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Research Paper

Impacts of hydration and dehydration on microfiltration point-of-use filters: performance and cleaning impacts

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ABSTRACT

This research examines the performance of two commercially available point-of-use (POU) microfiltration membrane filters (MF) under hydrated (wet) versus a multi-day dry period (dehydrated). Filter performance is monitored in terms of water quality and flowrate, as well as flowrate recovery following different cleaning regimes. The cleaning methods tested were backwashing with filtrate at room temperature, filtrate heated to 45 °C, filtrate at 45 °C with gentle shaking, and a vinegar solution (5% acetic acid). The selected cleaning methods reflect easily accessible cleaning methods with a goal to assess their impacts on flowrate recovery under both wet and dry conditions. After initial testing, hydrated MF flowrate varied between 197 ± 22 mL/min and backwashing with filtrate at room temperature was sufficient to maintain the membrane flowrate, while any of the other methods initially improved the system flowrate. In experiments where the filters were subject to a 5-day dry condition MF flowrates dropped to 65 ± 35 mL/min and filtrate at room temperature did not recover the flowrate sufficiently, however heated filtrate (45 °C) with/without gentle shaking was effective at recovering the MF for use. Water quality remained similar throughout the study, and 0 CFU/mL of *E. coli* were found in filtrate samples.

Key words: backwashing, hollow-fiber, membrane, microfiltration, point-of-use

HIGHLIGHTS

- This research provides a side-by-side comparison of POU membrane filters when maintained under wet versus dry conditions.
- Heated filtrate was found to positively improve membrane filter performance after fouling under all conditions.
- Overnight soaking of a dried membrane did not adequately recover membrane filter performance.
- Complete turbidity removal was observed under repeated wet and dry conditions.

INTRODUCTION

Access to safe drinking water is a human right and a global need. However, approximately 2 billion people still lack access to safely managed services, including 367 million using unimproved water sources (i.e., unprotected dug wells or springs), and 122 million users that collect and consume (untreated) drinking water directly from rivers, dams, lakes, and ponds (WHO & UNICEF 2021). Geographically, it is people from rural, low- and middle-income countries who suffer from lack of access to safe drinking water the most (WHO & UNICEF 2021; Prüss-Ustün *et al.* 2014).

In order to achieve universal coverage, access to drinking water services, sanitation, and hygiene need to scale up and alternative options for service and delivery need to be considered. Opposed to centralized drinking water systems, decentralized treatment options do not require a high level of expertise to operate and maintain and can be a viable option where centralized systems are not practical. For instance, point-of-use (POU) water treatment devices are relatively small (hand-held) pieces of equipment which treat water directly before use and are often easy to use. Over the past decade, diverse POU water treatments have emerged and include chlorination, media filtration, membrane filtration, and solar and UV disinfection (Peter-Varbanets *et al.* 2009; Pooi & Ng 2018; Wu *et al.* 2021; Fagerli *et al.* 2018). Of these options, hollow-fiber membrane filtration is an effective drinking water treatment process that allows easy adaptation into POU systems (Sobsey *et al.* 2008; Swearingen *et al.* 2020). Specifically, small hollow-fiber microfiltration membrane filters (MF) have been employed for camping and emergency situations as they are reported to operate at flowrate of approximately

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700 mL/min with complete turbidity removal, and high reduction in bacteria and protozoa ($\geq$99.9999%), which are responsible for waterborne diseases (Murray *et al.* 2017). Therefore, small microfiltration membrane filters can be considered as a relatively inexpensive but potentially effective solution to provide access to safe drinking water when properly used (Tintle *et al.* 2021).

Membrane fouling and associated decreases in filtration flowrate have been identified as a reason for filter disuse (Murray *et al.* 2015). Studies with follow up at 20–24 months report for disuse rates ranging from approximately 20 to 50% after installation (Goeb 2013a, 2013b; Kohlitz *et al.* 2013). Reported reasons for disuse include broken filters or filter parts, missing parts, and low flowrates (Murray *et al.* 2015). Of the reported reasons for disuse, few studies have assessed the impact of cleaning techniques on low flowrate recovery. Thus, investigating recommended cleaning protocols and their impact of flowrate filter performance may provide insightful information in this field. The influence of cleaning methods on flowrate recovery has been examined by Murray *et al.* (2015). This study utilized physical (soak in hot water and backwashing with deionized (DI) water) and chemical (soak in 5% vinegar and backwashing with DI water) cleaning methods to recover the flowrate of filters that had been used for 23 months in households. Soaking and backwashing were reported to restore the flow, however the actual flowrate values were not specified, as such the cleaning efficiency was not numerically determined. Heylen *et al.* (2021) tested three cleaning solutions on laboratory-assembled modules of three different brands of microfiltration hollow-fiber filters with various feed solutions and a high *E. coli* level (10^6 CFU/100 mL). In this study, the cleaning solutions included 0.5% sodium hypochlorite, DI water, and vinegar (6% acetic acid). One test observed >75% drop in the normalized flux regardless of the cleaning solution with high TOC feed water of 15 mg C/L. Meanwhile, a test with high turbidity (30 NTU) registered an overall drop in normalized flux of 0.28, 0.2, and 0.03 when backwashing with chlorine, DI water, and vinegar, respectively (Heylen *et al.* 2021). While the backwashing methods struggled to maintain the flow, *E. coli* removal remained high at an approximate log removal value (LRV) of 5.3. Further POU filters might be susceptible to dehydration or drying conditions when used in households. For instance, while one study noted that filter daily usage is approximately 2.5 h/day (Heylen *et al.* 2021); little research has considered the impact of a filter on flowrates where it has been left unused if homeowner is away for an extended time period. To date, studies have examined various time periods in which a filter remains under wet conditions have not compared these conditions to scenarios where the filter may dry out and how these drying conditions may impact the filter operation.

