García-Pacheco, R., Li, Q., Comas, J., Taylor, R.A., Le-Clech, P. Novel housing designs for nanofiltration and ultrafiltration gravity-driven recycled membrane-based systems. *Science of The Total Environment*, vol. 767 (1 May 2021), art. 144181. DOI
https://doi.org/10.1016/j.scitotenv.2020.144181

Novel housing designs for nanofiltration and ultrafiltration gravity-driven recycled membrane-based systems

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Abstract:

Ultra-low pressure gravity-driven membrane (GDM) systems have the potential to be significantly less costly and complex than conventional membranes for water treatment applications. To build upon this inherent advantage, this study assesses the reuse of recycled membranes in GDM systems for producing drinking water. Two reverse osmosis spiral-wound modules were recycled into nanofiltration (NF)-like and ultrafiltration (UF)-like membranes via controlled exposure to free chlorine. To operate the recycled membranes, two housing devices, based on a simple fitting and an advanced end-caps design, were developed. The recycled membrane systems were tested under a range of conditions (submerged vs. external system configuration and continuous vs. intermittent filtration mode). Synthetic river water feed solutions were used in the tests where performance, fouling, and clogging were measured. NF-like recycled membranes resulted in poor salt rejection and low permeability (~1.7 L m^{-2} h^{-1} bar^{-1}), but also in high rejection (>81%) of dissolved organic carbon. UF-like recycled membranes maintained their capacity to reject biopolymers (BP) (>74%) and featured up to 18-fold higher permeate rate than NF-like recycled membranes. The optimized operating conditions were found when the recycled membranes were housed in the end-caps device and operated intermittently (relaxation time plus forward flushing). Flushing reduced the fouling accumulation inside the membrane (only 12% and 40% of BP accumulation was observed in the NF-like and UF-like, respectively). However, the end-caps-based device was estimated to be more expensive during the economic analysis. To address this techno-economic trade-off, a decision-making tree was developed to select the appropriate configuration based upon the implementation context. Overall, this study concludes that these designs can serve as robust, low-cost (water production cost <1 USD ct. yr. L^{-1}), and light-weight GDM alternatives. This study is beneficial for developing compact GDM systems based on recycled spiral-wound membranes for both rural areas and emergency response.

Keywords: nanofiltration, ultrafiltration, recycled membranes, membrane relaxation, flushing, gravity-driven membrane system, household water treatment; spiral-wound.

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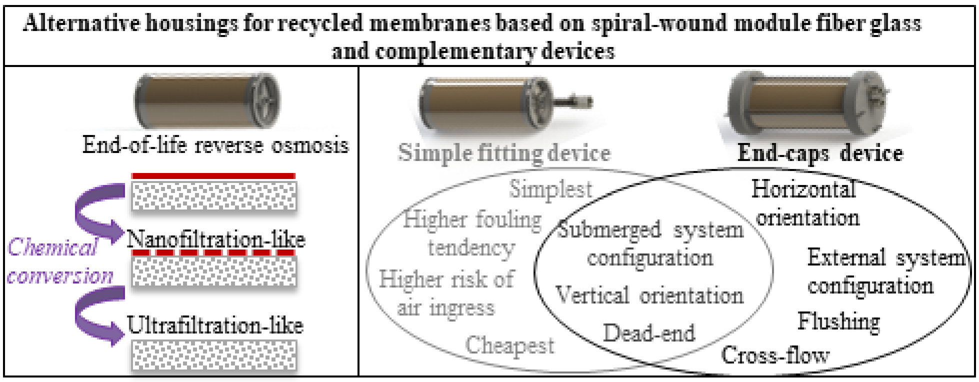
Graphical abstract:



Highlights

- Recycled spiral-wound membranes modules tested in gravity-driven membrane processes
- Novel membrane housing devices were developed for compact water treatment systems
- Membranes achieved permeability and rejection of organics for household treatment
- Intermittent operation (relaxation time and flushing) improved membrane performance
- A decision-making tree help to select the housings and the operation conditions

Abbreviations

BB: building blocks

BP: biopolymers

BSA: bovine serum albumin

CapEx: capital expenditures or investment

CP: concentration polarization

DI: deionized water

DOC: dissolved organic carbon

EoL: end-of-life

GDM: gravity-driven membrane

GDRM: gravity-driven recycled membrane-based

HA: humic acids

HS: humic substances

HWTS: household water treatment and safe storage

LC-OCD: liquid chromatography organic carbon detection

LMW: low molecular weight

MF: microfiltration

N.A.: No data available

NF: nanofiltration

OpEx: operational expenditures

PA: polyamide

PES: poly-ethersulfone

PSF: polysulfone

PVC: polyvinyl chloride

RO: reverse osmosis

TMP: transmembrane pressure

TAC: total annual cost

SRW: synthetic river water

SS: suspended solids

UF: ultrafiltration

WASH: water sanitation and hygiene promotion

1. Introduction

A lack of access to safe water resources is frequent following natural disasters and in rural locations [1]. In the last few decades, household water treatment and safe storage (HWTS) systems, have been gaining interest to support resilience and for water sanitation and hygiene promotion (WASH) actions for disease prevention [2]. These modular devices can be applied across the spectrum of short (emergency response), medium (early recovery), and long-term (international cooperation) programs [2]. Most HWTS systems are designed for point-of-use applications and are sized to deliver just enough water to meet the survival requirements (3-15 L day^{-1} per person[1]) [2].

Several reviews have compared HWTS systems for their use in potable water for rural areas and for emergency water supply [3–5]. An interesting subset of the HWTS field is gravity-driven membrane (GDM) systems, which are mainly based on ultrafiltration (UF) and microfiltration (MF) membranes. These offer high potential for situations where the electrical supply is intermittent, as GDM systems require no pumps and are easy to use, operate, and maintain. GDM systems are driven by the height difference between the feed tank and the membrane unit (i.e. typically requiring 40-200 mbar of pressure), enabling reliable, stable operation without backwashing, cross-flow or chemical cleaning, due to the phenomenon of low flux stabilization (in the range of 1-20 L m^{-2} h^{-1}) [6,7]. However, GDM systems using spiral-wound nanofiltration (NF) or UF membranes have not yet been investigated.

Although GDM processes appear attractive for HWTS systems, the following challenges have limited their application: i) low flux, ii) membrane price, iii) limited removal of small-sized soluble organics, such as humic substances (HS), building blocks (BB), and low molecular weight (LMW)-neutrals organics, and, iv) membrane fouling. Several of these challenges have been addressed (to some degree) in the literature.

The ultra-low pressure used in GDM systems is the main cause for their lower flux as compare to other pressure-driven processes [8,9] (i.e. challenge (i)). Due to the low flux, GDM systems require a relatively higher specific membrane filtration area per unit module volume compared with conventional systems [8,10], which impacts the total cost (estimated membrane cost at around 25 USD m^{-2} [11]) (i.e. challenge (ii)). The limited removal of small-sized soluble organics (i.e. challenge (iii)) is due to the physical pore size of the membranes but also because of biofilm activity [9]. Lastly, although it is generally known that membrane fouling (i.e. challenge (iv)) results from a biofilm layer of the rejected substances (e.g. particulate organic and inorganic material, organic aggregated colloidal material, and microorganisms) on the GDM surface [12], studies have indicated that the *rate* of membrane fouling is highly dependent on factors such as different types of feed water [6,7,13], membrane geometry (flat sheet or hollow fibers) [14,15], hydrodynamics [16], and operation mode (continuous or intermittent) [7,17].

To date, most of the investigations on GDM systems have focused on the submerged configuration [7–9,17–20], although some commercially available HWTS systems are designed to be used in an external configuration (e.g. Squirt [21], SkySpod [22], LifeStraw community [23] and ZeroTWO™ [24]). For all of these systems membrane fouling remains a core issue, although several fouling reduction techniques have been proposed, including membrane surface relaxation [11,17,25,26] and periodic application of shear stress (e.g. flushing [11,17,25] and backwashing [27]).

