Research Paper

Acceptability, effectiveness, and fouling of PointOne membrane filters distributed in South Sudan

Shannon Holding, Ilin Sadeghi, Trevor White, Anna Murray, James Ray III, Ayse Asatekin and Daniele Lantagne

ABSTRACT

The Sawyer PointOne™ household hollow fiber membrane filter (PointOne) efficaciously removes microbiological indicators in the laboratory, and is increasingly considered for emergency response. To our knowledge, PointOne effectiveness in emergencies had not been evaluated. In South Sudan, 773 PointOnes were distributed. For 13 months after distribution, household surveys were completed quarterly, water quality testing was conducted monthly, and post-mortem analysis was completed at study midline to assess acceptability, effectiveness, and membrane fouling, respectively. Recipients found PointOnes acceptable, with high rates of demonstrated correct use (97–100%) and correct backflushing (96–100%). PointOnes effectively reduced thermotolerant coliforms for four months. When surface water use increased, effectiveness dropped, with 38% of filtrate samples contaminated. After backflushing filters with 0.2% chlorine solution, effectiveness improved; however, 5–38% of PointOne filtrate samples remained contaminated over subsequent months. Irreversible fouling was documented during post-mortem analysis. These results highlight that while PointOnes can improve household water quality within an emergency, PointOnes can foul within 4–6 months of use, depending on influent water quality. It is recommended that future PointOne distributions include continuous monitoring and an appropriate cleaning regime, based on influent water quality, to ensure continued performance. Further research on source water quality impacts on PointOne performance is recommended.

Key words | emergency response, hollow fiber membrane, household water treatment, membrane fouling, microbiological effectiveness, point-of-use

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INTRODUCTION

Safe drinking water is an immediate priority in most natural disasters, conflicts, and outbreak emergencies (SPHERE 2011). Until normal water supply is restored, responders often encourage affected populations to use household water treatment (HWT) options such as boiling, chlorination, or filtration to ensure the microbiological integrity of drinking water (Lantagne & Clasen 2012a). HWT use has been found to successfully reduce the risk of disease transmission when effective HWT products are distributed with supplies and training (Lantagne & Clasen 2012b).

One HWT option recently promoted in development contexts, but not yet evaluated in emergencies, is the Sawyer PointOne™ Filter (PointOne), a hollow membrane fiber microfilter with 0.1 μm pore size (Murray *et al.* 2015). The PointOne is distributed with fittings to attach it to a 20-L bucket and a syringe for backflushing. To use the filter, water is poured into the 20-L bucket and the filter

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head is lowered, allowing water to flow by gravity through the membrane into a secondary storage container. Users are instructed to backflush the PointOne when flow rates slow, using clean water and periodically a mild chlorine solution. PointOne™ filters have an advertised lifespan of up to 10 years, and have been distributed in over 40 countries (Sawyer International nd).

PointOnes are efficacious in the laboratory at removing bacteria (>6-log reduction (>99.9999%)) and protozoan cysts (>5-log reduction (>99.999%)) (Erikson *et al.* 2013; Murray *et al.* 2017; Hydreion 2005), and at reducing diarrheal disease prevalence among users under five years old over a three-month follow-up period (Lindquist *et al.* 2014). However, laboratory efficacy does not ensure field effectiveness and poor safe storage of filtered water also contributes to secondary contamination. In Fiji, 71% of PointOne filtrate samples and 76% of stored filtered water samples were found to be contaminated with microbiological indicators three months after filter distribution (Kohlitz *et al.* 2013). However, results were limited by lack of source water quality testing, and small sample size. A recent study found new PointOnes tested in the laboratory had >7 log reduction (>99.99999%) of *Escherichia coli*, but PointOnes tested in households demonstrated only 1 log reduction (90%) after one or three years of use (Erikson *et al.* 2013). Additionally, 70% of filtrate samples from households had *E. coli* of >0 CFU/100 mL. To our knowledge, testing of PointOnes to date has not been completed using the WHO testing protocol (WHO 2016). It is recommended the manufacturer submit the product for WHO Scheme testing to evaluate laboratory efficacy, and additionally, to continue evaluating product lifetime and fouling during usage in field tests.