The overall performance of POU MF filters, off-the-shelf access and general ease of use has increased interest in utilizing these systems at the household level in developing countries by non-governmental organizations (NGOs) that supply water in communities in need. The list of less developed (often referred to as developing countries) is reviewed every 3 years by the United Nations and currently consists of 46 countries; these countries have Human Assets Index values below 60 and Economic Vulnerability Index values greater than 36 (UN 2023). In fact, Tintle *et al.* (2019, 2021) found substantial health and economic benefits when POU MF filters were coupled with initial training on filter usage which includes backwashing and handwashing. Unfortunately, the studies did not report any flowrate changes of the provided filters (Tintle *et al.* 2019, 2021). Another study examined POU MF filters flowrates and coliform contamination over a 13-month time period (Holding *et al.* 2019). In this study, initially 0% (no measurable coliforms) of filtrate samples from households where contaminated; however, by month 6, 40% of filtrate sample exhibited contamination with an average of 18 CFU/100 mL. Subsequently, a 0.2% chlorine backwash was incorporated and resulted in filtrate contaminated samples decreasing 5–25%, indicating that some usage of a chemical backwash may maintain filter safety. The cleaning instructions consisted of backwashing with clean water as well as the occasional usage of chlorine. In this study, initial flowrates of 480 mL/min dropped to an average of 100 mL/min with a range of 10–200 mL/min after 1 year (Holding *et al.* 2019). The drop in flowrate and the wide range of 10–200 mL/min raises questions to further explore cleaning methodologies. In a similar field study, where filters had been used for either 1 year or 3 years with a water source that contained approximately 5 NTU and >1,000 MPN/100 mL total coliforms, the effect of backwashing 3–4 times with filtered water on flowrate was investigated (Murray *et al.* 2017). After cleaning, flowrate averaged 77.2 mL/min, however, the flowrate prior to cleaning was not reported and the authors estimate that 77.2 mL/min is 11% of what expected of a new filter (719 mL/min) (Murray *et al.* 2017). Even though backwash methods were recommended by researchers in various studies (Murray *et al.* 2017; Holding *et al.* 2019), there was no monitoring on the effectiveness of the methods by comparing flowrates prior to and after cleaning.

Overall, POU MF filters can provide clean and safe drinking water to households in adequate quantities. However, there is a gap in the research regarding cleaning protocols as well as flowrates and flowrate recoveries. Limited studies examine declining head pressure flowrate data which is a better indicator of field usage or the impact of membrane drying and

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subsequent recovery. In this research, the difference between hydrated and dehydrated conditions and its impact on flowrate and flowrate recovery are examined with monitoring of other various water quality parameters. Dehydrated conditions are meant to replicate conditions where the filters might dry out after disuse within a household. Various cleaning methods with filtrate (warmed versus room temperature), and with readily available acetic acid (vinegar) were examined for subsequent impacts on flowrate recovery with two different commercially available POU MF filters. Units were fouled with a moderate TOC and hardness water as well as a Natural Water (Rideau River) source to determine resultant flowrates and the efficiency of the examined cleaning methods.

MATERIALS AND METHODS

Experimental setup

Two types of commercially available POU microfiltration membrane filters (Village Water® and Sawyer®) were utilized in this research. Both MF systems consisted of an encased U-shape hollow-fiber membrane with a nominal pore size of 0.1 μm. The filtration kits of F1 (Village Water®) and F2 (Sawyer®) included a plastic syringe of 60 and 50 mL, respectively, plastic tubing, and adapters to attach the filter to a container. The filters were assembled as suggested by the manufacturers, and tubing was installed at 4 cm from the bottom of a 20-L container to avoid filtration of settled particles. The first 15 L were filtered at declining head (C1, C2, C3) while a pump was used to always maintain a minimum of 5 L in the container until 20 L of water was collected for both Synthetic and Rideau River feed water tests. Figure 1 depicts the system setup.

Water quality

Model foulants representing total organic carbon (TOC) and calcium ions were selected to produce a mock raw water source (Synthetic Feed Water). Humic acid (Sigma-Aldrich) and calcium sulfate (Sigma-Aldrich) were selected as the main foulants in order to test for adsorptive organic fouling and calcium as a potential contributor to overall fouling (Alresheedi *et al.* 2019). The final Synthetic Feed Water characteristics had a TOC concentration of 6.2 mg C/L, a hardness of 188 mg/L $CaCO_3$/L, and a turbidity of 2.6 NTU. Humic acid and calcium sulfate solutions were prepared one-day (24 h) prior to any experiment with dechlorinated tap water and mixed to ensure materials dissolved. Additional tests with a natural water were directly sourced from a local river system (Rideau River, Ottawa, Ontario). The feed water characteristics are summarized in Table 1.

