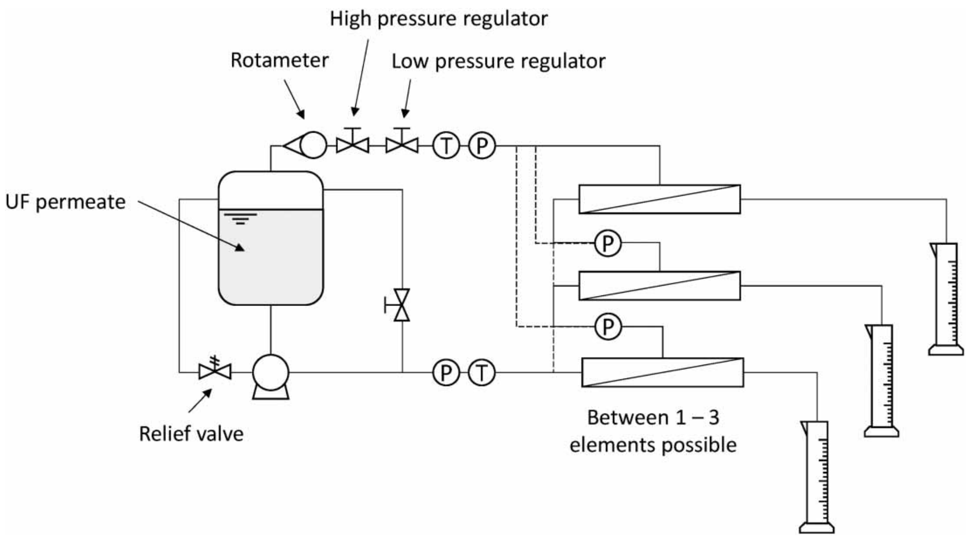


Figure 2 | Schematic of experimental apparatus used for cross-flow membrane filtration. The flow through the three 1812 elements could be adapted for the use of 1–3 elements in either series or parallel configuration.

Table 1 | Properties of the RO elements used in this study

Parameter	Unit
Manufacturer	TriSep
Membrane	TurboClean® 1812-X20-31
Membrane type	RO
Active layer	X-20™ Polyamide-Urea Thin Film Composite
Size (mm, diameter × length)	46.4 × 305
Feed spacer thickness (mm)	0.787
Membrane area per element (m^2)	0.230
Feed side effective flow section ($\times 10^{-3}$ m^2)	0.594
Manufacturer stated rejection[a] (%)	99.5

[a]Rejection measured to RR of 15% with initial salt concentration of 2,000 ppm.

2.2. Feedwater preparation and analytical methods

Chemicals were of reagent grade (Fisher, UK; Sigma Aldrich, UK). Human urine and faeces were collected from anonymous donors with informed consent through a process approved by the Cranfield University Research Ethics System (CURES: 2310/207; 2407/2017). The composition and flow of blackwater were estimated based on the mass balance of a single-household wastewater treatment system for six users. Average urine and faeces mass flows of 2.2 L $person^{-1}$ day^{-1} and 0.026 kg $person^{-1}$ day^{-1}, respectively were assumed (Rose *et al.* 2015). The faeces mass flow was below that nominally assumed per capita (0.128 kg $capita^{-1}$ day^{-1} Rose *et al.* 2015) to account for upstream solid/liquid separation by the toilet interface, where 80% total suspended solids removal has been demonstrated with source separation (Kamranvand *et al.* 2021). Tap water was used to simulate flush water comprising 2.7 L $person^{-1}$ day^{-1}, equivalent to the flow rate from a low flush toilet. Before use, these solutions were combined and mixed with a magnetic stirrer at 800 rpm for 30 min, to produce a homogenised blackwater. A two-stage ultrafiltration (UF)-RO unit was employed, comparable to that implemented for single-household drinking water production. The blackwater was filtered through a UF membrane (Figure A1, MP 1018-102, Koch Separation Solutions, USA) with a nominal pore size of 0.03 μm (area, 0.07 m^2) at a constant flux of 6 L m^{-2} h^{-1}, the cross-flow velocity (CFV) of 10 cm s^{-1}, and an average TMP of <50 mbar. To increase data production, synthetic blackwater was prepared based on the chemical analysis of urine in the initial screening phase for set conditions (Table 2) (Putnam 1971). Solutions of NaCl with equivalent conductivities to the estimated wastewater were used for the initial identification of boundary conditions (urine, 0.2 M NaCl; equivalent toilet wastewater 0.056 M NaCl) (Mercer *et al.* 2019a), to decouple dynamic fouling effects from the examination of osmotic pressure (and gross pressure) requirements. Chemical oxygen demand (COD), total ammoniacal nitrogen (NH_4-N), total nitrogen (TN), and total phosphorous (TP) were determined using standard photometric test kits (Spectroquant®; COD 114541; $NH4^+$-N 114559; TN 114763; TP 114763; Merck, UK). Solution pH was determined with a pH probe (4330, Jenway, Stone, UK) calibrated to standard buffers (4, 7, and 11) before measurement. Conductivity was recorded using a conductivity meter (CDH SD1, Omega, UK).