The use of recycled membranes in those systems has the potential to overcome some of the aforementioned barriers, such as the availability of membranes (i.e. availability of membrane surface to face challenge (i)), cost (i.e. challenge (ii)), removal of LMW or small-sized neutrals organics (i.e. challenge (iii)), and versatility in terms of the system configurations. The production of recycled membranes using free chlorine solutions is emerging as an alternative management to end-of-life (EoL) reverse osmosis (RO) membrane disposal [28,29]. Senán-Salinas et al. recently estimated that around 72% of EoL RO membranes could be recycled in that way [30]. UF-like and NF-like recycled membranes from EoL RO membranes used in desalination plants have demonstrated to be comparable to their commercially available homologues for cross-flow pressure-driven processes [31,32]. Amongst recycled membrane applications, only two cases assessed their potential use as HWTS system (submerged GDM system configuration) [28,33]. Indeed, the production cost of the second-hand membranes has been estimated to be between 1 USD m^{-2} [34] and 6 USD m^{-2} [30]), which could drop the cost of HWTS systems significantly. Since the NF-like and UF-like recycled membranes originate from standard RO spiral-wound membranes, the conventional pressure vessels used in desalination facilities, normally manufactured to host 6-8 membrane modules, remain the most used type of membrane housing available. Alternative membrane housings for single RO membrane modules are usually used for characterization and punctual tests [31], and other alternatives have been patented [35–38]. However, all of them feature complex arrangements, mostly focused on high-pressure resistance and most include an external housing (vessel) to host the whole membrane.

Less complex arrangements may enable low-cost and compact HWTS systems which utilize recycled spiral-wound membranes. However, appropriate membrane housings for this very specific application are still needed. At present, there is no simple, low-cost and design option or system configuration designed for GDM processes. It is also not well known how recycled membranes for producing drinking water can handle issues of fouling and clogging. Finally, strict validation methods are needed to limit the risk pathogen presence in the permeate [28].

In the present study, we investigate the development of two alternative membrane housings to the standard spiral-wound pressure vessels for recycled membranes. The focus is on a systematic approach at comparing membrane housings, system configurations (submerged vs. external) and operation modes (continuous vs. intermittent) in terms of their effect on NF-like and UF-like recycled membranes from a pristine RO spiral-wound membrane. Membrane performance, fouling, and feed spacer clogging were assessed. In addition, selected results were validated by using a recycled membrane from an EoL RO spiral-wound module. Since these key factors have not been investigated in any previous study, this will provide a systematic new data set for the GDM field. Critically, this study also used these results to investigate the technical and economic limitations of gravity-driven recycled membrane-based (GDRM) systems to identify promising HWTS designs for rural areas and emergency response.

2. Methods

In this study, a wide range of design and operation parameters such as membrane housing design, system configuration, membrane orientation, filtration mode and type of feed water were assessed to identify the optimal design and operating conditions for the NF-like and UF-like recycled membranes in dead-end GDM systems (see Table 1). A total of 51 short-term experiments using deionized water (DI) were carried out. These experiments (using the constant transmembrane pressure (TMP) of 0.16 bar) were repeated between 2-4 times, determining an experimental error of less than 12%. Moreover, 14 experiments using synthetic river water (SRW) solutions were carried out.

Table 1. Summary of studied parameters

GDRM system	Advanced	Simplest	
RO membrane origin	Pristine module	Pristine module EoL	Section 2.1
Spiral-wound recycled membrane type	NF-like UF-like	NF-like UF-like	Section 2.1
Membrane housing: spiral-wound module fiber glass with a complementary device	End-caps design	Simple fitting	Section 2.2
System configuration	Submerged External	Submerged	Section 2.3
Membrane orientation	Vertical Horizontal	Vertical	Section 2.3
Feed water	DI water SRW solutions	DI water SRW solutions	Section 2.4
Filtering modes	Continuous Intermittent: relaxation time plus forward flushing	Continuous Intermittent: relaxation time	Section 2.5.1

2.1 Membranes types and recycling process

A new and an EoL RO spiral-wound module (e.g. TM730HP-4611 from Dow Filmtec; with a 0.29 m length, a 0.12 m diameter and a 2.23 m^2 surface area) were used. According to the manufacture's specification datasheet, this membrane model is often applied in municipal and industrial systems. The main study was conducted based on the recycling (or conversion) of a pristine RO membrane. The EoL RO membrane was stored dry for 3 years (no information related to its operation life was available). The EoL RO membrane was rehydrated before being recycled, using a 50% w/w ethanol solution for 15 minutes—with full procedure described in [33]. This membrane presented external damage, which made it not possible to use the advance membrane housing described in Section 2.2. Thus, the recycled EoL membrane was used to confirm that the pristine recycled membranes have similar performance trends to the true EoL membrane.

To produce NF-like and UF-like recycled membranes, both pristine and EoL RO membranes were passively immersed in a solution containing 6,000 ppm of free chlorine, following an existing protocol from the literature [31]. In this process, the polyamide (PA) layer of the RO membrane was degraded to NF-like and UF-like levels by controlling the exposure time. The standard exposure dose of 6,000 ppm·h of free chlorine was enough to achieve the NF-like performance when using the EoL RO membrane, while a higher exposure dose was required for the pristine model (26,500 ppm·h). To achieve UF-like performance both membranes were overexposed to 300,000 ppm·h. Afterward, the membrane was thoroughly rinsed with DI water. Although the PA layer was chemically attacked, the membrane module maintained its original spiral-wound structure.

The success of the recycling process was confirmed by filtering DI water in gravity-driven conditions (Section 2.3). The resulting permeability values were compared to the permeability ranges found in literature (i.e. 1.5-15 and 10-50 L m^{-2} h^{-1} bar^{-1} for NF and UF performance, respectively [39]). Additionally, NF-like performance achieved by recycling the pristine RO module was further validated by using a cross-flow pressure-driven test (Section 2.7.1). The total degradation of the PA layer was not confirmed in this work. However, it was earlier demonstrated by the authors that UF-like performance was always achieved when RO membranes were overexposed at the same conditions [29,40].

2.2 Membrane housing devices

In this study the fiber glass of the spiral-wound module was directly used as the main part of the membrane housing of the GDRM system. Two additional devices were designed to complement the fiber glass housing, based on light-weight and low-cost materials appropriate for GDM systems. Taken together this represents an alternative solution to the conventional fiber glass or stainless steel membrane pressure vessels which are typically used for cross-flow pressure-driven systems (e.g. membrane testing [31]).

The lowest-cost device, named from here as the simple fitting, consisted of implementing a simple fitting in the permeate tube at the tail end side. Figure A1-1a (which can be found in the Supplementary data in Annex 1) shows that the simple fitting reduced the 0.019 m diameter of the permeate tube to a 0.003 m diameter for the flexible line. Both ends of the membrane module remained open, so the membrane only operated in a dead-end submerged system configuration (see Section 2.3, Figure 1-Scenario A). The feed water filled the module using both open ends of the membranes, while the treated water was collected using the permeate tube.

An advanced membrane housing design, named from here as the end-caps design, was also developed to close the open areas of the membrane end sides. This end-caps design was based on two recyclable polyvinyl chloride (PVC) end parts, matching with the diameter of the commercial RO module (as shown in Figure A1-1b in Supplementary data in Annex 1). The end-caps design included the mechanical fixing of these two end-caps to the membrane to prevent leakage from the feed and the permeate side of the module. While the liquid feed flow in and out of the shell side of the module was directed via feed inlet and outlet fittings, the treated water was directed out from the permeate collecting duct through the permeate outlet (see Section 2.3, Figure 1). In the present study, the system was set up to filter in a dead-end mode by blocking the concentrate stream with a valve. However, the concentrate line was used to flush feed water after a set relaxation time (see Section 2.5). The feed water was pumping in following the flow direction indicated by the membrane manufacture and the treated water was collected using the original permeate tube. Detailed figures of the end-caps design are shown in the Supplementary data (Annex 1) and in a recent patent [41].

2.3 System configurations

A pilot-scale GDRM system was set up for two distinct membrane system configurations: submerged and external, as shown in Figure 1. In the submerged configuration (Figure 1-Scenario A), the membrane was placed vertically inside the feed tank (20 L). In the external configuration, two membrane orientations were tested: vertical (Figure 1-Scenario B), as usually operates gravity-driven systems for HWTS and horizontal (Figure 1-Scenario C), as is commonly found for cross-flow pressure-driven spiral-wound membranes. In Scenario C, the membrane was placed close to the floor aiming at reproducing the most likely scenario in a potential HWTS application using the standard spiral-wound membranes (with 37 m^2 surface area and around 15 kg drained weight [42]). During the test, the room temperature was maintained at 20 ± 1 °C. In addition, the permeate line was filled with water and kept filled during the experiment.

The permeate collected during a given period of filtration was weighed in a balance and then recirculated to the feed tank (i.e. a batch operation). The permeate volume was calculated considering the water density as pure water. Therefore, the membrane permeability ($L\ m^{-2}\ h^{-1}\ bar^{-1}$) was obtained by dividing the permeate flow rate to the membrane surface area and the TMP. The TMP was estimated considering the effective water head, which includes the height of the water level of the tank and the height of the end of the permeate tube [17,43].