Data collection and measurements

Feed and filtrate water samples were collected during fouling tests. Feed samples were collected for all parameters once before every test. Filtrate samples were collected as follows: TOC and turbidity samples were taken every 5 L and the average of triplicate readings were recorded with twenty (20) liters of water processed in each test. Hardness and alkalinity samples were collected every 10 L and the average of duplicate measurements was recorded. Color was measured for filtrate samples collected during the first 5 L of filtration. Backwash samples were collected in four 250 mL Erlenmeyer (BW1, BW2, BW3, and BW4) to measure TOC and perform a standard carbon mass balance in order to determine the mass removal efficiency.

Figure 1 | POU filtration system setup (left), mixing of synthetic water in feed tank (center), membrane filters, and backwash syringes (right).

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Table 1 | Synthetic and Natural Water (Rideau River, ON, Canada) average feed water characteristics

Parameter	Synthetic Feed Water	Natural Water	Unit
Total organic carbon	6.2 ± 0.7	16.9 ± 2.9	mg C/L
• Background TOC	3.1 ± 0.6	n/a	mg C/L
• Humic acid (Aldrich)	3.1 ± 0.1	n/a	mg C/L
Total hardness	188 ± 6	198 ± 5	mg $CaCO_3$/L
• Background hardness	31.2 ± 3.1	n/a	mg $CaCO_3$/L
• Calcium sulfate	156 ± 3	n/a	mg $CaCO_3$/L
Alkalinity	36.1 ± 3.7	259.1 ± 1.8	mg $CaCO_3$/L
Turbidity	2.6 ± 0.4[a]	2.9 ± 1	NTU
E. coli[b]	10^3	n/a	CFU/mL

[a] Kaolin clay was added incrementally to the Synthetic Feed Water until it reached the target turbidity value.

[b] *E. coli* was added to the Synthetic Feed Water during an *E. coli* challenge test only.

In addition, to identify potential water quality changes after cleaning the membrane, filtrate water samples were collected to analyze TOC concentrations every 5 L during recovery tests. Tests were completed at room temperature conditions of 20 ± 2 °C.

Water quality measurements were carried out as follows: turbidity was measured using a Thermo Scientific Orion AQ3010 turbidity meter, and a Thermo Scientific Orion Star A series pH meter was used to measure the pH. To determine hardness, samples were titrated with EDTA at pH 10 using Eriochrome Black T indicator following Standard Method 2340C (APHA *et al.* 2017). Alkalinity was determined by titration using H_2SO_4, with phenolphthalein and methyl orange indicators following Standard Methods: 2320 (APHA *et al.* 2017). Color was determined following the spectrometric multiwavelength method using 10 ordinates for spectrophotometric color determinations (Standard Method 2120D) (APHA *et al.* 2017). TOC concentrations were measured using a Jenway 7415 Scanning UV/VIS spectrophotometer, based on a calibration curve done with known concentrations. The known TOC stock solution was measured using a Shimadzu TOC-L CPH equipment following Standard Methods 5310B (APHA *et al.* 2017). *E. coli* (10^3 CFU/mL) was added to the Synthetic Feed Water and measured only during the *E. coli* test and followed the method 1604 (USEPA 2002).

Filtrate flowrate was measured manually with a timer and a volumetric container. Four flowrate data points were taken during fouling tests, and each data point represents the flowrate registered when filtering 5 L of feed water. Two flowrate data points were collected during recovery tests, as 10 L were utilized to evaluate the cleaning efficiency.

Experimental plan

In this research, an initial conditioning phase was conducted where water (Synthetic Feed Water) was filtered through new filters to assess any initial flowrate reductions. This was followed by examining different cleaning protocols under hydrated condition to simulate continuous usage; wherein the filter was maintained in regular usage and such that water was present at all times within the MF body. The POU MFs were also tested under dehydrated (dry) conditions, wherein the filters were allowed to dry out for a 5-day period. Finally, to examine POU MF filters integrity, a bacterial challenge test was conducted which consisted of filtering 10 L of Synthetic Feed Water spiked with *E. coli* to make a 10^3 CFU/mL *E. coli* concentration. The added *E. coli* (K-12, ATCC® 29947, Cedarlane Laboratories) was subsampled from a working stock solution prepared by transferring 100 μL thawed *E. coli* stock standard to 9,900 μL of No. 3 Nutrient Broth (Sigma-Aldrich) in a 15 mL conical vial. The vial was then incubated at 37 °C for 18–19 h which was the beginning of the stationary phase, the sample was collected and stored at 4 °C for up to 3 days prior to testing, with 10 mL of working stock solution added to the 10 L of Synthetic Feed Water. *E. coli* concentrations were enumerated as per USEPA Method 1604 (USEPA 2002).