2.3. Data analysis

For this study, there exists two potential definitions for water recovery. These have been defined as the batch RR and the operating RR. The batch RR is defined as the ratio of the cumulative volume of total permeate collected (V_p) to that of starting feed volume (V_f) for that batch calculated as:

$$RR = \frac{V_p}{V_f} \quad (1)$$

Table 2 | Composition of the synthetic toilet wastewater used in this study, based upon the characterisation mentioned in Putnam (1971)

Chemical group	Compound	Concentration in urine determined in reference Putnam (1971) (g L^{-1})	Calculated concentration in synthetic blackwater (g L^{-1})
Inorganic salts	Sodium chloride	8.00	3.32
	Potassium chloride	1.64	0.682
	Potassium bicarbonate	0.661	0.275
	Potassium sulphate	2.63	1.09
	Magnesium sulphate	0.783	0.325
Organic ammonium salts	Ammonium hippurate	1.25	0.519
	Ammonium formate	0.0880	0.0366
	Ammonium citrate	0.756	0.314
	Ammonium lactate	0.394	0.164
Organic compounds	Urea	13.4	5.57
	Creatinine	1.50	0.625
	Creatine	0.373	0.155
	Glycine	0.315	0.131

Dilution of determinands is to compensate for the presence of flush water in the blackwater.

The operating RR gives an indication of the RR per pass at a specific time point during the batch process. This is a dynamic value over the course of the batch process and has been defined as r:

$$r = \frac{\dot{Q}_p}{\dot{Q}_f} \quad (2)$$

where $\dot{Q}_p$ and $\dot{Q}_f$ are the volumetric flow rates of the permeate and feed, respectively at a specific timepoint in the batch process. The rejection of specific components (i) of the feed/retentate were determined from the measured concentration at defined time intervals during the experiment and from discrete permeate samples using:

$$Rejection_i = \left(1 - \frac{C_{i,p}}{C_{i,f}}\right) \times 100\% \quad (3)$$

where $Rejection_i$ is the rejection of component i, $C_{i,p}$ is the concentration of component i in the permeate, and $C_{i,f}$ is the concentration of component i in the feed. The work required to perform the separation by the RO process was calculated using:

$$W = P \overset{t}{\dot{Q}_f} \quad (4)$$

where W is the work required for the separation, P is the applied TMP, $\dot{Q_f}$ is the feed flow rate, and t is the time to achieve required separation. In this study, 80% pump efficiency has been assumed (Warsinger *et al.* 2016). To determine economic viability, net present value (NPV) was used to calculate revenue based on a sanitation affordability index of US$0.05 person^{-1} day^{-1} and taking into consideration the time value of money:

$$\text{NPV} = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} - \text{CAPEX} + \text{Unit Cost} \quad (5)$$

where R_t is the net cash flow over the time interval t and i is the discount rate estimated as 6% (Table 3). The sanitation affordability index is used in the NPV calculation to represent the financial threshold at which those most in need can afford to pay. Consequently, a positive return indicates that the technology may be affordable for implementation in the proposed context (revenue may flow directly from the government or through end user's spending capacity). The system price is amortised over a defined period of 15 years and then netted against the affordability index, resulting in the residual daily income, which forms the positive cash flow for the NPV calculations. The UF pre-treatment was excluded from the cost analysis. The total system flow rate is 33 L day^{-1} (Table 3). Preliminary UF trials indicate sustainable fluxes of 3–6 kg m^{-2} h^{-1} using low pressure pumps (Supplementary Material, Figure A2), suggesting that a conservatively designed, and cost-effective UF system can be realised. However, robustness testing of the UF system is to be undertaken in a follow-on study, to clarify feasibility and cost. The primary focus of this study was to establish the economic and practical feasibility of RO for blackwater treatment, as costs associated with high-pressure pumps and RO pressure vessels are significant cost items (Table 3), making system costs unique from those experienced in conventional point-of-use application.

3. RESULTS AND DISCUSSION

3.1. Feed pressure and approach velocity determine energy demand in the batch open-loop RO

The impact of feed pressure on product recovery and rejection in open-loop batch RO with a single element was studied using a synthetic saline feed, with a conductivity equivalent to a real concentrated blackwater (Figure 3). Increasing feed pressure improved water flux to achieve higher water productivity per pass, and reduced processing time from 10,317 to 2,190 s to achieve a RR exceeding 85%. Processing time and number of passes are important criteria for conversion, as this reduces the normalised pumping energy demand. Consequently, despite the higher feed pressure, operating at 30 bar reduced pumping energy from 21 to 12.5 kWh m^{-3} (Figure 3). Concentration polarisation, membrane resistance, and residence time can account for the significant difference between the theoretical separation energy (red dashed line, Supplementary Material, Appendix A) and actual energy demand. Higher operating feed pressures in open-loop batch RO configuration also improved

Table 3 | Assumptions made for OPEX and CAPEX in NPV calculations

OPEX/CAPEX assumptions		Relative cost fraction (%, at US$100 element^{-1})
Power cost (US$ kWh^{-1})	0.24	
Calculated energy requirement (kWh day^{-1})[a]	0.162	
Interest rate (%)	6	
Lifetime (years)	15	
Capacity (L day^{-1})	33	
Required system RR (%)	85	
Feed pressure (bar)	30	
RO element cost (US$ element^{-1})	25–200	7.27
Membrane area per element (m^2)	0.23	
Number of elements	1	
RO element replacement rate (years)	1–5	
Pipework cost[b] (% of total equipment)	10	0.73
RO housing (US$)	150	10.9
Pump cost (US$)	50–1,000	72.7
Pump efficiency (%)	80	
Operation time (h day^{-1})	3	

[a]Based on five population equivalent scale system.
[b]Assumes a system operating lifetime of 15 years.

rejection, particularly as RR increases (Figure 3), where the higher selectivity can be explained by the relative dependency of water permeability on pressure, whereas salt permeability is largely independent of TMP (Shrivastava *et al.* 2015). The loss in selectivity is exacerbated at lower pressures, which risks compliance failure on product quality (ISO 30500 2018) and as operating TMP approaches the osmotic pressure of the solution, permeability loss becomes significant.