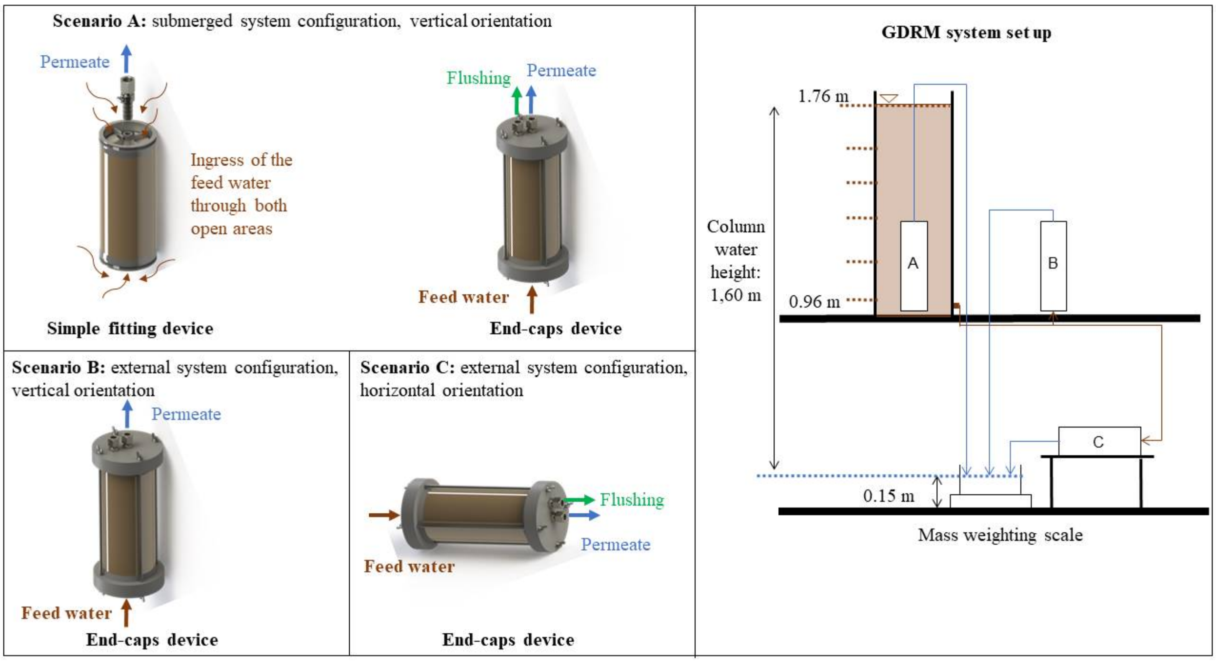


Fig 1. Set-up of the GDRM system using submerged (Scenario A) and external (Scenario B and Scenario C) system configurations. In Scenario B, the membrane was placed vertically at the same height than in Scenario A. In Scenario C the membrane was placed horizontally. Note that the blue permeate lines were always filled with water, while brown lines represent the feed line.

2.4 Feed water solutions

2.4.1 Deionized water tests

DI water tests were conducted for comparison of membrane housing devices at various TMP levels. The water level of the tank was kept constant for all the selected TMP tests, during 30 minutes of each test. The TMP varied from 0.16 to 0.08 bar, so these values were used to determine the membrane permeability. Both membrane housing designs and the three system configurations were studied for both NF-like and UF-like recycled membranes.

DI water was also filtered before and after conducting the fouling test (see Section 2.5). After each set of experiments using SWR feeds, the NF-Like and UF-like recycled membranes were backwashed (0.43 L m^{-2} h^{-1}) and DI water was tested again for comparison with the initial values.

2.4.2 Synthetic river water tests

Fouling tests were conducted with SRW solutions (with 900 µS cm^{-1} of conductivity, neutral pH and 2-6 mg L^{-1} of dissolved organic carbon (DOC), given by bovine serum albumin (BSA), humic acids (HA) and alginate. The SRW solutions were renovated in each experiment. The SRW solutions were used to assess both membrane housing devices for NF-like and UF-like recycled membranes configured in Scenario A and Scenario C, at a constant pressure of 0.16 bar.

Two SWR feed solutions were used. Feed A simulates pre-filtered river water (i.e. 80 mg L^{-1} $MgSO_4$, 400 mg L^{-1} NaCl, 12 mg L^{-1} BSA, 12 mg L^{-1} HA) which was employed when using the NF-like recycled membranes and the UF-like recycled EoL membrane. The second solution, Feed B (i.e. 80 mg L^{-1} $MgSO_4$, 400 mg L^{-1} NaCl, 30 mg L^{-1} BSA, 30 mg L^{-1} HA, 6 mg L^{-1} alginate acid and 300 mg L^{-1} diatomaceous earth), was used with the UF-like recycled pristine membrane to accelerate fouling on the membrane surface (due to increased organic content and suspended solids compared to Feed A). All the chemicals were analytical grade reagents. The concentration of the main organic fraction of Feeds A and B are shown in the supplementary data (Table A2 in Annex 2).

2.5 Assessment of continuous and intermittent operation

2.5.1 Filtering modes

The impact of two filtration modes (continuous and intermittent) on the NF-like and UF-like recycled membrane performance and feed spacer clogging were evaluated, for both GDRM systems (simple and advanced) and two system configurations (i.e. Scenario A and Scenario C). The total filtration time was 6 h. The intermittent condition was tested because it simulates a more realistic operation mode for HWTS systems. Thus, in this work, the operation mode consisted of cycles of 1 h of filtration, followed by a relaxation time of 40 minutes (or 12 h in the case of the last cycle). For the advanced GDRM system, relaxation time was followed by a thorough flushing of 10L of the feed water (at ~140 $L\cdot m^{-2}\cdot h$ for 2 minutes at 0.16 bar), while for the simple GDRM system flushing was not possible. Flushing was conducted by opening the valve of the concentrate line, which was already filled with feed water at the beginning of each experiment (no additional components or input energy was required for this step).

2.5.2 Membrane rejection and fouling

The feed and permeate water samples were collected initially and after 1 h and 6 h of filtration for further analysis. The major component rejection (% R) was calculated following Equation 1. Where, C_p and C_f are the specific concentration measured at permeate and feed, respectively.

$$\% R = \left(1 - \frac{C_p}{C_f}\right) \cdot 100 \qquad \text{Eq. 1}$$

To assess the percentage of organic fouling accumulation (% FA) inside the module (i.e. DOC and the organic fractions), the feed concentration reduction was calculated following Equation 2. Where $C_{f\text{-}0}$ and $C_{f\text{-}6}$ are the concentration of feed components at the beginning and after 6 h of duration, respectively.

$$\% FA = \left(\frac{C_{f-0} - C_{f-6}}{C_{f-0}}\right) \cdot 100 \qquad \text{Eq. 2}$$

The accumulation of solid inside the membrane was calculated with a mass balance by considering the initial SS added to the tank (6 g) and the SS contained in the water samples collected after applying the following cleaning process: drainage after filtering SRW model solution, drainage after filtering DI water, and the 10 L backwashing process.

2.6 Water quality analysis

Conductivity, pH, and turbidity were tested with a multiparameter sensor (Hanna Instruments HI9829). The SS were determined following the APHA 2540 D method. DOC and the organics fractions were analyzed based on size exclusion (Toyopearl TSK HW-50S, diameter 2 cm, length 25 cm) using a dual column liquid chromatography organic carbon detection (LC-OCD), system model 8, based on the Gräntzel thin film reactor developed by DOC Labor, Germany [44]. Chromatographs were interpreted using the DOC Labor ChromCALC 2013 software. Thus, the organic components used such as BSA, HA and alginate represented in the chromatographs as biopolymers (BP), HS and polysaccharides (which elute at similar retention time than BP), respectively [45]. Other organic fractions studied in this work are the BB (which reflects breakdown products of HS with lower molecular weight) and LMW-neutrals (which reflect organic fractions with even lower molecular weight) [44].

2.7 Further testing and economical assessment for decision-making

2.7.1 Cross-flow pressure-driven test

Cross-flow pressure-driven assays (up to 4.4 bar) using the end-caps device were conducted to assess the membrane performance after being exposed to free chlorine, to confirm the partial degradation of the RO PA layer. Tests were run for 30 minutes for filtering different saline concentration solutions, up to 3750 μS cm^{-1} (e.g. 2000 mg L^{-1} NaCl or 2000 mg L^{-1} $MgSO_4$). The feed flow was maintained constant at 3 L per minute and the room temperature was maintained at 22 ºC. Another goal of this study was to demonstrate the mechanical resistance of the advanced membrane housing device (end-caps) for using the NF-like recycled membrane in standard cross-flow filtration.