Experiments were conducted to evaluate the proposed cleaning methods (Table 2) under hydrated and dehydrated conditions. Cleaning consisted of permeate (P) at room temperature, permeate heated to 45 °C (P45), P45 + gentle shaking of the unit, and backwashing with a vinegar solution (PV). Heating the permeate to 45 °C reflects cleaning procedures in larger scale systems where cleaning solutions are heated at times to assist with solubilization of adsorbed contaminants on the membrane surface (Shi *et al.* 2014; Gruskevica & Mezule 2021). Each experiment consisted of a fouling test, where

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Table 2 | Backwash cleaning methods utilized: hydrated and dehydrated experiments

Test code	Cleaning method	
P	Filtrate	Filtrate collected at the end of the fouling test
P45	Filtrate at 45 °C	Filtrate collected at the end of the fouling test was heated to 45 °C prior to backwashing and used immediately
PS45	Filtrate at 45 °C + Shake	Filtrate collected at the end of the fouling test heated to 45 °C. Procedure as follows: three gentle shakes + filtrate heated to 45 °C
PV	Diluted vinegar	500 mL of vinegar (5% acetic acid) + 500 mL of filtrate

20 L of Synthetic Feed Water or Natural Water (Rideau River, ON, Canada) were filtered per membrane unit. Fouling tests were followed by the application of one of the cleaning methods to evaluate the cleaning efficiency and flowrate recovery. Immediately after cleaning 10 L of filtrate was passed through each filter to determine the membrane flowrate recovery. After measuring the flowrate recovery, membrane filters again subject to a new fouling test and were kept wet (hydrated phase) or were left to dry out (dehydrated phase). The cleaning methods were designed to be economically affordable and easy to implement by people from small rural and remote communities. Therefore, to simulate household usage, the provided syringes were used to backwash the membrane filters. Backwashing followed general manufacturer recommendations of backwashing until water flows clear, in this study the backwash volume was kept constant for all experiments and 1 L of cleaning solution was used. In some cases, where filters did not appear to produce water during a fouling filtration test, it was observed that air entrainment occurred and under such conditions filters a brief backwash of 50 mL with previously collected filtrate to remove air bubbles in the system was implemented.

RESULTS AND DISCUSSION

Initial flowrate performance: conditioning phase

The conditioning phase intended to assess the initial flowrate performance of the MFs and identify initial drops in flowrate. Severe flowrate drops have been observed in POU hollow-fiber membranes in laboratory and field studies (Holding *et al.* 2019; Heylen *et al.* 2021). Thus, an initial conditioning phase is recommended to compare results to more realistic flowrate values for subsequent recovery analysis. The flowrate was measured when the 20-L container was initially filled with unaltered tap water. MF type F1 had an initial flowrate of 766 mL/min, while MF type F2 registered an initial flowrate of 886 mL/min. Subsequently, tests with the Synthetic Feed Water solution (20 L) were passed through the membrane. The initial flowrates were observed to quickly decrease to between 300 and 470 mL/min for F1 and F2, respectively. The flowrate in both filter types continued to drop over this conditioning phase and were backwashed with filtrate every 20 L until a stable flowrate was observed, which occurred after 140–180 L of filtered water: with a stabilized flowrate of approximately 200 ± 21.8 mL/min at the start of a filtration cycle for both filter types.

Flowrate performance under hydrated and dehydrated conditions

Initial tests were conducted with membranes that mimic POU filters that are kept in continuous usage and thus stay under hydrated (wet) conditions at all times. In these experiments, the first set of hydrated tests was then followed by the 5-day dehydration tests, and then kept under hydrated (wet) conditions to ensure robustness of results. During the evaluation of the four proposed cleaning methods, F1 and F2 averaged a flowrate of 178 and 181 mL/min, respectively, over the initial 10 L of filtration; a statistical comparison of the two MFs did not denote a difference in overall flowrates ($p > 0.05$), as such all results were subsequently combined for analysis.

As MF tests were conducted under a declining head format, a flowrate reduction of over 20 L of filtration was expected due to fouling and the decreasing water head pressure. The flowrate declined from an average of 197 mL/min in the first 5 L collected to 95 mL/min over 20 L of water collected, with a relatively consistent standard deviation in results of approximately 20 mL/min. Thus, if a MF was operated continuously and maintained in a hydrated condition, it would be possible to collect 20 L of water in approximately 156 min, with the first 10 L collected in under 1 h but the second half taking nearly twice that duration under declining head conditions.

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Recognizing that under real-world scenarios a homeowner may not use the MF on a daily basis and that disuse could result in a dry membrane filter, it is important to understand how the filter would operate under such conditions. MF disuse due to low flowrates is one commonly reported factor (Murray *et al.* 2015). As can be observed in Figure 2, MFs that have been left out to dry (unused) for a 5-day time period exhibit a substantial drop in flowrate. While the hydrated MF initial flowrate was 197 ± 21 mL/min, this value dropped to 65 ± 35 mL/min when the MF experienced the dehydration conditions; meanwhile, at the end of the 20 L filtration cycle, the hydrated MF flowrate declined to 86 ± 22 mL/min and the dehydrated MF flowrate dropped even further to 48 ± 19 mL/min. As a result, under declining head conditions, it would take upwards of 374 min to collect 20 L of water, which is nearly 2.5× the amount of required time to collect 20 L of water when the membrane was in continuous use and remained hydrated.