Increasing the CFV slightly improved RO rejection at the initial stage of the batch cycle through diminishing concentration polarisation (Jang *et al.* 2019) but the salt rejection became comparable as feed concentration increased at higher RRs (Figure 4). Considerably higher product recovery per pass was identified by reducing the CFV, which extended element residence time, resulting in a 77% reduction in energy demand from 21 to 4.8 kWh m^{-3}. However, an increased probability for longer term fouling/biofouling of the RO membrane from real blackwater will likely necessitate sustaining higher CFV, and so the cost of extending residence time at higher CFV through increasing number of elements per stage or accepting higher pumping costs for a single element approach must be considered.

3.2. Increasing elements per stage is preferential to element width as $\Delta P_{energy} < \Delta Q_{energy}$

The impact of stage design was investigated by increasing the number of elements in the open-loop batch RO system to improve product conversion per pass, and reduce the energy required for water production. Membrane elements in parallel were also investigated to simulate wider modules that improve gross product conversion per pass with a linearly scalable pressure drop (Figure 5). The time required to achieve >85% product recovery, decreased from 2,832 to 1,500 s and 960 s as elements were added in parallel. The velocity was fixed in each element; thus, it is the increase in effective cross-sectional area from 5.94 to 17.8 cm^2 which improves conversion through increasing flow rate. As such, scaling-up element width did not improve product conversion efficiency per pass, but instead reduced the number of passes required to achieve the desired concentration. Consequently, the normalised energy requirement for water recovery does not change (Figure 5), but the potential for concentration polarisation should reduce through the shorter path length (Maskan *et al.* 2000). However, the salt rejection was comparable to multiple elements in series, indicating that the specified CFV of 0.028 m s^{-1} was sufficient to limit polarisation (Jang *et al.* 2019), while the difference in polarisation effects between configurations may be less evident in open-loop batch RO. Increasing the number of elements in series, therefore provided comparable processing times to

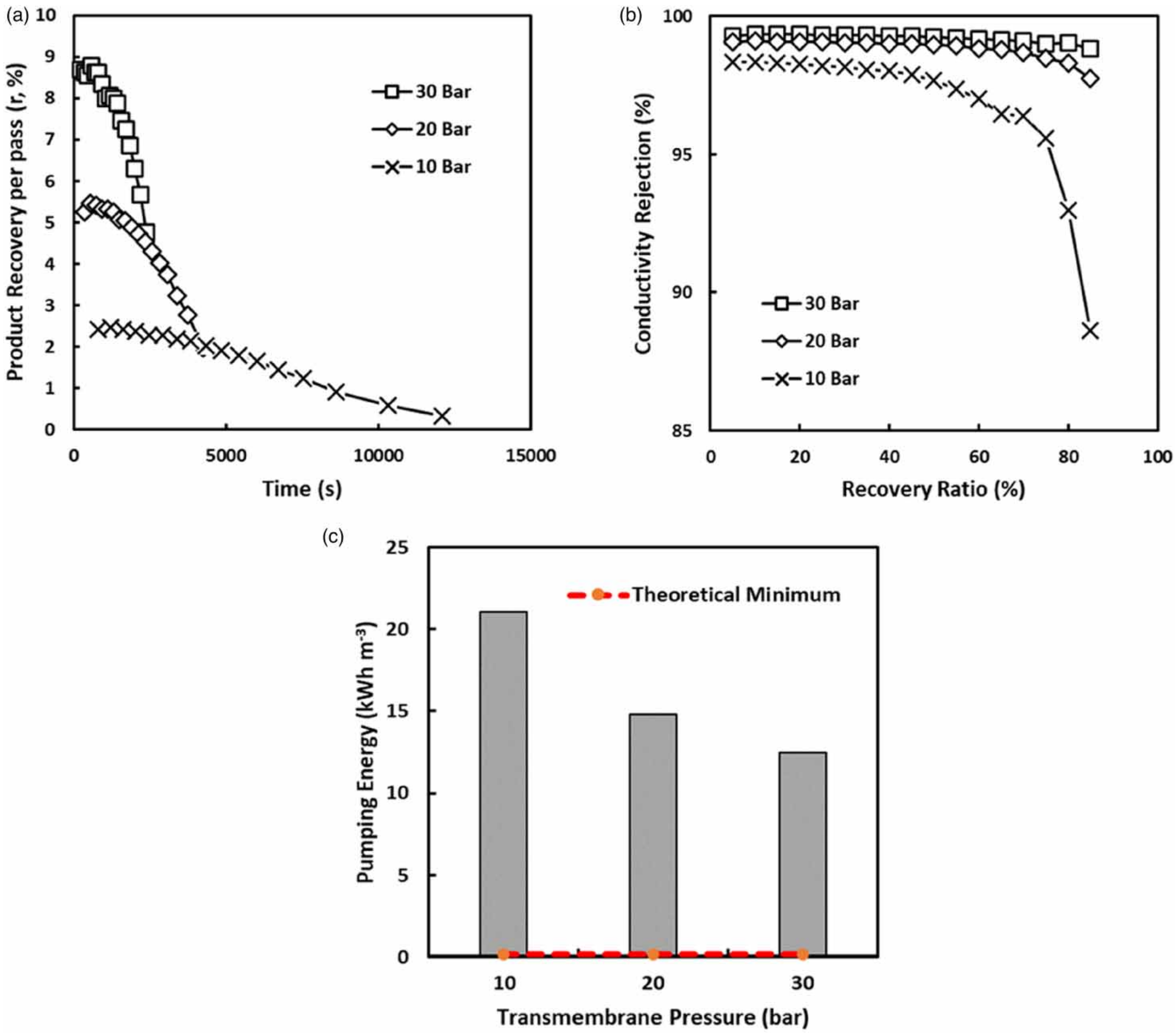


Figure 3 | Effect of TMP on (a) RR per pass; (b) rejection; and (c) pumping energy for a single 1812 element. Experimental conditions: CFV 0.084 m s^{-1}; 25 °C; feed volume 10 L; RR >85%; and feed concentration 0.056 M NaCl (equivalent conductivity to blackwater).

achieve product recovery >85%, but increased product recovery per pass, in doing so reducing the energy required for product water recovery from 4.9 to 1.6 kWh m^{-3} for a one- and three-element stage, respectively (Figure 5).