2.7.2 Economic assessment

After determining the technical performance, the next step in the present study considered the economic performance of the proposed designs. The first step in this analysis was to determine the capital expenditures or investment cost (CapEx) of the GDRM system. This included the novel membrane housing devices and one recycled membrane, which was calculated on an annual equivalent cost (AEC; USD/year) using Equation 3.

$$AEC = C_0 \left[\frac{r(1+r)^n}{(1+r)^n - 1}\right] \qquad \text{Eq. 3}$$

In Eq. 3, C_0 represents the cost of each item at year 0 (USD), r is the discount (interest) rate per period (e.g. assumed as 2 % per year), and n is the number of years (e.g. the lifespan). A conservative lifespan of only one year was selected aiming at the application of the GDRM system in an emergency response context or early recovery projects. The operational expenditures (OpEx) were considered negligible because of the simplicity of the system, with no need for electrical inputs or cleaning products (few cleanings are expected in long-term operation due to the phenomenon of flux stabilization [7]). Therefore, the total annual cost (TAC), which is the sum of CapEx and OpEx was assumed to be equal to CapEx.

The cost of producing NF-like and UF-like membranes can be lumped as a cost for the EoL RO recycling process. According to the literature [30], the production cost of 4500 membranes using a passive recycling system was around 6 USD m^{-2}, including membrane characterization and transport costs. In this work, the selling cost of the recycled membranes (NF-like and UF-like membranes) was assumed to be 7 USD m^{-2} (data used in this study), which would include the company profits.

The cost of the simple fitting device and the rest of the parts of the GDRM system (e.g. those described in Sections 2.2 (Figure A1-1 in Annex 1 in Supplementary data) and Section 2.3 (Figure 1)), were found from online suppliers (in Australia), where most of the materials were purchased. The end-caps device cost was estimated by knowing the quantity of PVC material used and the labor (e.g. person-h) needed to manufacture it (excluding design time).

3. Results and discussion

3.1 Initial DI testing

The main objective of the initial DI water tests was to assess the relative hydraulic advantages of the end-caps device compared to the simple fitting, the impact of the system configuration (submerged vs. external) and the membrane orientation. For that purpose, 20 L of DI water was filtered with no water recirculation, until the tank was empty.

Table 2 shows the average permeability values of the NF-like and UF-like recycled pristine membranes for the distinct TMP. Similar permeability values were obtained when using both membrane housings in the submerged system configuration and membranes were fully covered with water (TMP 0.16-0.10 bar). Therefore, the use of the end-caps device does not seem to have a significant impact on hydraulic membrane performance. Membrane orientation, vertical or horizontal, does not seem to have any impact neither (during external system configuration testing).

Table 2. NF-like and UF-like recycled pristine membrane permeability (L m^{-2} h^{-1} bar^{-1}) values filtering DI water in continuous mode. The simple fitting and end-caps devices are compared using the submerged configuration system and all Scenarios. It is shown the average of data achieved varying TMP from 0.16 to 0.10 bar (using data of 4 experiments, n=4), and at 0.08 bar of TMP (one experiment, n=1).

Parameter			Permeability (L m^{-2} h^{-1} bar^{-1})			
System configuration			Submerged		External	
Scenario - Membrane orientation			A-Vertical	A-Vertical	B-Vertical	C-Horizontal
Membrane housing			Simple fitting	End-caps	End-caps	End-caps
RO membrane origin	**Recycled membrane type**	**TMP (bar)**				
Pristine	NF-like	0.16-0.10, n=4	7.5 ± 0.1	7.9 ± 0.1	7.6 ± 0.0	8.0 ± 0.1
		0.08, n=1	**3.5 ± 0.3**	7.8 ± 0.3	7.5 ± 0.2	7.9 ± 0.1
	UF-like	0.16-0.10, n=4	18.2 ± 0.0	17.8 ± 0.2	19.2 ± 0.1	19.3 ± 0.3
		0.08, n=1	**6.6 ± 0.3**	17.2 ± 0.7	19.3 ± 0.2	18.8 ± 0.1

N.A.: No data available

However, differences in permeability were observed in the submerged configuration system, when the membrane was not fully covered by water. When using the simple fitting, the permeability values decreased up to around 3-fold (highlighted in Table 2). Air entered inside the membrane module when the water level was lower than the membrane height. The negative impact on the water permeability was due to the reduction of the active membrane surface. These results are in concordance with the previous publication, where a totally or partially submerged flat sheet gravity-driven UF membrane performance was assessed [8]. The end-caps device prevented this effect, keeping the membrane surface fully covered by water. Therefore, the permeability was maintained constant at any hydraulic pressure.

Considering the application of the system using a single membrane module for HWTS and aiming at preventing the risk of air ingress in modules, the end-caps device seems to be a better option than the simple fitting. Nevertheless, further study was conducted to assess the impact of those configurations on fouling. The external system configuration using the membrane vertically (Figure 1-Scenario B) was not tested further due to the complexity of the set up.

3.2 Synthetic river water tests

The following sub-sections evaluate the NF-like and UF-like recycled membrane performance as a function of the following variables: i) the filtration mode (continuous vs. intermittent), ii) the system configuration (vertically-submerged vs. horizontally-external) and iii) the accumulation/sorption of the organic compound and SS on the membrane surface. To assess the potential risk of clogging of feed water, the membrane permeate was continuously circulated to the feed tank. For instance, for this series of experiments, during the 6 h of filtration, the NF-like recycled pristine membrane filtered of a total of 3.5 L of feed water, while the UF-like recycled pristine membrane filtered 34.2 L.

3.2.1 Permeability

3.2.1.1 Assessment of NF-like recycled membrane performance

Figure 2 shows the permeability and salt rejection when operating in continuous and intermittent filtration modes for the NF-like recycled membrane submerged in the feed tank (Scenario A) and externally configured (Scenario C). The recycled pristine membrane was housed in both the simple fitting (Figure 2-a) and the end-caps devices (Figure 2-b and Figure 2-c). Continuous filtration results show that the initial permeability (around 2.1 L m^{-2} h^{-1} bar^{-1}) decreased over time until reaching a plateau (around 1.7 L m^{-2} h^{-1} bar^{-1}), where the rate of deposition and accumulation of foulants were balanced by back diffusion and re-dissolution [46]. The recycled EoL membrane (Figure 2-d) showed a similar permeability.

During the intermittent filtration, in each filtering cycle, permeability temporary increased, followed by a decrease towards the stable value. A slight improvement was observed when flushing was applied after the relaxation time (membrane hosted in the end-caps device).

Indeed, no significant membrane performance differences were observed between cycles 2 and 4. In all cases, a longer relaxation time (12 h between cycles 5 and 6) improved the average membrane permeability.

In contrast to what typically occurs in cross-flow pressure-driven systems with NF membranes, a sharp decline in salt rejection was observed in the first h of filtration to fall under 16% after 80 minutes. This is likely caused by the formation of a boundary layer near the membrane surface, which appears when salts are rejected, also referred to concentration polarization (CP). In the CP layer, the salt concentration is higher than the salt concentration in the bulk solution, which can explain the low rejection values and the permeability reduction [47]. The decrease of the salt rejection at the beginning of the following cycle compared to the last cycle was, therefore, linked to the formation of the CP layer. There was also a salt diffusion effect when the filtration stopped and it took around 30 minutes to stabilize again to the plateau. Salt diffusion might occur due to the high concentration of salt over the membrane surface. The combination of membrane relaxation and flushing (Figure 2-b and Figure 2-c) has the greatest impact to improve the salt rejection compared to apply only the relaxation time (Figure 2-a). It was hypothesized that water flushing was responsible for the decrease of the thickness of the boundary layer near the membrane surface [48]. Low salt rejection will limit the application of NF membranes to only freshwater feeds, but they could still serve in HWTS, much like UF membranes (with null salt rejection capability).

Continuous filtration results also confirmed that the usage of the end-caps device does not have a significant impact on the membrane performance. In all the three tested Scenarios, fouling was mostly reversible, since the permeability recovered generally well after applying backwashing (data are shown in Supplementary data in Table A3-3 in Annex 3). A comparison with other similar studies was not possible, since NF membranes have never been used in GDM systems for producing drinking water before. However, the impact of combining relaxation time and flushing has been earlier reported using UF membranes (as will be discussed in the comparison below).