In this study, the 5-day dehydration period negatively impacted the filters performance causing an overall reduction in flowrate of 58%; thus, if a proper cleaning protocol is not developed to recover the dry MF, it may fall into disuse. It is recommended that future studies examine a variation in time periods that MFs may be left to dry, including shorter time intervals (1–2 days), to further investigate this potential issue.

Figure 3 compares the impact of cleaning method on the hydrated and dehydrated MFs. When the MFs are hydrated, any method of backwashing maintains the filter flowrate under the conditions tested. Meanwhile, for a dehydrated MF, room temperature permeate alone is not sufficient to recover the flowrate to the conditions observed under hydrated conditions. Overall, it appears that while a POU filter may suffer from some level of drying, treating the filter system with warmed filtrate (with or without shaking) has the best recovery overall. This could be a vital piece of information to communicate, as a user may be discouraged from using a POU filter if the flowrate cannot be recovered. Frequency and education of backwashing method may impact user's ability to recall what cleaning method to utilize; thus, a program which recommends and trains on situation-dependent cleaning is important.

Backwash optimization of dehydrated MF

Initial dehydration experiments consisted of filtering water through the MF without any form of pretreatment in order to create a direct comparison with the hydrated results. Based on the low initial flowrates observed and the improved results from backwashing, it was decided to investigate if a pretreatment strategy could be implemented to improve flow before a user tried to filter water through a dehydrated MF. To improve and facilitate filters usage in households after dehydration, two protocols were tested to recover the filter for use: overnight soaking (ONS) followed by a 50 mL backwash or

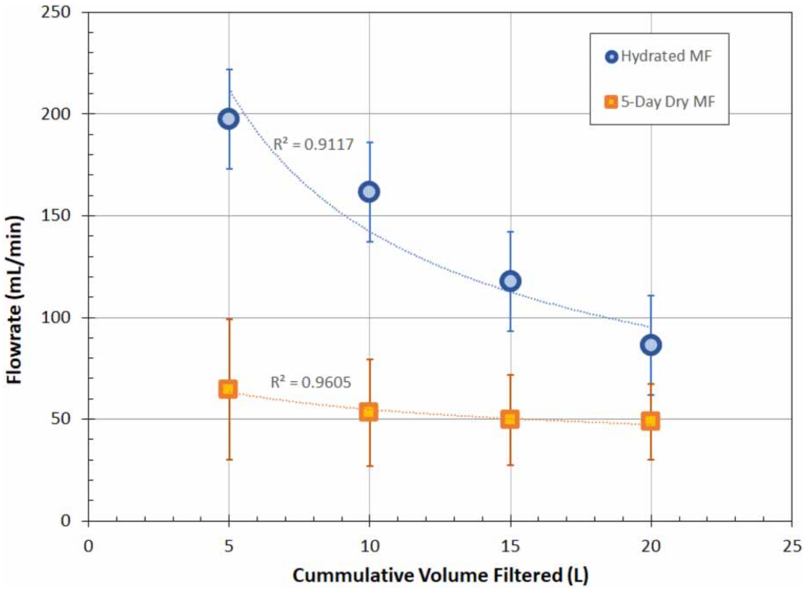

Figure 2 | Comparison of observed flowrate (mL/min) under 20 L declining head filtration using Synthetic Feed Water cycles from hydrated membrane filters versus membrane filters that had been left to dry for a 5-day time period (each sample represents $n = 12$–16 measurements, error bars are standard deviation).

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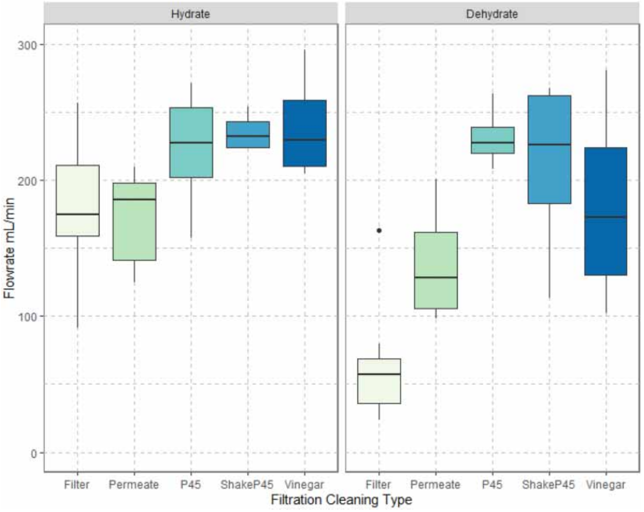

Figure 3 | Comparison of impact of cleaning methods on flowrate recovery for hydrated and dehydrated membrane filters for tests using Synthetic Feed Water; Box and Whisker plot with box edges representing 25th and 75th percentile flowrate values observed, and whiskers 5th and 95th percentile values observed.

backwashing with 150 mL of warmed water (45 °C) and gentle shaking (PS45). Interesting, although an overnight soak with a brief backwash (50 mL) would seem an intuitive technique to recover a dried MF, it was only moderately effective. Untreated dehydrated membranes had an average initial flowrate of 65 ± 35 mL/min; ONS improved the average initial flowrate to 100 ± 45 mL/min, while backwashing with 150 mL of warmed water followed with some gentle shaking (or tapping) of the unit (optimized-PS45) improved the initial flowrate to 234 ± 24 mL/min, which is similar to the higher volume PS45 results observed earlier. Thus, a much shorter backwash (150 mL) with warmed water seems possible to achieve similar results with regards to flowrate recovery. In all tests, it is clear that using a warmed water backwash step was beneficial to cleaning and recovery of the MF.