3.3. Water quality produced from blackwater using a open-loop batch RO configuration

An initial water flux of 54 kg m^{-2} h^{-1} for blackwater was higher than for the synthetic (47 kg m^{-2} h^{-1}), but flux decline was similar for both feedwaters during the open-loop batch RO cycle, indicating that the reduction in flux with increasing RR was ostensibly due to the increase in osmotic pressure (Figure 6). Importantly, this flux establishes that a single 1812 element (0.23 m^2) can enable water recovery from a full-scale system under these conditions (water capacity for six-person system 33 L day^{-1}), operating only 3 h every 24 h. Therefore, whereas a multi-element stage can improve energy efficiency in water recovery, capital cost will favour a single element design. Product water quality was compared against reference values set out within ISO30500 on non-sewered sanitation systems (American National Standards Institute (ANSI) 2016). Rejection for total phosphorus, pH, and COD met the cited reference values for discharge and reuse (Table 4). *Escherichia coli* was below the limit of detection in the RO permeate sample. This compares to an *E. coli* concentration in the UF feed of 3.44 $\log_{10}$ CFU mL^{-1}, corresponding to a total log reduction value (LRV) of 5.44. A COD reduction of 96% was sufficient

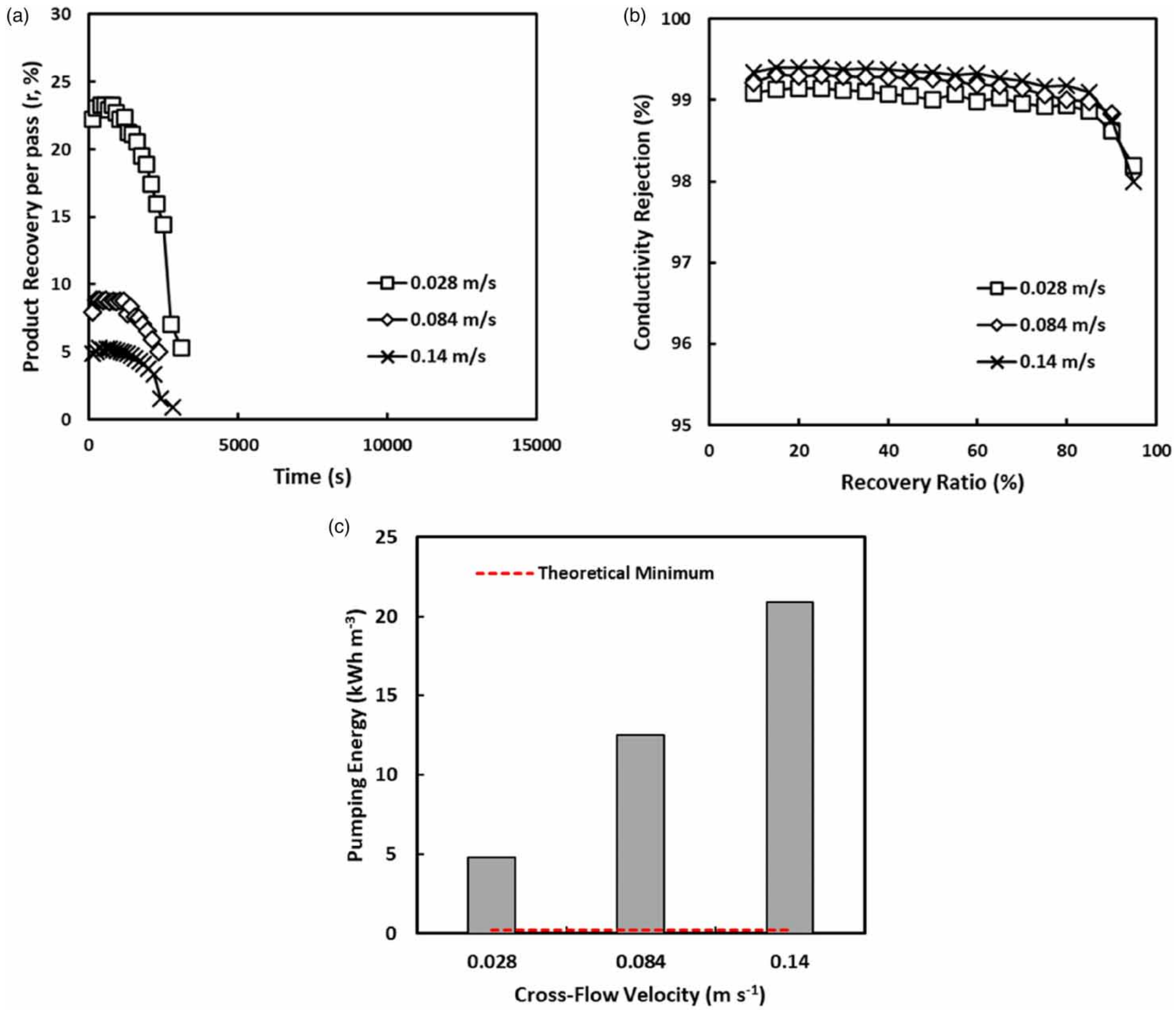


Figure 4 | Effect of the CFV on (a) RR; (b) rejection; and (c) pumping energy for a single 1812 element. Experimental conditions: feed pressure, 30 bar; 25 °C; feed volume, 10 L; RR >85%; and feed concentration 0.056 M NaCl (equivalent conductivity to blackwater).