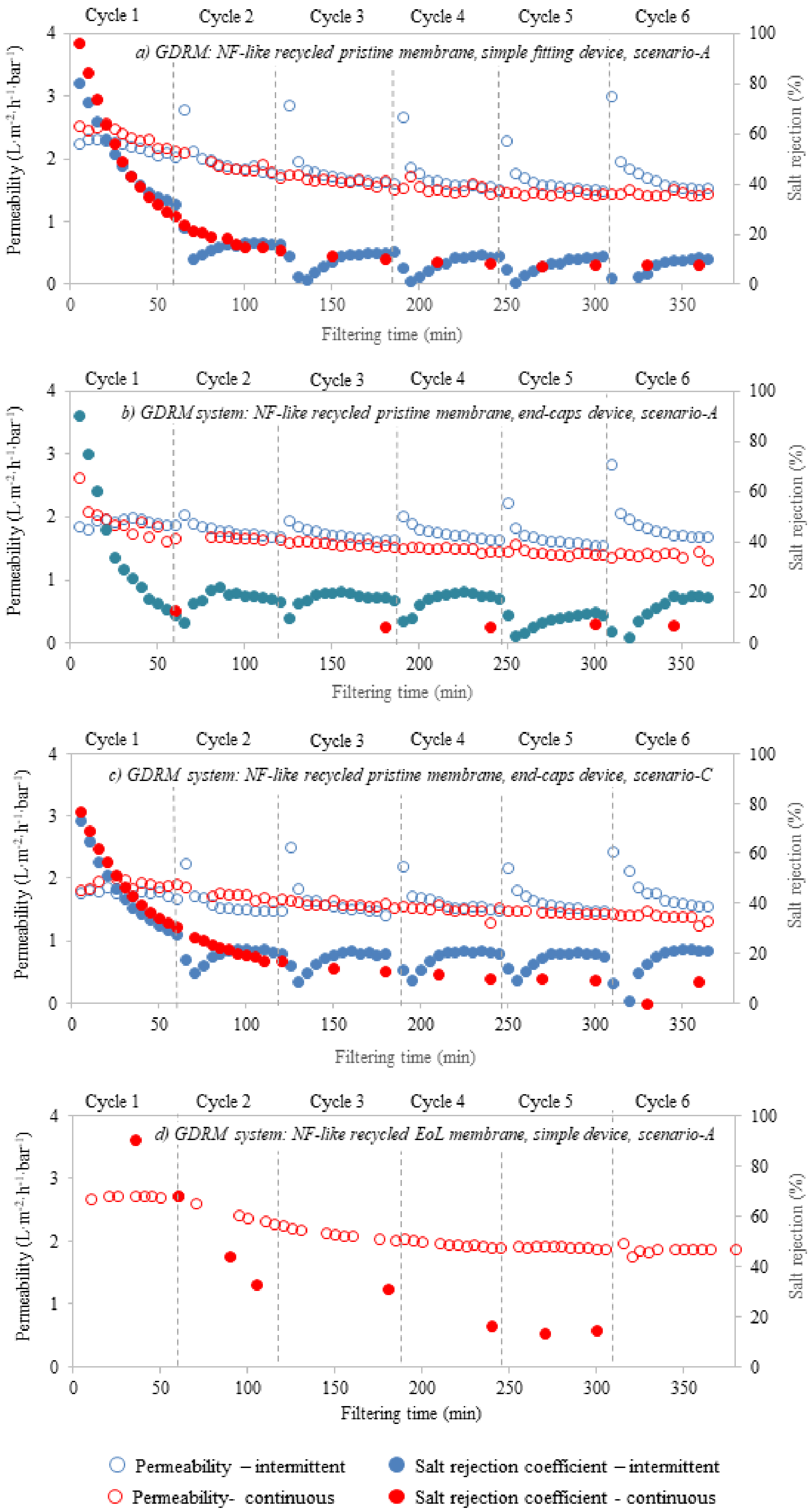


Figure 2. Permeability and salt rejection of the NF-like recycled pristine membrane: a) Submerged configured using the simple fitting (Scenario A), b) Submerged configured using the end-caps device (Scenario A), c) External configured using the end-caps device (Scenario C) and d): Permeability and salt rejection of the NF-like recycled EoL membrane submerged configured using the simple fitting (Scenario A). Table A3-1 (Annex 3 in Supplementary data) shows the average values and the standard deviation of all the cases. [Note: In figure b), between cycle 4 and 5, no flushing was applied].

3.2.1.2 Assessment of UF-like recycled membrane performance

Figure 3 shows the permeability when operating in continuous and intermittent filtration modes for the UF-like recycled membranes submerged in the feed tank (Scenario A) and externally configured (Scenario C). The recycled pristine membrane was housed in both the simple fitting (Figure 3-a) and the end-caps devices (Figure 3-b and Figure 3-c). The UF-like recycled EoL membrane was housed in the simple fitting (Figure 3-d) and the salt rejection coefficients were below 5% in all the cases (not shown in the figure).

Despite the accumulation of SS (Section 3.2.4) and of protein (see Section 3.2.3 Table 4), which is known to cause severe fouling in low-pressure UF process [49,50], the permeability of the recycled pristine membrane slightly declined during the first h and then it remained constant over time in both filtration modes. The low average permeability indicated a permeate flux rate around 2.6 L m^{-2} h^{-1}, which was lower than the typical reported standard stabilized flux of 4-10 L m^{-2} h^{-1} for UF GDM systems operated long-term [6]. However, it was still similar to studies that treated diluted wastewater (15 mg L^{-1} DOC) [18] and grey water [51]. This can be mainly attributed to several factors: i) the nature of the PSF layer of the recycled membranes, which are designed to support the PA layer of the RO membranes; ii) the feed water quality, a SRW solution rather than natural water, and iii) the membrane modules type, which in our study was spiral-wound rather than hollow fiber. However, higher initial permeate flux for spiral-wound UF recycled modules also resulted in higher flux decline, even though the feed was SS-free. The initial flux of the UF-like recycled EoL membrane (7.4 L m^{-2} h^{-1}) is expected to be above its critical value, while the UF-like recycled pristine membrane operated below it (around the aforementioned flux of 2.6 L m^{-2} h^{-1}), without showing any reduction in permeability [52]. The spiral-wound membrane configuration has an impact on the critical flux compared to other configurations used in

GDM systems (i.e. hollow fiber), due to lower shear rates [53]. Therefore, the critical flux for the recycled spiral-wound UF membrane is expected to be within the standard range of the stabilized flux reported in the literature for GDM systems (i.e. 4-10 L m^{-2} h^{-1} [6]).

When operating with the UF-like recycled pristine membrane housed in the end-caps device, an improvement in the permeability was not observed when applying flushing after the relaxation time (when using the end-caps device). However, previous studies using UF GDM systems to treat surface water reported that intermittent operation, when combined with forward flushing, further enhanced the membrane performance [11,17,25]. Shi et al. [17] demonstrated that only applying membrane relaxation or shear stress (flushing cross-flow velocity at 360 m h^{-1}) was ineffective in improving the stable flux in long-term filtration, while their combination enhanced the stable flux by 70%.

As occurred with NF-like recycled membranes, the permeability recovered after applying backwashing indicating the reversibility of fouling (values are shown in Supplementary data (Table A3-3 in Annex 3).