An additional concern with using membrane filters is development of membrane fouling, as it can adversely impact the use of membranes for water treatment. Membrane fouling is caused by interrelated water quality parameters including, but not limited to: turbidity; particulates; organic content; biofilm-forming bacteria; hardness; and metal ions such as iron, manganese, and lead (Alpatova *et al.* 2004; Peng *et al.* 2004). Reversible fouling arises from physical accumulation of particulates on the membrane surface. Irreversible fouling occurs when organic biomacromolecules, such as proteins, humic acids, and polysaccharides, adsorb to the membrane (Kimura *et al.* 2004). Some of these compounds, such as natural organic matter, are naturally present in surface water, and others are generated by organisms in water. In addition, biomacromolecules can bind together inorganic particulates, exacerbating fouling and preventing removal by physical methods (Schafer *et al.* 1998), and initiate biofouling by helping microorganisms in the influent water adhere to the membrane surface. These microorganisms can then grow and form impermeable biofilms (Peng *et al.* 2004). While reversible fouling can be removed by mechanical means (e.g. backflushing with water), irreversible fouling requires removal with chemical additives (e.g. vinegar or chlorine solution) (Ferrer *et al.* 2016). A recent evaluation of PointOne filters used for almost two years in Honduras identified irreversible fouling as the primary reason filter performance had declined (Murray *et al.* 2015). However, this study was limited by small sample size and tested PointOnes only at two years after installation.

Since December 2013, armed conflict in South Sudan has contributed to more than 2.1 million refugees seeking international assistance, and an estimated 1.8 million internally displaced persons within South Sudan (OCHA 2017). For internally displaced persons in South Sudan, often in unstable living situations with significant health concerns and limited household assets, a compact, portable HWT option that can treat surface water is needed. The responding organization Medair, with funding from the Office of US Foreign Disaster Assistance (OFDA), suggested PointOnes could be appropriate to provide safe water to this population. Due to concerns about field effectiveness and fouling, the response was implemented with a comprehensive monitoring program. The filter manufacturer, Sawyer, was aware of the monitoring study and provided technical input on filter maintenance.

Herein we present results from 13 months of monitoring PointOne filters distributed in South Sudan, including data on filter acceptability, microbiological effectiveness, and membrane fouling.

METHODS

Household surveys were completed on a quarterly basis; water quality testing was conducted at sources and households on a monthly basis; and post-mortem analysis of selected filters was conducted at study mid-point.

Household selection and survey methods

In total, 773 filters were distributed to households in an internally displaced persons settlement in Renk County, South Sudan. One filter kit was provided to every household in the settlement between November 2015 and January 2016. Filter kits included the PointOne attached to a 20-L bucket, an additional 20-L bucket with lid for storing filtered water, and a plastic syringe for backflushing. The filter kits were fully assembled by project staff before distribution.

Distribution was conducted in groups of 20–30 household representatives with a 1–2 hour training on the benefits of drinking filtered water, particularly on reducing diarrhea in young children. The filter kit was introduced, and proper operations and maintenance (including backflushing) explained. Participants were asked to demonstrate correct use, setup, and backflush maintenance of the PointOne before being provided with the pre-assembled filter kit. Stickers with graphical instructions explaining use and maintenance of the filter were affixed to filter buckets. As part of the broader humanitarian project activities in the community, refresher messages on the filter operation and maintenance (including prevention of fouling) were provided through community events, household visits and a small group behavior change communication network.

Quarterly household surveying began in January 2016. Household selection was conducted using lot quality assurance sampling methods. The settlement was divided into five supervision areas with 19 households randomly selected from each supervision area, resulting in 95 surveys conducted each quarter. All household visits were unannounced; when the selected household was not available, the household was replaced with the next household to the right. The surveys were prepared in English, and translated into, and administered in, Arabic to an adult household member after obtaining consent. Local enumerators were trained to conduct surveys, with supervision provided by Medair staff. The surveys included questions on filter use and habits, measurement of filter rate, observation of filter condition, and respondent demonstration of use and backflushing. De-identified data was provided to Tufts University, and the Tufts University Institutional Review Board considered this work exempt from review.

Water quality testing

Monthly water quality testing began in December 2015. Source water samples were collected from five principal water collection points serving the settlement, including four tapstands and one donkey cart filling station. The source water is from the Nile River, from a distribution system not operated by Medair which comprises sand filtration and a raised water tower that provides (intermittent) pressure to the tapstands. Samples were collected aseptically after an initial flush through the tap, stored at ambient temperature (as ice was not available), and analyzed within four hours using a Wagtech Potatest membrane filtration kit (Thatcham, UK). Plates were incubated for 24 hours using a portable incubator at 44 °C. Colonies were counted, and reported from <1 colony forming unit (CFU) of thermotolerant coliforms (TTC) per 100 mL to >100 CFU/100 mL. Surface waters were tested, as above, in November and December 2016, when donkey cart operators used surface water.

Each month, 60 households were randomly selected for water quality testing; the number of households sampled was proportionate to the total households in each of eight settlement blocks. The number of samples collected was representative (8% of 773 households) and achievable with resources available. From January to July 2016, a water sample was collected from the household water container. If TTC was present, the household was revisited within a week after the initial analysis was completed and a sample collected directly from the filter to determine whether contamination occurred during storage or through the filter. As a response to results from January to July 2016, all filters were backflushed with a 0.2% chlorine solution in August 2016, as suggested by the filter manufacturer to disinfect the filter from any potential contamination introduced during backflushing. From August 2016 to January 2017, samples were collected only directly from the filter due to resource constraints.