to achieve Category B status (discharge). The residual permeate *s*COD is associated with high permeability low-MW uncharged organic molecules (e.g., urea) and volatile organic compounds (e.g., *p*-Cresol) (Mercer *et al.* 2019b), which may require a further polishing stage (e.g., granular activated carbon (GAC)) to achieve Category A status for reuse (American National Standards Institute (ANSI) 2016). While TN and COD rejection met ISO30500 reference values at the outset of batch cycling, both determinands fell below this specification following progressive product recovery. This can be accounted for by the decline in selectivity imposed by the reduction in flux following the progressive increase in osmotic pressure (Shrivastava *et al.* 2015), as evidenced by the increase in permeate ammonia coincident with the reduction in flux having achieved a RR >70%. This increase in transmission of free ammonia can also be attributed to the hydrolytic transformation of urea to ammonium, coupled with the progressive increase in pH towards the pKa, shifting the equilibrium of ammonium towards ammonia, which was observed in this study (Kamranvand *et al.* 2020). Rejection may be therefore improved by increasing feed pressure to rebalance selectivity but may also be controlled by reducing fluid residence time (storage) to constrain the hydrolysis of urea. System certification using ISO30500 will characterise rejection at a systems level (i.e., across both UF and RO). While this does not improve the net rejection for determinands which are poorly rejected by UF (e.g., ammoniacal nitrogen), this multi-barrier approach will improve overall conformance for wider determinands. Importantly, this study

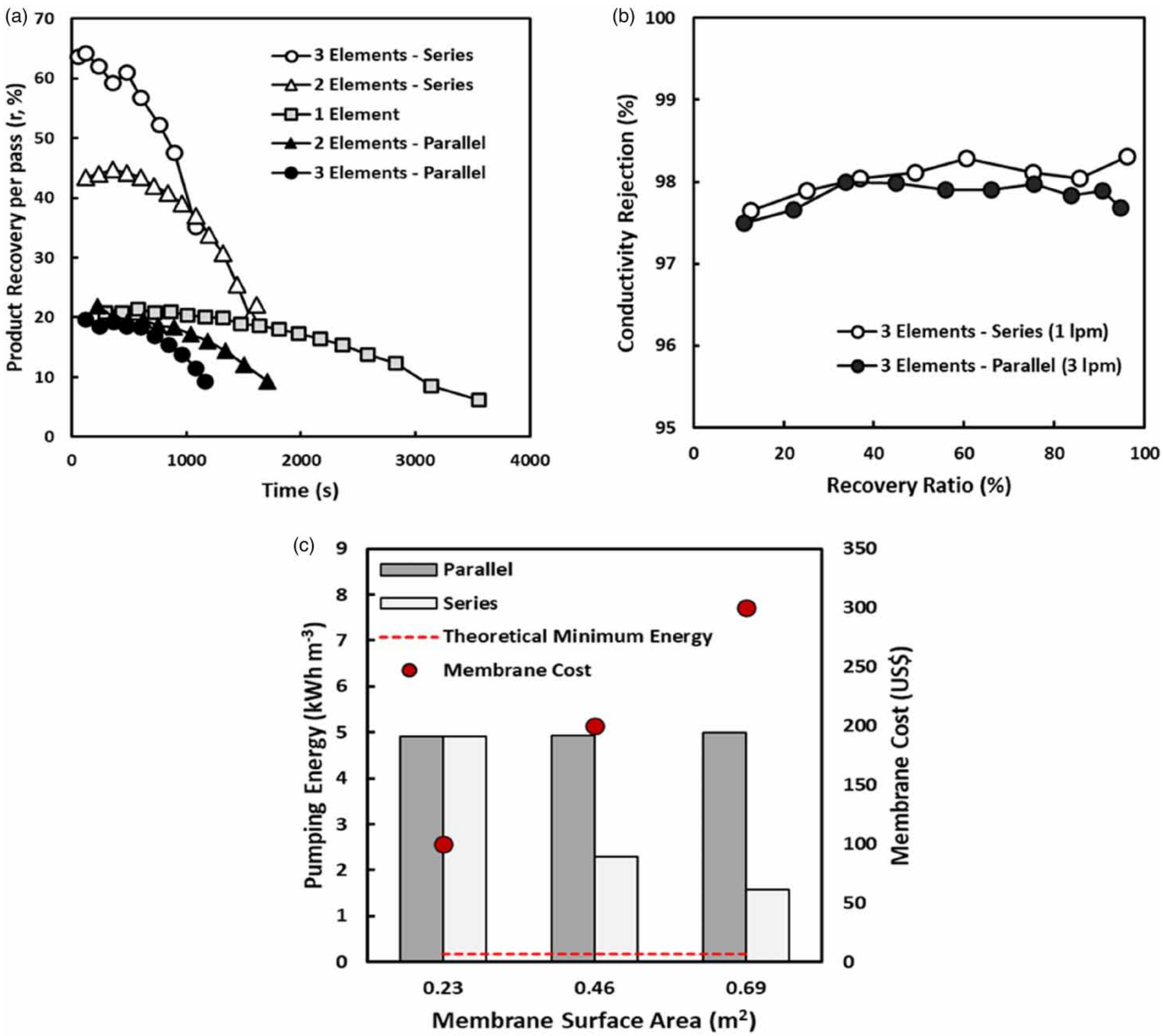


Figure 5 | Investigating a stage design for the batch open-loop RO at fixed velocity, increasing the total membrane area through increasing module number in series or in parallel: (a) impact on product recovery per pass; (b) rejection; (c) pumping energy and membrane cost. Experimental conditions: CFV 0.028 m s^{-1}; 25 °C; feed volume 10 L; concentration 0.056 M NaCl; and TMP 30 bar.

evidences that a single-stage batch open-loop RO can recover high-quality water from concentrated blackwater, creating an enabling sanitation solution.