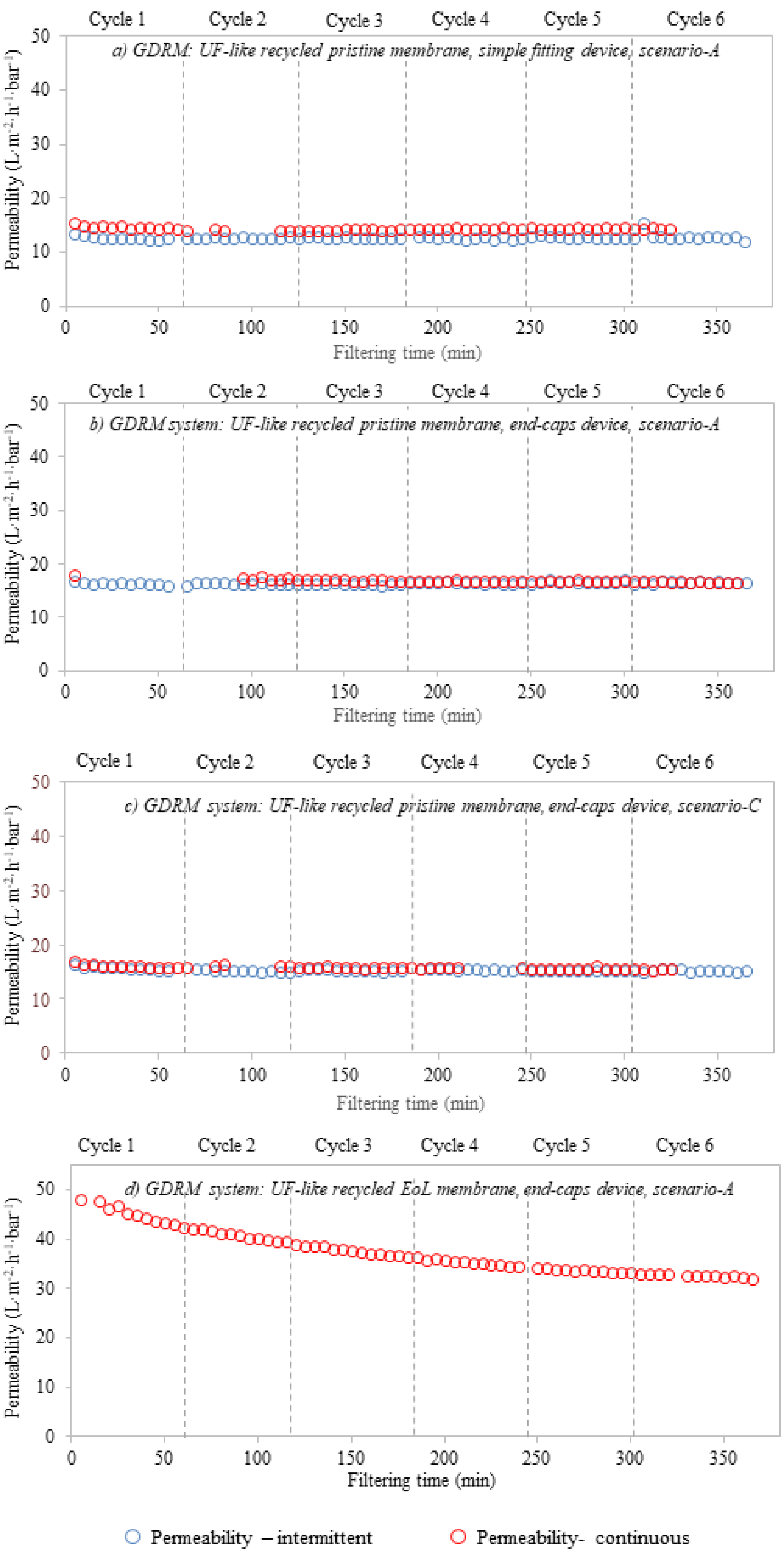


Figure 3. Permeability of the UF-like recycled pristine membrane: a) Submerged configured using the simple fitting (Scenario A), b) Submerged configured using the end-caps device (Scenario A), c) External configured using the end-caps device (Scenario C) and d) Permeability of the UF-like recycled EoL membrane submerged configured using the simple fitting (Scenario A). Gaps in the figures are due to experimental issues of the data acquisition device. Table A3-2 (Annex 3 in Supplementary data) shows the average values and the standard deviation of all the cases.

3.2.2 Organic rejection

Table 3 shows the rejection coefficients (average values for the observed rejection and the standard deviation) of DOC and four fractions: BP, HS, BB and LMW neutrals, with no distinction of the system configuration and filtering mode. The NF-like membrane showed a high ability to separate organic compounds, reaching rejection coefficients above 77% in both recycled pristine and recycled EoL membranes. The UF-like recycled pristine membrane still rejected protein (at above 99% BP) but only 36% and 61% rejection was observed for BB and LMW-neutrals, respectively. The UF-like recycled EoL membranes showed lower protein rejection (around 74%), being in concordance with the high permeabilty results.

Although HS is potentially larger compounds than BB or LMW-neutrals, similar concentration was observed in the feed and the permeate streams when using recycled UF membranes. It was hypothesised that HS were not able to form aggregates with bigger size as occurred in long-term GDM filtration investigation, and therefore the HS easily permeated [46]. Very low rejection of HS has been reported in the literature for UF membranes [27], where rainwater was treated by submerged hollow fiber GDM system. However, the long-term operation of other UF GDM systems showed above 20% rejection [46,54]. On one hand, such a difference compared to the HS rejection observed in our work could be explained due to the molecular size. Ding et al. [54] used bigger HS molecules, in the range of 1000-3500 Da, while in our work the average size was defined around 600 Da. On the other hand, in long-term experiments (operating during several weeks), the bio-fouling layer developing on the membrane surface is expected to act as a secondary barrier, enhancing the rejection of organics such as BP, HS [54], BB and LMW compounds [27].

Table 3. Rejection (in %) observed filtering SRW solutions using recycled membranes. Average and standard deviation with no distinction of the system configuration and filtering mode (A total of six experiments (n=6) for each membrane type was used when using the recycled pristine membrane data, while only one experiment (n=1) represents the case of using the recycled EoL membranes).

Parameter	Organic rejection (%)			
System configuration	Submerged and external		Submerged	
Scenario - Membrane orientation	A-Vertical and C-Horizontal		A-Vertical	
Membrane housing	Simple fitting and End-caps		Simple fitting	
Feed solution	A	B	A	A
Filtering mode	Continuous and Intermittent		Continuous	
Number of experiments, n	n=6	n=6	n=1	n=1
RO membrane origin	Pristine		EoL	
Recycled membrane type	NF-like	UF-like	NF-like	UF-like
DOC	88.6 ± 3.2	48.0 ± 14.6	81.5	37.8
BP	99.4 ± 0.5	99.7± 0.4	93.1	74.2
HS	97.2 ± 3.0	12.5 ± 4.4	81.7	22.0
BB	84.8 ± 11.0	35.7± 10.6	82.6	35.0
LMW-neutrals	77.9 ± 5.8	61.2 ± 14.0	78.7	30.7

3.2.3 Fouling accumulation

Due to the mode of filtration (recycling of permeate into feed tank), the accumulation of foulants on the membrane was expected. It was assumed that in short-time experiments, the degradation of organic substances in the feed was negligible. Therefore, the reduction of the organic fraction concentrations at the feed after 6 h of filtration compared to the initial values represented the percentage of fouling accumulation (FA) inside the membrane. Table 4 shows the FA values of BP and HS for the NF-like and UF-like recycled membranes operating in the submerged and external system configurations, in the continuous and intermittent filtering mode. Similar FA was observed during continuous and intermittent filtration when the recycled pristine membrane was housed in the simple fitting. The simple fitting device does not enable water flushing after the relaxation time. Thus, applying only membrane relaxation did not have a significant impact on preventing fouling accumulation inside the module. In this case, the lowest FA was observed when the recycled pristine membrane was housed in the end-caps device and operated intermittently (i.e. lower reduction of the feed organic fraction concentrations over time). Therefore, less fouling accumulated inside the module. This is again a consequence of the combination of the filtration relaxation and water flushing.

The combination of relaxation time and flushing is expected to reduce the fouling tendency over the membrane. For instance, in the case of the NF-like recycled pristine membrane, 23% and 16% FA of BP and HS, respectively, were observed when filtering in continuous mode (using both housings devices). However, less than 12% FA of both compounds was observed when flushing was applied after the relaxation time. These results also proved that the BP and HS accumulated or deposited inside the membrane module, but there was no significant adsorption or aggregate deposition over the membrane. Deposition and adsorption of BP and HA have been earlier reported as potential fouling mechanism in GDM systems [26,46]. For UF-like recycled pristine membrane, around 40% FA of the BP concentration in the feed was observed when flushing was applied, while more than 87% FA was detected when membrane operated continuously. Chawla et al. [11] observed that the foulant load delivered per unit membrane area was lower (around half) when hollow fiber UF membranes operated intermittently comparing with a 24 h continuous filtration. However, this could be attributed to the fact that the total filtering time in both operation modes were different. In addition, other investigation also highlighted that applying high cross-flow conditions after the membrane relaxation caused a higher reduction of foulants accumulation [17].

When using the recycled EoL membranes (i.e. with the simple fitting device and the continuous filtering mode), a higher FA was observed. The NF-like recycled EoL membrane showed 51% and 47% FA of BP and HS, respectively. The UF-like EoL membrane showed 79% and 45% FA of BP and HS, respectively. This could be due to the residual fouling expected in the EoL RO membrane, even after applying the recycling protocol.

Table 4. FA (in %) of BP and HS inside the membrane module after 6 h of filtration when using recycled NF-like and UF-like recycled pristine membranes housed in the designed devices and operated in the submerged and external system configurations in continuous and intermittent filtration modes.