Data were entered into, and reviewed in, Microsoft Excel (Redmond, WA, USA).

Post-mortem scanning electron microscopy (SEM) and elemental analysis

Two PointOne filters (labelled B5 and B7) were removed from randomly selected homes in separate blocks within the settlement on July 6th, 2016 and stored in separate, sealed plastic bags. The filters were transported to the United States in hand baggage and shipped to Tufts University in Medford, MA. The filters arrived in August 2016, and were stored unopened at room temperature until analysis in September 2016. A new PointOne was purchased to serve as a control.

The filters were cut open at the inlet side, visually examined, and photographed. Several membrane fibers from each filter were removed and imaged with a Phenom G2 Pure Tabletop SEM (FEI, The Netherlands) at increasing magnification levels. Images were collected from the outer surface, inner surface, and cross-section of the membranes. Membranes were frozen in liquid nitrogen and fractured using a microtome blade for cross-sectional imaging, and cut with a razor along the hollow core to image interior membrane surfaces. Energy dispersive spectroscopy (EDS) (Zeiss Supra 55 VP) at 20 kV was used to characterize elemental composition of inner and outer membrane surfaces (1–10 μm) from the three filters. Samples were sputter-coated (Cressington 108 manual, Ted Pella Inc., CA, USA) with Au/Pd (60/40) for 30 seconds at 30 milliAmps in an argon atmosphere to prevent charging and beam damage.

Table 1 | Household survey results

	January 2016	April 2016	July 2016	October 2016	January 2017
Number sampled	94	95	95	95	95
Household size, mean (range)	7.1 (2–13)	7.0 (1 OFDA 15)	6.7 (1 OFDA 12)	6.7 (2 OFDA 14)	7.1 (1 OFDA 18)
Water sources	72%: tapstand 28%: donkey cart 0%: Surface	55%: tapstand 20%: donkey cart 23%: surface	83%: tapstand 17%: donkey cart 0%: surface	62%: tapstand 31%: donkey cart 7%: surface	65%: tapstand 32%: donkey cart 3%: surface
Liters collected/day, mean (range)	128 (20–300)	153 (20–450)	115 (2–400)	134 (40–400)	129 (10–300)
No wait time for water	68%	44%	60%	65%	41%
Collect and store in same container	1%	6%	3%	2%	2%
Water storage container clean on observation	96%	90%	96%	49%	67%
Water storage container covered on observation	90%	80%	77%	41%	54%
Report using filter	95%	100%	97%	89%	100%
Report using in last 24 hr	8%	87%	91%	89%	68%
Filter $\leq$ 20 L per day	38%	28%	47%	43%	17%
Filter > 20 L per day	62%	72%	53%	57%	83%
Consider filter adequate for household needs	99%	95%	100%	90%	96%
No reported problems with filter	90%	75%	88%	56%	89%
No reported problems with bucket	99%	99%	97%	89%	97%
User demonstrated correct use	97%	97%	100%	100%	100%
User demonstrated correct cleaning	99%	96%	100%	100%	100%
Filter appeared used on observation	99%	96%	100%	100%	90%
Filter set up at visit	93%	100%	100%	90%	86%
Filter flow rate (L/min), mean (range)	0.12 (0–0.48)	0.11 (0.02–0.40)	0.09 (0–0.18)	0.05 (0–0.21)	0.10 (0.01–0.20)
Reported backflushing after every use	17%	23%	17%	41%	44%

RESULTS

Household survey

Each quarter, 94 or 95 households were surveyed (Table 1). Average household size was about seven people. The primary water sources included tapstands and donkey carts, with the use of alternative surface water sources (e.g. nearby river) fluctuating from 0% of households in January 2016, to 23% in April 2016, 0% in July 2016, and <10% of households in October 2016 and January 2017. The higher reliance on surface water in April was due to a temporary breakdown in the tapstand system. The majority (94–99%) reported using a separate container for collecting water from the container used for storing treated water. Based on enumerator observation, the percent of water storage containers that were clean was 96% in January 2016, and 49–67% in October 2016 and January 2017; covering of storage containers also began at 90% and fell to 41–54% potentially

Table 2 | TTC results for source water, stored household water, and direct filter effluent