3.4. Cost considerations for the batch open-loop RO

The economic viability of the batch open-loop RO for low-income single-household application was characterised using annual cash flows stimulated by the sanitation affordability index (US\$0.05 $person^{-1}$ day^{-1}) for a six-person system (US \$109.5 y^{-1}), where a positive NPV (discount rate 6%) indicates an economically viable solution (Table 3). Critical capital cost items were identified and their significance to valuation weighted through sensitivity analysis. At a single-household scale, the dominant cost items are the feed pump and membrane (unit cost and replacement frequency over 15-year lifetime). While economies of scale are achieved for pumping in large-scale high salinity RO applications with multistage centrifugal pumps, pump selection for high-pressure low flow applications is considerably more difficult, deferring instead to metering pumps with a minimum unit price of ~US\$1,000 (Figure 7). Plunger pumps match the system curve (Figure 7) which are

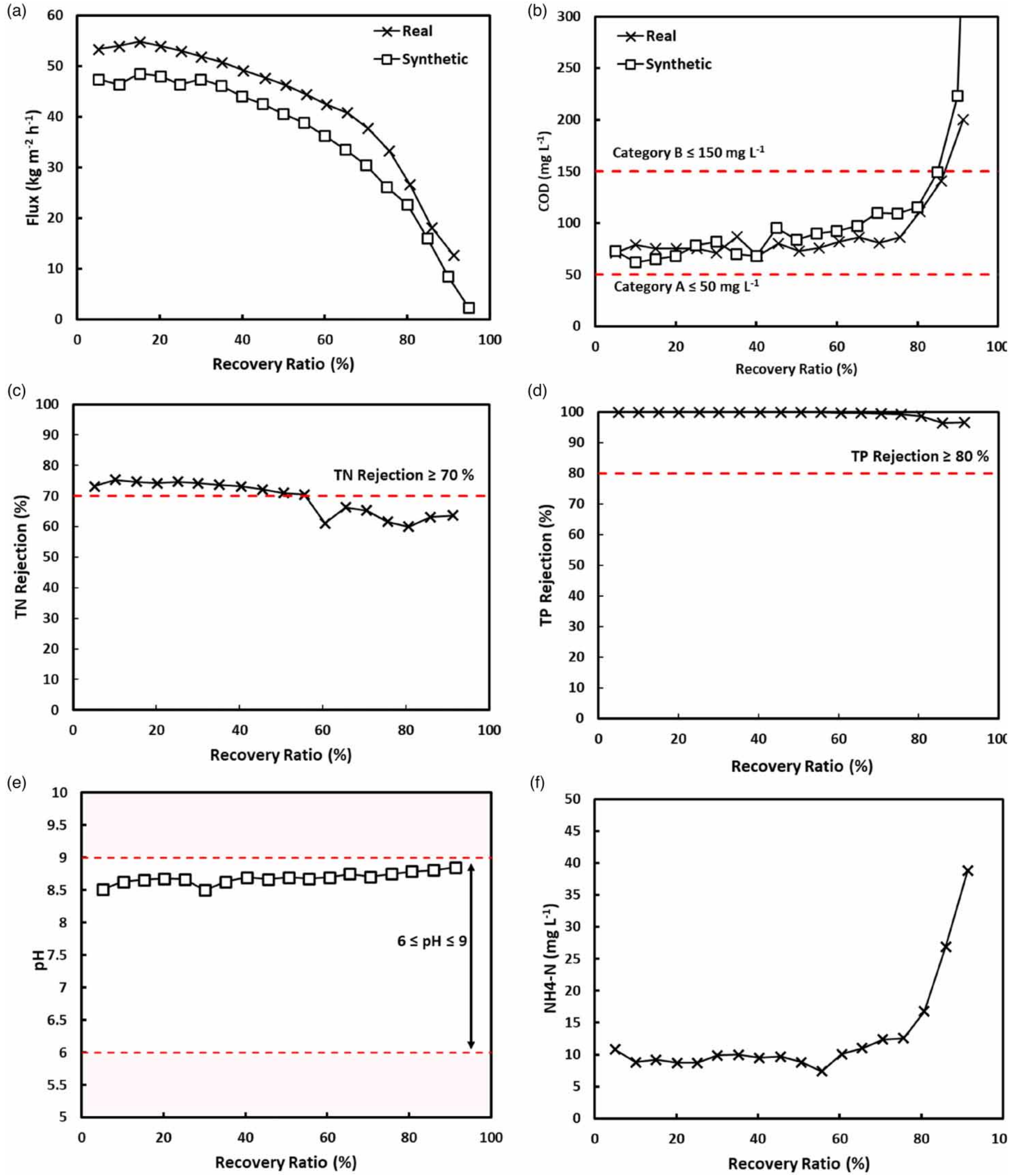


Figure 6 | Impact of blackwater feed on rejection in the batch open-loop RO: (a) flux; (b) permeate COD concentration; (c) TN rejection; (d) TP rejection; (e) pH; and (f) ammoniacal nitrogen concentration in permeate from single 1812 element. Guideline values introduced are from those adopted by ISO30500. Experimental conditions: single element; 30 bar; 0.084 m s^{-1}; and 25 °C.