Analysis of individual membrane fiber

After testing was finished, the filters were disassembled and examined under a scanning electron microscope (SEM). What can be seen in Figure 4 is individual POU MF fibers; interestingly despite using identical cleaning regimes and observing similar flowrate results between the two systems, F1 has a buildup of material on the fiber when compared with F2. Although each MF assessed filtered approximately 400–500 L of water, POU MF filters are often used in the field for periods over a year (Holding *et al.* 2019; Tintle *et al.* 2021); a continuous buildup of material on the membrane fibers such as observed in F1 may be detrimental to the filter's effectiveness over a longer time frame. However, the initial buildup observed in this

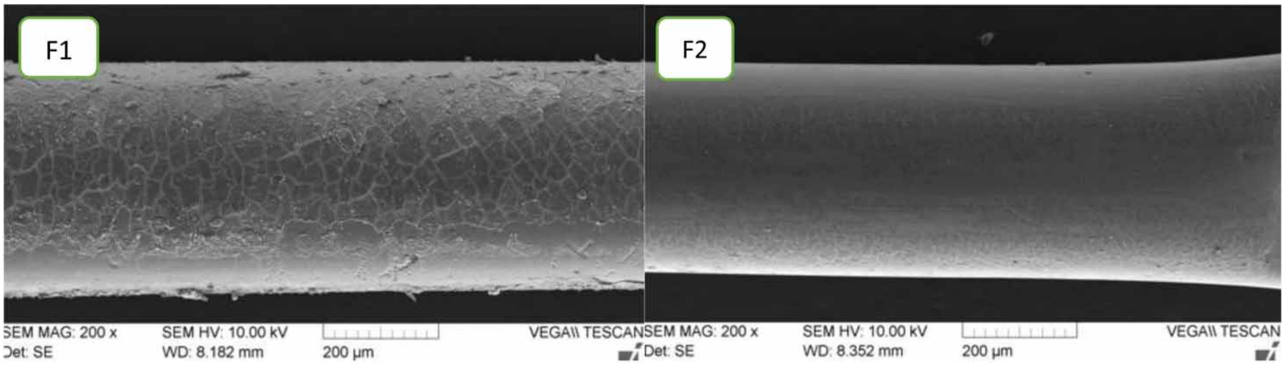

Figure 4 | Scanning electron microscope images of individual hollow-fiber membrane strand with F1 (left) and F2 (right).

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study may have acted as filter aid at this stage of fouling development and explain why a more detrimental impact on flowrate was not observed (Basu & Huck 2004). Thus, additional investigation of MFs is recommended to determine at what point the observed debris may result in a larger negative impact on the system performance.

Backwash mass removal efficiency

The TOC removal efficiency during backwashing was investigated in both filter types under hydrated and dehydrated conditions to identify if any cleaning method was associated with greater TOC removal that could be correlated to flowrate recovery. In these experiments, 1 L of backwash water was used to clean each membrane after a fouling test, with the backwash water collected in 250 mL increments in order to help assess how many stages of backwash water may contribute to the best recovery of the MF. It is important to note that the cleaning syringes provided by the manufacturers only holds 50 mL of water, and thus this may represent an issue if a user finds the backwash step (utilizing the syringe) difficult in some manner. It is recommended to study the efficiency of the proposed cleaning methods with a reduced volume of ≤ 250 mL in subsequent research. In addition, the first 250 mL of water collected post-backwashing, during the filtration recovery stage was collected in order to determine if residual carbon was flushed out into the filtrate.

Figure 5 compares the amount of carbon removed by backwash type and within each collection increment (of 250 mL water). BW1, which represents the first 250 mL of backwash water collected, generally contains the highest amount of carbon in both the hydrated and dehydrated experiments. In the hydrated experiments, the total mass removed for Permeate (P) and Heated Permeate (P45) appear to be similar; although the P45 removed a larger amount of carbon during the first backwash (approximately 33%) compared to the cleaning method P; similarly, PS45 demonstrated an even larger first flush removal (60%) compared to P. Interestingly, both P45 and PS45 have similar recovery results of 223 and 235 mL/min, respectively; thus, the mass removal did not directly correlate to the observed flowrate recovery. Of particular note however the TOC is recovered using the vinegar solution. Very little TOC was observed in any of the backwash flushes with the vinegar backwash (PV), however, the first filtrate collection of 250 mL contained a noticeable increase of TOC (approximately. 6 mg/L) when compared to any of the other cleaning methods. It appears that the PV solubilizes the organic carbon in some way that promotes its passage through the membrane and into the cleaned water. This is an undesirable effect as it may then result in undesirable organics passing into the drinking water. As such, it would not be recommended to use a vinegar cleaning solution based on the results observed in this study. Figure 6 contains images of the collected backwash water observed from a PS45 experiment as well as a PV experiment, which were representative of the images observed in multiple cleaning steps. It can be observed that the PS45 contained a significant amount of removed TOC in the first backwash, while each of the PV steps visually contained very little TOC during the four backwash steps.