Parameter				**FA (in %) of BP and HS after 6 h of filtration**					
System configuration				Submerged				External	
Scenario - Membrane orientation				A-Vertical		A-Vertical		C-Horizontal	
Membrane housing				Simple fitting		End-caps		End-caps	
Filtration mode				Continuous	Intermittent (relaxation)	Continuous	Intermittent (relaxation +flushing)	Continuous	Intermittent (relaxation + flushing)
Recycled Membrane Type	NF-like	Organic fraction	BP	26.8	30.6	23.5	4.6	19.1	12.0
			HS	21.6	22.9	15.2	0.0	10.5	6.5
	UF-like	Organic fraction	BP	82.7	83.3	94.6	45.7	78.3	33.8
			HS	9.0	3.3	12.8	23.4	10.1	11.9

3.2.4 Suspended solids

The fate of the SS was assessed during filtrating by the UF-like recycled pristine membrane. During the experiments, the systematic reduction of turbidity at the feed was observed over time. On average, feed turbidity dropped from an initial value of 75 to 14 NTU after 6 h of filtration. As a result, feed turbidity was used as an in-situ indicator of the accumulation of the SS inside the module. Although the tank was aerated to mix the solution, a settlement was observed in the feed tank. At the end of the filtration, it was estimated that around 52 ± 11% of the original SS loading (6 ± 0 g) settled. In addition, no particles were detected neither in suspension nor in the permeate stream (after 6 h). Therefore, around 39 ± 8% of the original SS loading was trapped inside the membrane. Although the positive effect of cross-flow velocity on fouling limitation has been demonstrated well in literature [55,56], no clear correlation between the filtering modes was detected. Therefore, we were unable to determine the positive effect of flushing during the intermittent filtration to prevent the accumulation of

SS. This was due to the negligible cross-flow velocity applied (8.5 10^{-5} m s^{-1}), which was estimated according to the literature [56]. Consequently, such a low cross-flow velocity limited the shear rate necessary to flush SS particles away from the feed spacers. Indeed, it might be even lower when using bigger recycled spiral-wound modules (standard size of 8 inches diameter and 37 m^2 membrane surface), due to the feed spacer channel pressure drop [56]. The usage of a standard spiral-wound UF-recycled membrane at the same experimental conditions of the present work (GDM and flushing of 138 L m^{-2} h^{-1} feed water) might drop the flushing cross-flow velocity to 3.8 10^{-5} m s^{-1}.

Between 23 and 78% of the solid trapped inside the membrane were recovered in the flushing stage. However, neither the flushing nor the backwash fully recovered the SS. Although the membrane accumulated particles after each filtering cycle, no significant changes in permeability were observed in the subsequent experiments. This was also observed by Peter-Varbanets [46], which demonstrated that adding particles in the feed water (30 and 300 mg L^{-1} kaolin) did not influence the level of flux stabilization in long-term UF GDM filtration. However, in longer operation the accumulation of SS inside the module will clog the membrane. Therefore, further tests are encouraged to determine which concentration of SS limits the membrane performance compromising its lifetime.

3.3. Further testing and economic assessment for decision-making

Additional experiments were carried out to complement the main research. The limitation of separating salts using the NF-like recycled membrane, how to reduce the SS ingress into the membrane module and an economic analysis were assessed. All experiments together were used to develop a decision-making tree to select the appropriate membrane housing devices and the operating conditions to apply the recycled membranes for HWTS.

3.3.1 Pressure-driven test

The NF-like recycled pristine membrane was characterized in a pressure-driven cross-flow system (up to 4.4 bar) using the end-caps device and saline solutions. The resistance of the end-caps device was tested during 12 h of operation. Contrary to the observation operating with the GDM system, the membrane was able to reject salts up to 89%. Results shown in Supplementary data (Table A4 in Annex 4) are similar to earlier studies focusing on several kinds of NF-like membranes [31,57]. Therefore, NF-like recycled membranes hosted in the end-caps device could be suitable for cross-flow pressure-driven processes at a low feed salinity (below 4000 µS cm^{-1}).

3.3.2 Preliminary economic assessment

An economic assessment was carried out in this study which conservatively assumes only one year lifespan for the GDRM systems (aiming at its application in emergency response and early recovery WASH projects). The operational cost was assumed to be negligible over one year for this type of GDRM (with no electrical or chemical inputs required). When using the simple fitting, the TAC was 46 $USD.yr.^{-1}$. As shown in Supplementary data (Table A5-1 in Annex 5), the main cost of the system was attributed to the water containers and the recycled membrane (39% and 34% out of the total, respectively). The fitting associated with the membrane housing represented only 21% of the total investment. However, when the end-caps membrane housing was employed (Table A5-2 and Table A5-3 in Annex 5), the manufacturing of the device was the most important contributor, with 74% of the TAC (on average 176 $USD.yr.^{-1}$ TAC). Despite the fact that the end-caps device showed a marginal technical advantage, it cannot be manufactured by standard and existing items like the simple fitting device. Thus, while the cost of the first end-caps prototype was USD 130, it would drop significantly if massive production and/or by manufacturing in local workshops.

These results show that the GDRM system is a low-cost solution (defined by 0.01-0.10 USD L^{-1} [4]) that could compete with the commercially available HWTS systems based on UF membranes for humanitarian context (Table A5-4 in Annex 5 in Supplementary data). Although many commercial HWTS systems claim to have a lifespan up to 10 years (same as membranes), the lifespan of those HWTS systems in an emergency response context depends of many factors (e.g. the treated water quality and membrane surface [3], the risk of the membrane getting dry, replicates of the natural disaster etc.). Therefore, a relative cost comparison was done considering one year lifespan, operating intermittently 8 h per day 7 days a week. DI water production for the recycled pristine membranes and the calculated TAC were used for the present case, while the clean water production and the selling price were employed in the case of the commercial systems. The water production cost of 4 out of 5 commercial HWTS based on hollow fiber UF membranes was lower or equal to 0.2 USD ct. yr. L^{-1} (Squirt, Sawyer Point, Orisa and SkyPod systems). The GDRM system using UF-like recycled membranes and the simple fitting showed a potential water production cost of 0.2 USD ct. yr. L^{-1}, therefore it would be the most approachable solution to the market. The GDRM system based on the end-caps device with a water production cost of 0.9 ct. USD yr. L^{-1}, would be closer to the Safir EAWAG (0.7 USD ct. yr. L^{-1}, flat sheet membranes), the familiar LifeStraw HWTS (1.1 USD ct. yr. L^{-1}, hollow fiber membranes) and the Paul (1.3 USD ct. yr. L^{-1}, flat sheet fiber membranes) systems. Operating with the NF-like recycled membrane would increase up to 2.5-fold the water production cost, since its water production is remarkably lower than the UF-like recycled membrane.

3.3.4 Decision-making tree

In this study, the optimized operating conditions using the GDM system were found when the recycled membranes were housed in the end-caps device and operated intermittently (relaxation time plus forward flushing). The NF-like recycled pristine membrane performance at the optimized condition was 1.7 ± 0.1 L m^2 h^{-1} bar^{-1}, around 20% salt rejection and close to 89% DOC rejection. At this condition, less than 12% FA of BP and HS were observed when flushing was applied after the relaxation time. The UF-like recycled pristine membrane performance at the optimized condition was 16.0 ± 0.5 L m^2 h^{-1} bar^{-1} and 48% DOC rejection. At this condition, around 40% of FA of BP were observed when flushing was applied after the relaxation time. However, a wide range of contextual factors might condition the feasibility of applying the optimized conditions.

Based on this present work and complementary literature, a decision-making tree (Figure 4) was developed to select the most appropriate type of the spiral-wound recycled membrane, the appropriate membrane housing device, and the setup system configuration. As shown in Figure 4, the water quality (pH, conductivity and turbidity) determines whether using GDM systems or not and the need for a pre-treatment. For drinking water use, desalination technology is recommended when feed conductivity is higher than 2500 μS cm^{-1} [58]. NF-like recycled membranes could be housed in the end-caps device in a low-pressure (up to 4 bar) cross-flow driven system when water has low salinity [2500-4000 μS cm^{-1}] (See Table A4 in Annex 4 in Supplementary data). Otherwise, for water with lower conductivity, both NF-like and UF-like recycled membranes could be used in a GDM system. The height between the water level of the tank and the end of the permeate tube should be enough to achieve the necessary TMP. Ultra-low pressure can be achieved from 0.4 m [7] up to 3 m [21] (1.6 m was used in the present work).