Month	Number of source water samples collected	Number (%) samples >100 CFU/100 mL TTC range (CFU/100 mL)	Number of households sampled	Number (%) samples contaminated with any TTC in stored household water	Min–max (avg) CFU/100 mL	Number (%) samples contaminated with any TTC directly from filter	Min–max (avg) CFU/100 mL
December 2015			60	7 (12%)	0–31 (1)	0 (0%)	0–0 (0)
January	5	0 (0%) 7–16	60	15 (25%)	0–> 100 (21)	1 (2%)	0–17 (1)
February	5	4 (80%) 16–>100	60	9 (15%)	0–70 (3)	0 (0%)	0–0 (0)
March	5	5 (100%) >100	60	35 (58%)	0–> 100 (44)	2 (3%)	0–> 100 (4)
April	0	–	60	25 (42%)	0–> 100 (22)	23 (38%)	0–> 100 (81)
May	5	5 (100%) >100	60	41 (68%)	0– 100 (41)	24 (40%)	0–> 100 (23)
June	5	0 (0%) 56–80	60	44 (73%)	0–> 100 (40)	24 (40%)	0–> 100 (18)
July	5	5 (100%) >100	60	45 (75%)	0–> 100 (44)	14 (23%)	0–> 100 (44)
August	4	4 (100%) >100	60	*Not tested*		23 (38%)	0–> 100 (27)
September	5	3 (60%) <1–>100	60	*Not tested*		15 (25%)	0–> 100 (11)
October	4	0 (0%) <1–13	60	*Not tested*		6 (10%)	0–> 100 (0.6)
November	5	0 (0%) 4–62	60	*Not tested*		3 (5%)	0–30 (0.7)
December	5	1 (20%) 11–>100	60	*Not tested*		22 (36%)	0–> 100 (14)
January 2017	4	0 (0%) 3–24	60	*Not tested*		14 (23%)	0–> 100 (9)
Total	*57*	*28 (49%)* *0–>100*	*780*	*221 (46%)*	*0– > 100 (27)*	*171 (29%)*	*0–> 100 (16)*

Note that filters were cleaned with chlorine solution in August 2016.

Note: No source samples collected in April as water system was not functioning, people collected raw surface water instead.

due to loss of lids and reduced motivation in upkeep of the aging containers.

The majority (89–100%) of households reported using the filter to produce treated drinking water, with 68–91% reporting using it within the last 24 hours (after January 2016) (Table 1). Most households (53–83%) reported filtering more than 20 L per day, and 90–100% of households stated the filter supplied adequate water for their household drinking water needs. The majority of households (56–90%) reported no problems with their filter. Across all 474 households, 57 respondents (12.0%) reported the filter was too slow, 31 (6.5%) reported problems/breakages with the bucket, filter, or syringe, and four (0.8%) reported aesthetic problems such as not improving water or tasting bad.

The majority of respondents demonstrated correct use (97–100%) and correct cleaning (96–100%) of the filter to the enumerator (Table 1). On observation, most filters appeared used (96–100%), undamaged (94–100%), and were set up at the time of the visit (86–100%). Flow rates varied from an average 0.12 L/min to the lowest average of 0.05 L/min in October 2016. During this month, 19% of respondents reported flow rates were too low. Although observations indicated the filters were still in use, it is possible that people may also have been using other sources of drinking water such as rainwater collection. Filter backflushing rates changed over time, with increasing households reporting backflushing after each use from 11% in January 2016 to 44–54% in October 2016 and January 2017 and a decreasing number reporting backflushing multiple times per day (from 49% in January 2016 to 11% in January 2017). About 20% of households reported backflushing ‘once a day’ or ‘when filters slows’.

Water quality testing

The majority (95%) of the 57 source water samples were contaminated with TTC, with 28 (49%) having greater than 100 CFU/100 mL, indicating ‘high risk’ source waters (Table 2, Figure 1).

In total, 780 households were visited for water quality testing (Table 2, Figure 1). From December 2015 through July 2016, 46% of stored household water samples (221 households) were contaminated with TTC (range 12–75% by month). The contamination ranged from <1 to >100 CFU/100 mL TTC, with averages between 1 and