convenient for RO as the produced flow is independent of the head imposed (Green & Perry 2007), and have been specified for small-scale RO systems, but forms the largest contribution to system cost (Table 3). To achieve a break-even NPV at a fixed element cost of US$100, pump cost must be reduced to ~US$250 (Figure 8), through material selection, pump simplification,

Table 4 | Feed and permeate water quality analysis for the real and synthetic blackwater

	Synthetic toilet wastewater		Real toilet wastewater				
	RO feed	**RO permeate**	**UF feed**	**RO feed (post UF)**	**RO permeate (final effluent)**	**ISO30500 criteria (Bartels *et al.* 2005)**	**ISO30500 passed**
Conductivity (mS cm^{-1})	8.76	0.63	4.50	3.68	0.14	n/a	n/a
*t*COD (mg L^{-1})	2,370	132	4,100	2,150	89.8 (96%)	[a]50 mg L^{-1}/[b]150 mg L^{-1}	✓[b]
*s*COD (mg L^{-1})	2,370	132	2,630	2,150	89.8 (96%)		n/a
TN (mg L^{-1}; rejection, %)	2,600	1,986 (23.6%)	2,000	1,900	583 (69.3%)	70% reduction	✗
TP (mg L^{-1}; rejection, %)	–	–	166	85	0.537 (99.4%)	80% reduction	✓
pH			6.81	8.14	8.69	$6 \leq pH \leq 9$	✓
NH_4^+-N (mg L^{-1})	108	13.9	139	147	12.8	n/a	n/a
E. coli (log_{10} CFU mL^{-1})	n/a	n/a	3.44	<-1 (LOD)	-2 (LOD) (LRV: >5.44)[c]	LRV ≥ 6	✗

LOD, limit of detection; LRV, log reduction value; TN, total nitrogen; TP, total phosphorus.
[a]Category A for reuse.
[b]Category B for direct discharge.
[c]Zero *E. coli* colonies were detected in the RO permeate sample.

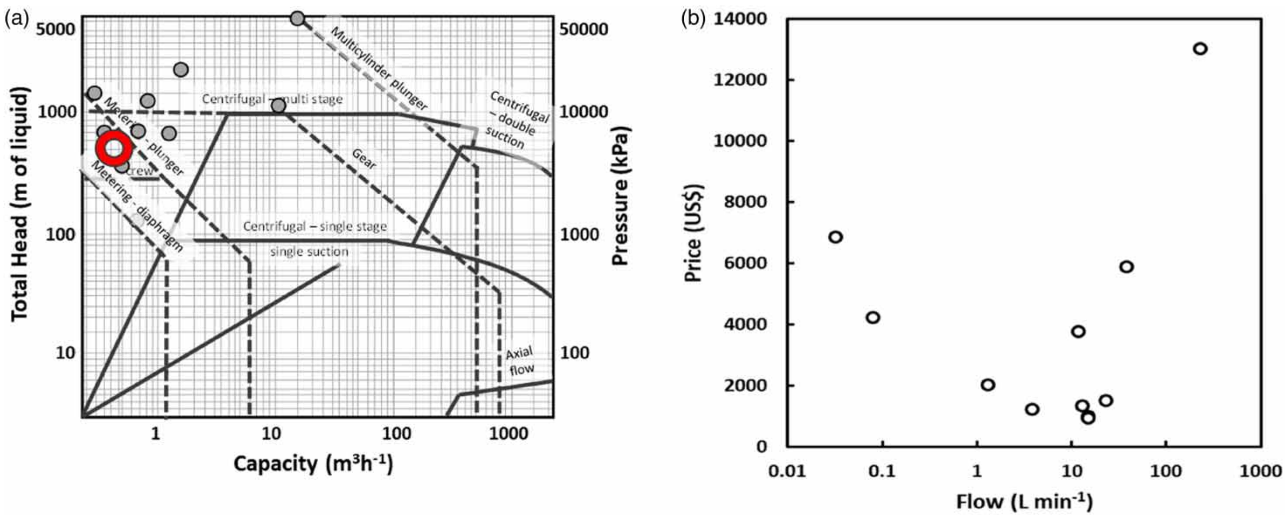


Figure 7 | (a) Pump selection guide with a red circle indicating system operating point for the batch open-loop RO at full scale (approximately six people system). Grey circles indicate the maximum operating point for commercially available pumps. Solid lines refer to total head (m of liquid) and dashed lines refer to pressure (bar) (adapted from Karassik 1999). (b) Cost comparison of metering pumps for this application, indicating a current retail cost of around US$1,000 for delivery. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wrd.2022.084.

or economies of scale, where material selection should consider corrosion and pressure limitations. Based on a pump cost of US$250, the significance of membrane replacement and unit cost have been evaluated (Figure 8). While RO element lifetime is important, break-even on NPV is more strongly weighted towards unit cost than replacement frequency. Due to the lower usage of 1812 RO membranes, unit cost is presently around US$150–200, which equates to ~US$650 m^{-2}. However, due to widespread application and roll-to-roll processing, large-scale RO membrane costs are closer to ~US$35 m^{-2} (Lu *et al.* 2007). With a 3-year membrane lifetime and 1812 element cost of US$25 (~US$109 m^{-2}), a positive NPV of US$267 indicates that pump costs could be increased to more than US$500 while maintaining a break-even NPV. The additional investment made available to pumping, can therefore increase financial viability. A single 1812 element can also process the daily blackwater