According to our study, water with turbidity up to 75 NTU could be directly treated by the GDM system. However, during long-term use, membranes could rapidly clog. Therefore, it is preferable to install a pre-treatment to preserve the membrane lifespan. A relative low-cost simple cartridge device with popular filtering materials (e.g. 100% cotton T-shirt) could be implemented to reduce SS (see Table 6 in Annex 6 in Supplementary data). However, pre-treatment might limit the feed flow to the membrane unit. For conventional cross-flow pressure-driven processes using NF membranes, pre-treatment must be implemented with feed turbidity higher than 0.2 NTU [48].

The selection of the membrane type will rely on the compromise between the treated water production and the level of purification needed. If LMW-neutrals organic compounds, BB, HS or other substances with similar size are expected to be present in the water (typical river and lake waters with these compounds has around 4 mg L^{-1} DOC [7]), then NF-like recycled membranes should be selected. For treating bigger compounds such as BP, UF-like recycled membranes are more efficient, since they produce a higher volume of water.

To decide which system configuration is better suited to the application, membrane users are invited to consider some additional variables, such as tank dimension, location, safety, and (of course) the cost of the system. When the conditions are appropriate to use the submerged configuration, both membrane housing devices could be selected. However, it is more appropriate to use the end-caps device, if it is feasible to afford its cost (around 0.9 USD ct. L^{-1} $yr.^{-1}$). The end-caps device enables flushing after relaxation time, which is a way to induce shear stress on the membrane surface to mitigate fouling and potentially substantially improve the GDM system performance over its life (see Section 3.2). In this work, no significance differences were observed related to the membrane orientation. However, when operating with standard spiral-wound size (8 inches diameter and 37 m^2

surface), the easiest setup was found to be the external configuration, placing the membrane horizontally and close to the floor, while vertical orientation is more practical when membranes are submerged. As it was also demonstrated in this work, the intermittent mode of operation will be the optimal filtering mode. However, membrane users will have to pay attention on storing the membrane module wet for long-term preservation [33]. In that sense, the end-caps device could prevent air ingress better than the single fitting device.

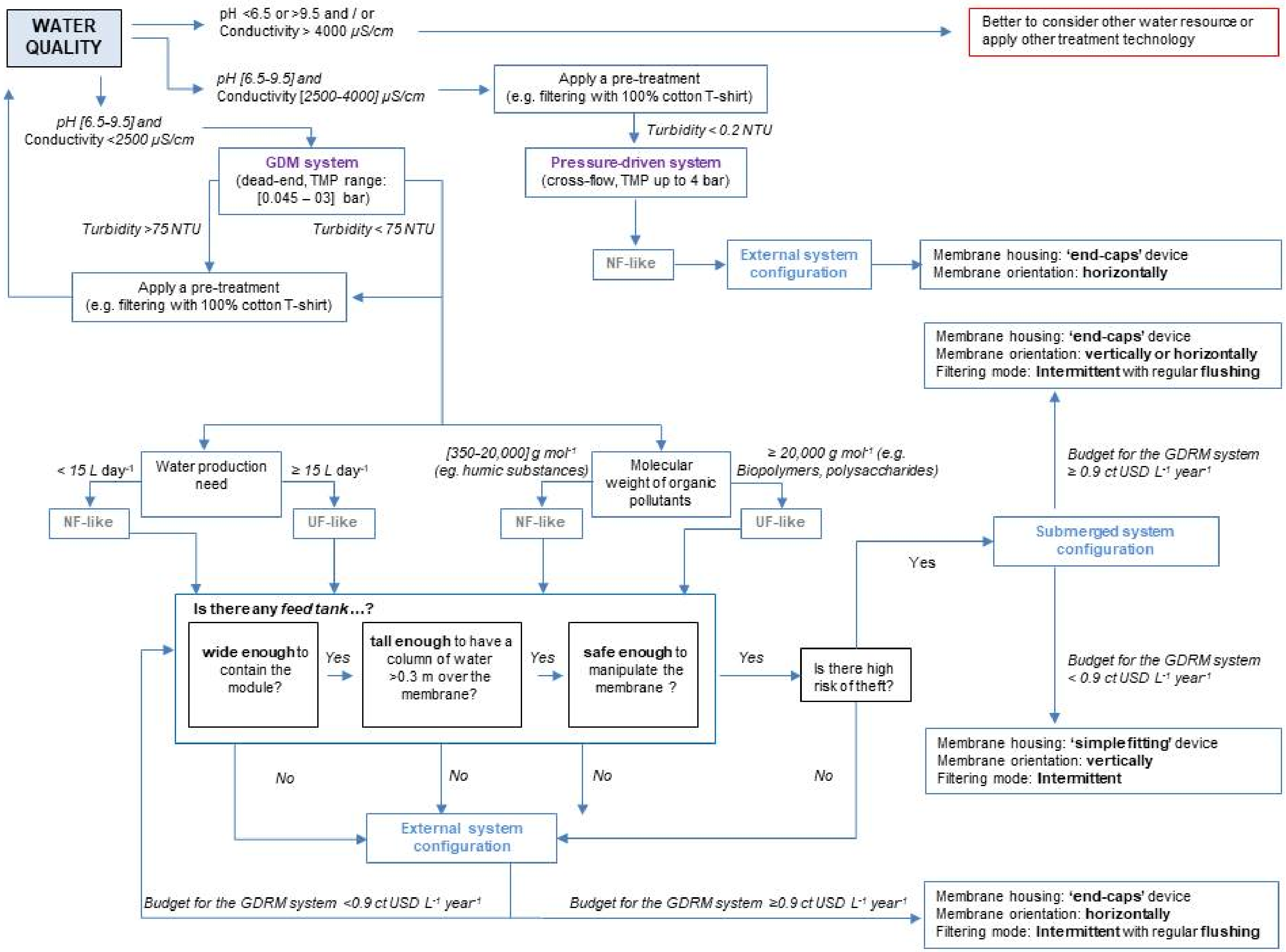


Figure 4. Decision-making tree for the selection of the most appropriate membrane housing device and operating conditions. The starting point is the water quality.

4. Conclusions

Two million EoL RO membranes per year are expected to be discarded from the desalination industry and disposed of in landfills, by 2025. Membrane recycling is a potential alternative solution to prolong the lifespan of the filter, which can be reused in other water treatment sectors.

This study focused on the development of two alternative membrane housings to the standard pressure vessels that are based on profiting the fiber glass of the spiral-wound recycled membranes with additional devices (simple fitting or end-caps). The new alternatives are suitable to apply a single recycled membrane module for HWTS in rural, decentralized areas and emergency response. Both membrane housings are simple, robust, cost-effective and light-weight, easily transportable and easy to set up and disassemble, which make them adequate for housing these types of membranes in GDM systems. It was demonstrated that the end-caps device was the most versatile solution. It enabled the use of NF-like and UF-like spiral-wound recycled membranes in a GDM system with external configuration (first tested worldwide) and showed other relative advantages (air ingress prevention and flushing) compared to the membrane housing with the simple fitting.

From the experiments, it can be concluded that recycled membrane-based gravity-driven systems could achieve an acceptable water production for emergency contexts, in terms of quantity (NF-like up to 1.7 L h^{-1} m^{-2} bar^{-1} and UF-like up to 37.2 L h^{-1} m^{-2} bar^{-1}) and quality (up to 89% DOC rejection). The affordable membrane surface cost per area (around 7 UDS m^{-2}, i.e. challenge (ii)) could help addressing the limited flux of GDM systems (i.e. challenge (i)) by using higher membrane surface than usual. Indeed, the high rejection values of: protein (up to 99%), HS (up to 97%), BB (up to 85%) and LMW-neutrals (up to 78%)

observed for the NF-like recycled membranes are particularly interesting. This could shed light on increasing the limited rejection capability of small sized organics of standard GDM systems (i.e. challenge (iii)). Additionally, it was demonstrated that the combination of membrane relaxation and flushing of the feed water could be a beneficial and easy practice to be implemented at household level to reduce membrane fouling (i.e. challenge (iv)).

The economic study showed that compact systems using the novel membrane housing with recycled membranes could produce water with less than 1 USD ct. yr. L^{-1}, being competitive with other commercial HWTS systems. Further scaled-up implementation to create GDM systems using the standard spiral-wound recycled membranes is encouraged, including long-term operation tests to assess bacteria separation and the flux stabilization. Water potabilization and urban waste reclamation are potential application fields.

Acknowledgements

The authors acknowledge the financial support of the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 712949 (TECNIOspring PLUS) and to the Agency for Business Competitiveness of the Government of Catalonia for the grant TECSPR17-1-0019 Mem2.0 project. Special thanks to UNSW staff (Paul Brockbank, Khorshed Chinu and Yun Ye), and the collaborative companies such as TELWE S.A. (Jordi Gabarro), IMDEA Water and SACYR.

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