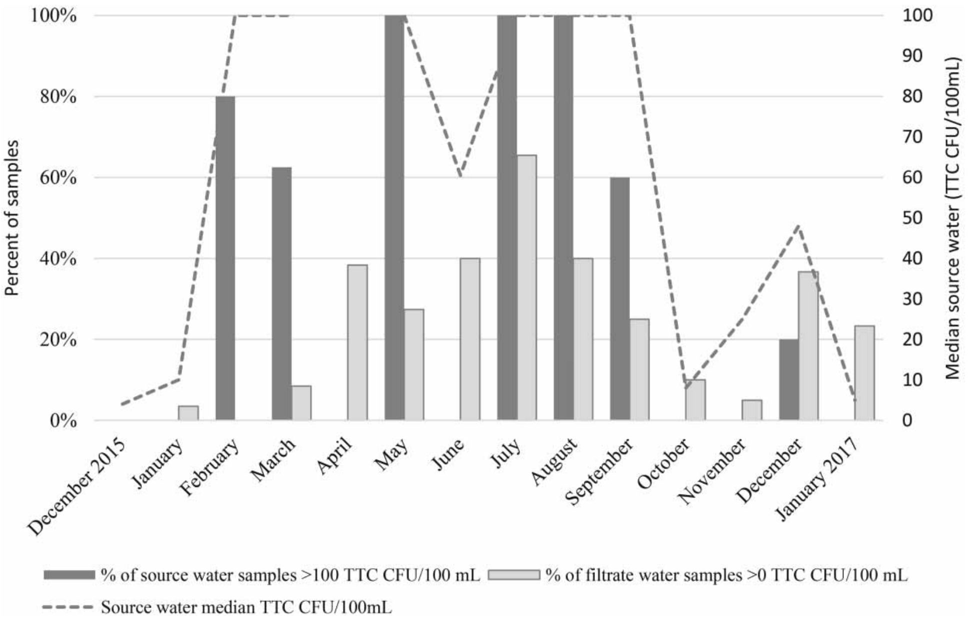

Figure 1 | Percent of source water samples with TTC >100 CFU/100 mL and filtrate samples >0 TTC/100 mL, plus source water median values. Please note source water quality results were missing for the month of April.

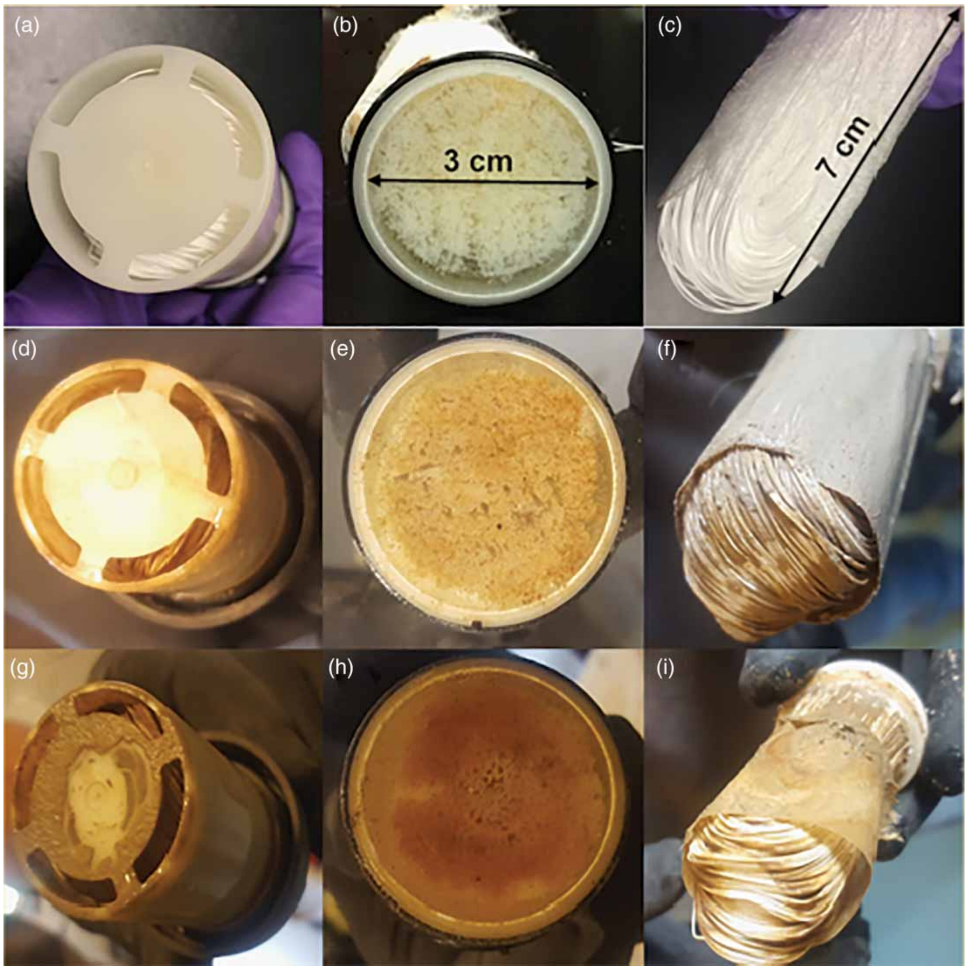

Figure 2 | Filter disassembly images. Top row, new filter; middle row, B5; bottom row, B7. Left column exterior; middle column view from top; right column fibers.

44 CFU/100 mL each month. In these samples, it is not possible to distinguish between contamination caused by an ineffective filter or by recontamination in storage.

Therefore, between December 2015 and July 2016, 189/221 households with contamination were revisited and a direct from filter sample collected (Table 2, Figure 1). Initially, the rates of filter contamination were low (ranging from 0 to 3% with TTC counts of >0 CFU/100 mL). However, from April there was a sudden increase in the number of direct filter effluent samples that were >0 CFU/100 mL to 38%, continuing into May and June, where 40% of samples were contaminated. From August 2016 to January 2017, after cleaning with 0.2% chlorine solutions, the water quality improved with 5–25% of direct from filter samples testing positive.