Water quality

Water quality of feed and filtrate samples were monitored throughout the study to assess the performance of the various cleaning methods. Both filter types tested achieved a high turbidity removal from a feed value of 2.6 ± 0.4 NTU to a filtered

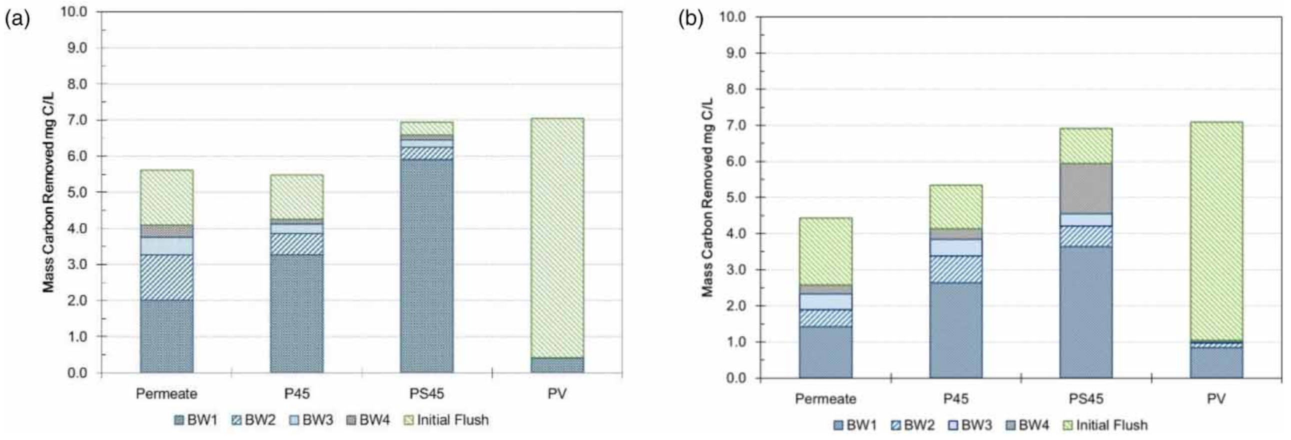

Figure 5 | Mass removal associated with Synthetic Feed Water source from membranes during backwash step (BW1–BW4) and initial flush (250 mL) of membrane filters under (a) hydrated and (d) dehydrated conditions.

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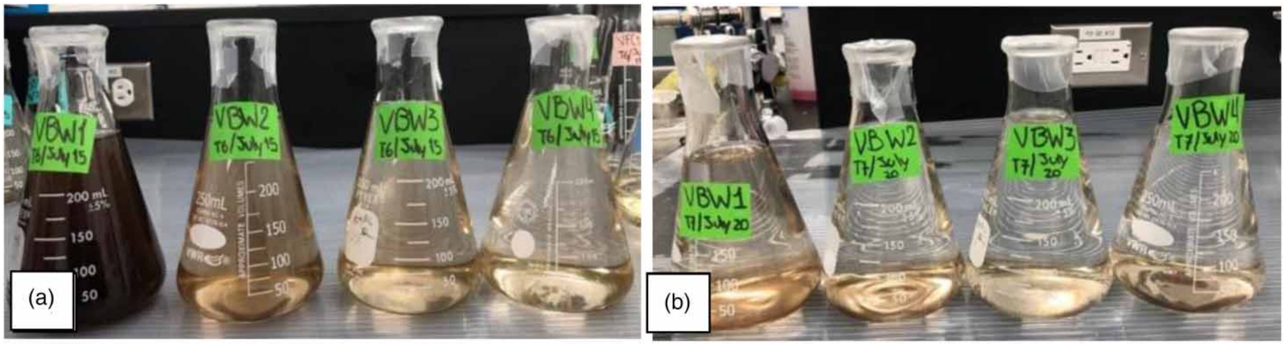

Figure 6 | Visualization of TOC (*source*: Synthetic Feed Water) removed during four backwash steps: (a) a PS45 under hydrated conditions and (b) a PV under hydrated conditions. Images are left to right (BW1, BW2, BW3, and BW4).

value of 0 NTU under the hydrated and dehydrated phases. TOC measured in filtrate water was on average approximately 1.3 mg C/L for both filters. Calcium was not retained by the membrane, and feed and filtrate concentrations remained consistent having on average 188 ± 6 mg $CaCO_3$/L in terms of hardness and 36.1 ± 3.7 mg $CaCO_3$/L of alkalinity. The presence of dissolved organic carbon coming from humic acid caused a small amount of color in the finished water. After measuring selected ordinates for spectrophotometric color determinations, filtrate samples had a dominant wavelength between 575 and 580 nm, which indicates a slight yellow tone in water. The bacterial removal efficiency of the filters was assessed when filters had filtered 402–414 L of water and undergone both hydrated and dehydrated test conditions. During the bacterial removal test, 10^3 CFU/mL *E. coli* was added to the feed water with 0 CFU/mL found in the filtered water samples. Thus, the membrane demonstrated robustness to undergoing various hydration, dehydration, and cleaning cycles.