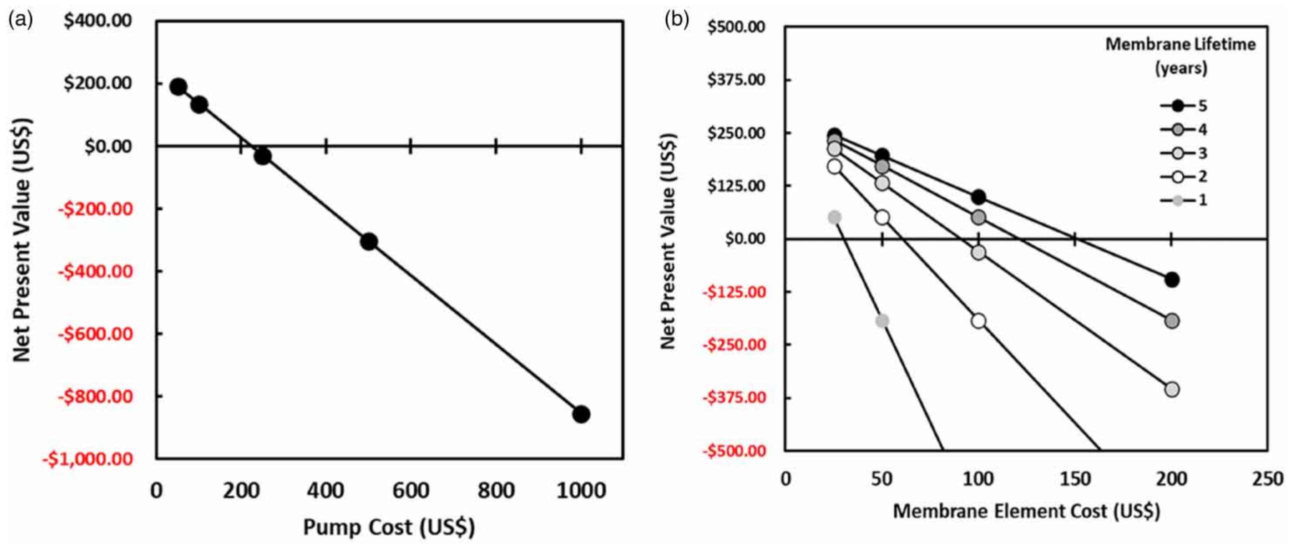


Figure 8 | Cost evaluation for the batch open-loop RO membrane system: (a) NPV indicating a break-even price point of ~US$250 for the pump (assuming a membrane lifetime of 3 years, element cost as US$100) and (b) impact of membrane lifetime and element cost on NPV (assuming an initial pump cost of US$250).

load from a single house in 3 h, suggesting that a lower membrane area element could be constructed to reduce cost, provided this does not risk robustness to sealing and the high operating pressures required.

4. CONCLUSIONS

In this study, a batch open-loop RO system has been investigated to enable clean water production from blackwater produced at decentralised scale. For single-stage batch processing, a multi-element configuration was most advantageous in reducing specific energy demand (kWh m^{-3}) towards the theoretical minimum energy requirement for separation. However, limited flush water inclusion can reduce daily fluid volume to between 1.5 and 5 L $capita^{-1}$ day^{-1}. Consequently, the total daily volume is sufficiently low at a single-household scale (~30 L day^{-1} for six people) to impart a negligible gross energy demand, in which case the decision as to which configuration is best will be determined by cost. This low flow rate was complemented by high fluxes in real blackwater, suggesting a single 1812 element, commonly used for *domestic* drinking water production from tap water, is also sufficient for single-household blackwater treatment. The 1812 elements for low pressure RO (i.e., tap water) are US$30, around five times less than the high-pressure 1812 element cost. While slight modifications in the spiral wound element are required for mechanical strength (e.g., spacer selection and outer wrap), together with consideration of material compatibility for high concentration of free ammonia and other potentially corrosive components, it is conceivable that a similar price point can be achieved at comparable economies of scale of production. This price point falls within the sanitation affordability index and reduces cost sensitivity to element replacement frequency. However, the system cost is presently dominated by the high-pressure pump, requiring a reduction in the unit cost of around 50% to ~US$500 to permit use at a household scale. Reciprocating pumps with comparable pressures and flows (100 bar, 8 L min^{-1}) have been designed for pressure washers by simplifying material and design (and market penetration) to achieve a unit cost of US$100, which when complemented with investment to reduce RO element cost, can deliver an affordable sanitation solution. For the batch open-loop RO, permeate quality sufficient for discharge is achieved. However, the osmotic retardation of flux, coupled with the dynamic transformation of nitrogen species at higher RRs (and extended residence times) were observed to slightly hinder water quality. Permeate quality did not achieve the reuse standard due to the transmission of *s*COD. As with nitrogen, this may be improved by increasing feed pressure to enhance selectivity or incorporating a polishing step. Importantly, high-quality water was recovered from blackwater and at a cost near to the affordability index for sanitation. While the value of this water maybe in its reclamation, the direct discharge of this water provides for a safer environment, and through promoting a large reduction in stored volume within pit latrines, creates an indirect economic benefit in reducing pit emptying costs (US$35–95 $household^{-1}$ $annum^{-1}$). The focus of this research was to examine whether

RO could offer a viable solution for decentralised water reclamation. Having now confirmed the potential, further research is required to evidence long-term robustness, particularly with reference to scaling and fouling mechanisms, to identify suitable long-term operational strategies. While the feed matrix is complex, the redox environment, elevated pH and high feed ammonia concentrations have demonstrated inhibition in a wide range of microorganisms, which may reduce biofilm growth ordinarily observed in classical applications.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Data underlying this paper can be accessed from: http://dx.doi.org/10.17862/cranfield.rd.16674337.

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