Post-mortem scanning electron microscopy and elemental analysis

To investigate the extent of fouling on/within the membranes and to assess the effectiveness of the backflushing procedure, membranes' outer and inner surfaces and cross-sections were imaged using SEM. The two used filters were received without visible damage, with both the inlet and outlet sealed until analysis began. Visual inspection of the used filter interiors showed the majority of the membrane surface (raw water side) was discolored and covered by a brown fouling layer interrupted by small, clean, white areas where backflushing removed patches of the foulant layer, creating paths of least resistance without fully removing the rest (Figure 2). New filter membrane fibers were flexible and difficult to break. Used fibers, in contrast, had become brittle and broke easily.

The SEM images of the outer surface of a new membrane fiber show submicron-sized open pores. This side faces the feed water during use. In the used filter membranes, these pores are blocked by a thick fouling layer (Figure 3). Fouling was visible throughout the thickness of the membrane fibers (Figure 4) and on the inner pores of used membranes (Figure 3).

Elemental analysis of the new filter's surface by EDS identified carbon, oxygen, and sulfur, as expected for polysulfone or polyethersulfone membranes typically used for water treatment (Table 3). The outer and inner membrane surfaces of the used filters showed carbon from organic fouling, and inorganic foulants exhibited by large amounts of silicon, aluminum, and iron, and smaller amounts of magnesium and calcium (Table 3). The foulant layer was sufficiently thick that little to no sulfur, from the chemical structure of the membrane, could be detected at the typical penetration depth for EDS analysis of approximately 1 micron.

DISCUSSION

In an emergency response program in South Sudan, recipients found PointOnes acceptable: despite challenges with the filters people consistently used the filters to produce treated drinking water, with high rates of demonstrated correct use (97–100%) and correct backflushing (96–100%). Additionally, PointOnes effectively reduced TTC for four months. However, when surface water use increased,