Hydration and dehydration impacts with a natural surface water source

The same hydration and dehydration procedure that was used for the Synthetic Feed Water tests was used for a Natural Water source (Rideau River, Ontario, Canada). This was done to assess any differences between the two feed waters as well as determine the impacts of dehydration when using a Natural Water source. The two most effective cleaning methods from the dehydrated Synthetic Feed Water tests were used for the testing of the Natural Water source and were identified as P45 and PS45.

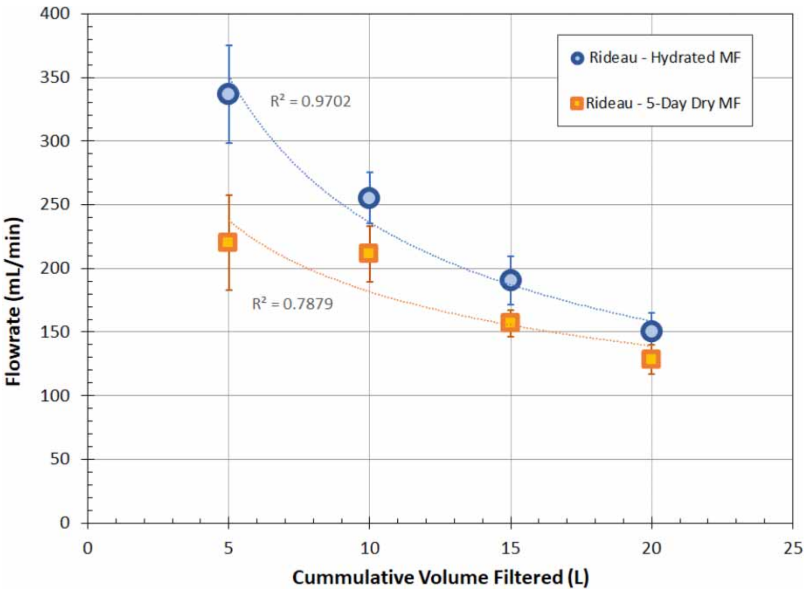

Figure 7 | Hydration and dehydration flowrate comparison (Natural Water Source: Rideau River).

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The observed flowrates with the Natural Water source (Figure 7), were much higher than the Synthetic Feed (laboratory prepared) Water. The initial hydrated flowrates were 336 ± 38 mL/min with a decline to 150 ± 14 mL/min over the 20 L test; while dehydrated flowrates were 220 ± 37 mL/min and declined to 128 ± 12 mL/min over the test duration. The P45 and PS45 backwash methods when applied to the dehydrated membranes were able to recover the flowrates to the original hydrated flowrate ranges with values of 310 ± 25 and 364 ± 20 mL/min, respectively. The hydrated recovery tests demonstrated more variability in the results with the P45 recovery 300 ± 68 and PS45 438 ± 43 mL/min. Changes in water chemistry may explain the higher flowrates with the Natural Water; although the measured TOC content of the Natural Water (16.9 mg/L) was greater than the Synthetic Feed Water tests (6.9 mg/L), it is possible that the Natural Water (source: Rideau River water) was in a smaller size fraction. It is noted that the water collected during testing for the Natural Water source was during spring runoff which may also account for the high TOC value observed. The comparison of results between both water types highlights the need to all take into consideration site-specific water quality and that it would be recommended for a provider to conduct on-site testing to verify usage and cleaning protocols where possible.

CONCLUSIONS

This research investigated potential operation conditions of POU membrane filter where it remains water saturated (hydrated) or experiences a drying period (dehydrated). This research found that overall, currently recommended backwash procedures for hydrated membranes appear are reliable; however, if the membrane experiences a drying (dehydration) period that backwashing with room temperature water was insufficient to recover the membrane filter flowrate; whereas warming the water provided significant improvements to recover the POU system. As loss of flowrate is an important factor in disuse, it is recommended for field researchers to investigate warming the water to assist with membrane filter recovery and to subsequently share this information with users. Overall findings are:

- POU MF that remained hydrated was easily recoverable after fouling by any backwash method attempted. Although slightly higher initial recoveries were noted when warm filtrate was used for the backwash step.
- When a POU MF dried out, over a 5-day time period, significant drops in flowrate occurred. In such instances, a warm water backwash was best suited to recovering the flowrate performance of the POU MF.
- In this study, hydraulic backwashes (P, P45, PS45) were more efficient at removing mass from both filters under hydrated and dehydrated conditions than the vinegar solution (PV), which can reduce maintenance costs of the filters in field. Applying motion to the filter case enhanced the mass removal efficiency on both filters during both phases, but a greater mass removal was not always related to a greater flowrate recovery.
- Both filters remained robust to removal of turbidity throughout testing with feedwater values of 2.6–2.9 NTU and filtrate values of 0 NTU observed. Calcium ions were not retained by the membranes which suggest that organic carbon was the main foulant. Finally, no *E. coli* colonies were found in the filtrate, indicating a certain robustness of both membranes when exposed to adverse conditions.

It is recommended that additional experiments be conducted on POU MFs that have dried out. In particular, varying the drying time period, water source and backwash volume would be insightful in future research.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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