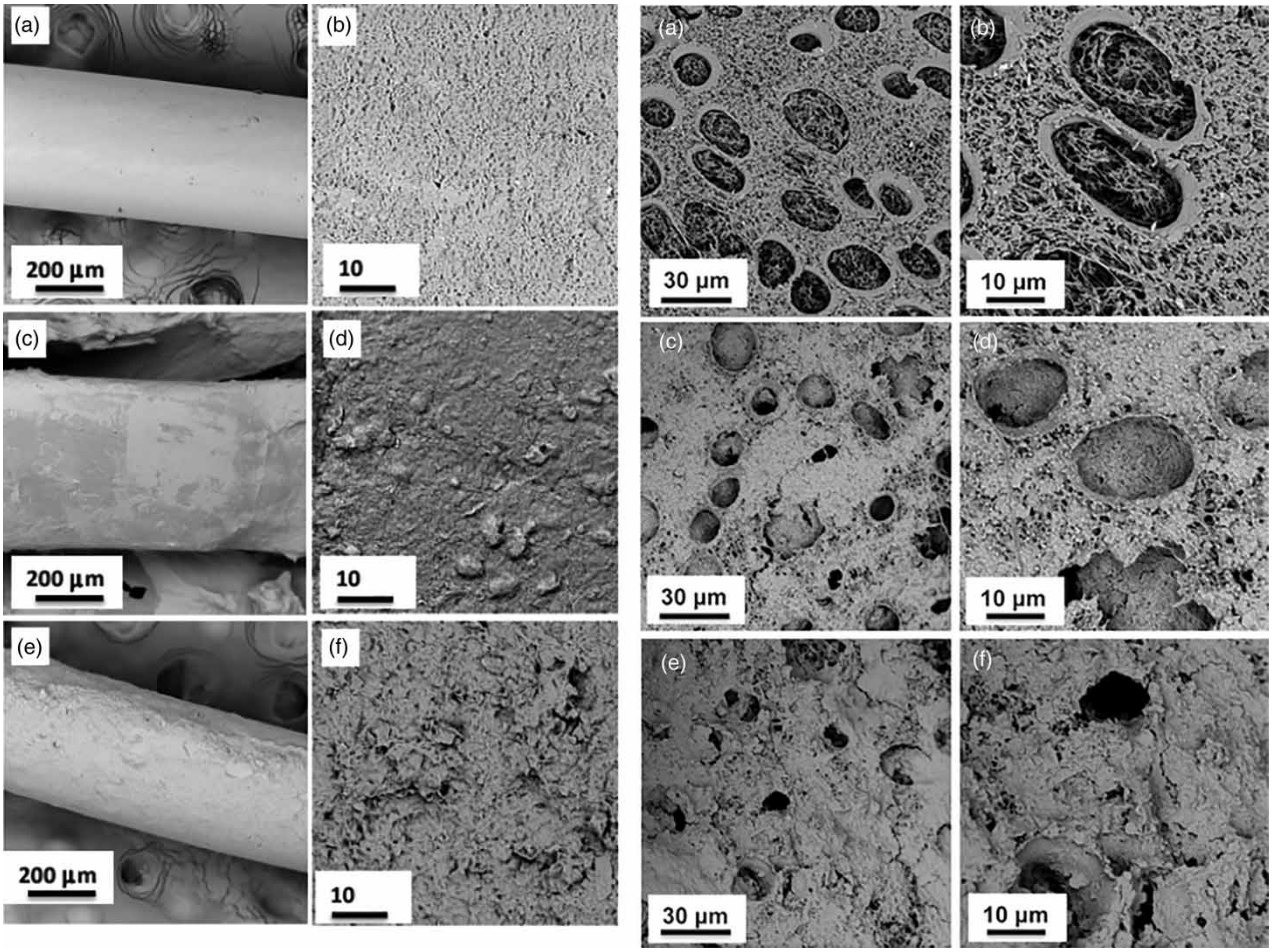

Figure 3 | Scanning electron microscopy of outer surface (left side) and inner surface (right side) of the membrane. Top row, new filter; middle row, B5; bottom row, B7.

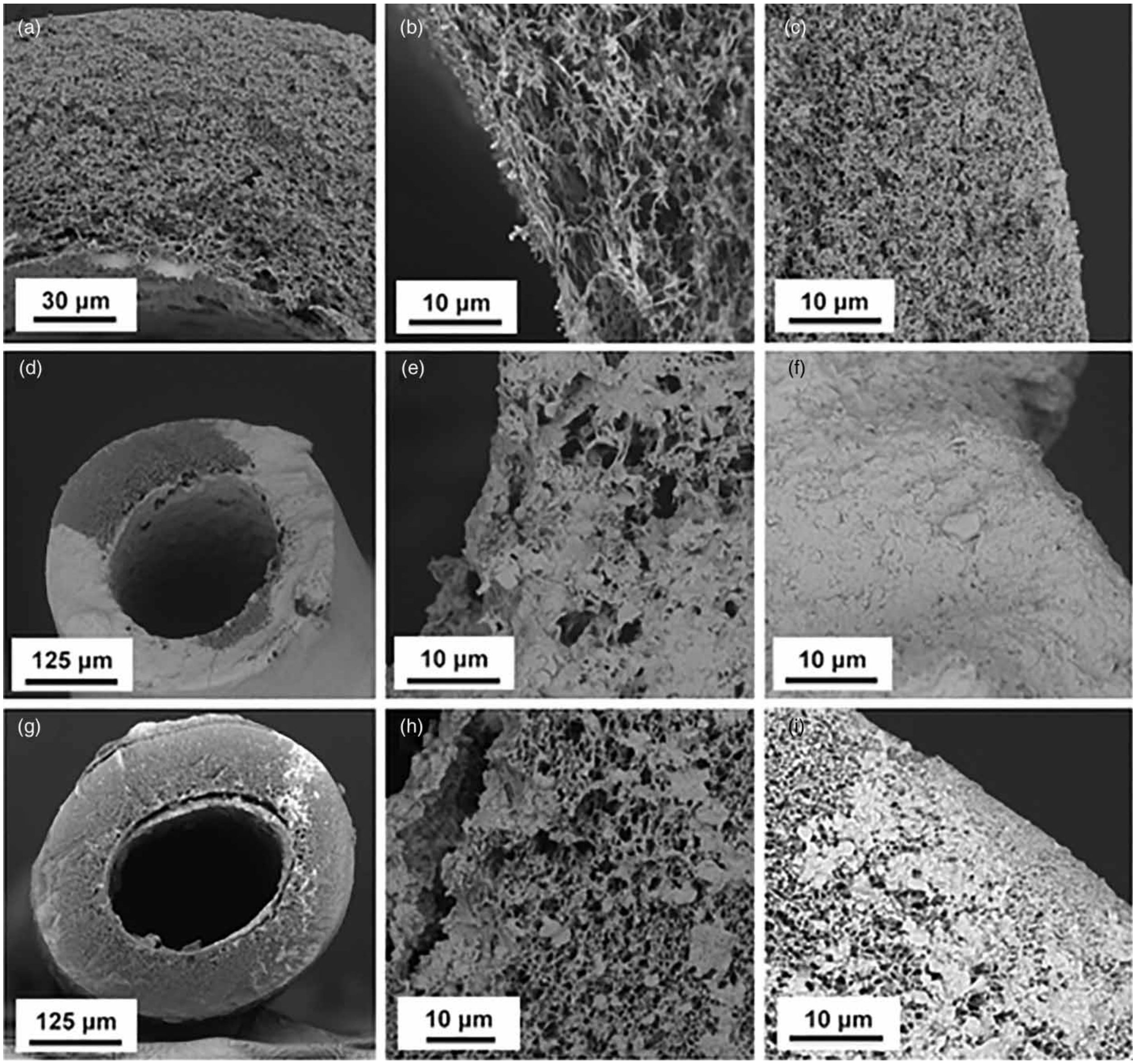

Figure 4 | Scanning electron microscopy of cross-section of membrane. Top row, new filter; middle row, B5; bottom row, B7. Left column, membrane; middle column, inside; outer column, outside.

effectiveness dropped with 38% of filtrate samples being contaminated. After backflushing filters with 0.2% chlorine solution, the treated water quality improved, although 5–25% of filtrate samples remained contaminated due to fouling on both the feed and permeate side of the fibers. Irreversible fouling was documented during post-mortem analysis, further indicating the backflushing procedure was not sufficient for effectively managing fouling during use. These results highlight that PointOnes can be acceptable to, and appropriately used by, recipients in emergency contexts, although there is potential for fouling within the initial 4–6 months of use. It is unclear whether fouling was related to duration of use or coincided with deterioration in source water quality.

In this program, high levels of training and support provided during PointOne distribution supported sustained knowledge on filter correct use and maintenance. However, initial high rates of safe storage (including cleaning and

Table 3 | Elemental analysis results

Element	New membrane, outer surface (%)	New membrane, inner surface (%)	B5 used membrane, outer surface (%)	B5 used membrane, inner surface (%)	B7 used membrane, outer surface (%)	B7 used membrane, inner surface (%)
C	75.74	75.20	21.90	20.30	5.92	11.07
O	15.04	13.95	34.83	42.02	34.47	37.46
S	9.22	10.85	6.22	3.96	–	1.32
Si	–	–	17.75	17.65	28.26	27.39
Al	–	–	8.54	8.74	14.61	11.92
Fe	–	–	8.46	5.13	13.90	7.83
Mg	–	–	1.35	1.55	1.74	1.99
Ca	–	–	0.95	0.65	1.09	1.04

covering the storage containers) fell over the 13-month study; indicating drop-off of behavior change. The reliance on safe water storage and handling practices in filters without an integrated safe storage component, although common to many interventions, remains a concern when using PointOnes.

Irreversible fouling can become increasingly difficult to manage if not remedied early in the formation process. Results presented herein demonstrate that backflushing only with water is insufficient, similar to previously documented results (Murray *et al.* 2015), and chlorine solution backflushing is also necessary, but not sufficient, periodically. These combined results are indicative of a common problem with PointOnes. Based on these results, it is recommended future PointOne distributions include ongoing monitoring and development of an appropriate cleaning regime based on influent water quality characteristics (e.g. backflushing to partially remove cake layers, alkaline solutions to remove microorganisms and organic material, and acidic cleaning to remove inorganic scale (Mo & Huanga 2003)). As ongoing monitoring and specific cleaning procedure development is not always possible, another option is to have a shorter PointOne lifespan. However, this may not be cost effective or practical.

Overall, PointOne use in all phases of an emergency context has the potential to provide targeted protection against bacteria and protozoa in drinking water at the household level; however, to accomplish this goal with appropriately designed programming, ongoing monitoring, and specific cleaning recommendations are necessary.

Limitations of this work include limited number of filters analyzed in the laboratory for membrane fouling, source water not tested beyond bacteria, and stored household water samples not tested for TTC for the entire evaluation. As such, we cannot isolate source water characteristics that contributed to filter membrane fouling, or know the extent these results apply to situations with different water sources. Additionally, although users were trained (and observed) in filter operation and maintenance, self-reported user behavior cannot be verified. The findings may be different if conducted within a more stable development context as compared to the emergency context of this study.

CONCLUSIONS

The Sawyer PointOne filter is efficacious at removing bacteria in the laboratory, and is currently marketed for emergency response use. In this investigation we identified that: (1) the filters were acceptable to the recipients and recipients correctly used and maintained the filters over time; (2) the filters were initially effective at removing TTC, although there was a decline in filtrate water quality after four months, coinciding with deterioration in source water quality; and (3) analyzed filters were irreversibly fouled. A cleaning campaign resulted in partial, but not complete, reduction of TTC count in filtrate. It is recommended that future PointOne distributions include monitoring, and develop an appropriate cleaning regimen based on influent water quality. Further research of PointOne performance is recommended, including: systematically characterizing the impact of source water quality on filter performance, establishing a cleaning regimen to manage fouling based on source water quality, testing the filter in development contexts where use might not be as high, and testing individual filter influent and effluent results.

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