  Journal of Water, Sanitation and Hygiene for Development | 07.1 | 2017

Research Paper

Laboratory efficacy and field effectiveness of hollow fiber membrane microfilters used for household water treatment in Honduras

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ABSTRACT

The Sawyer PointONE™ hollow fiber membrane filter is increasingly promoted for long-term household water treatment in developing countries. Limited data demonstrate PointONE™ microbiological laboratory efficacy and short-term diarrheal disease reduction among users, but household microbiological data is lacking. To compare laboratory and household PointONE™ filter microbiological performance, we enumerated *Escherichia coli* (*E. coli*) and total coliforms in source and filtrate water from: (1) one new filter with *E. coli*-spiked water (10^7–10^9 CFU/100 mL) in the laboratory, (2) one new filter with natural Maine and Honduran surface waters, and (3) 50 filters used in Honduran homes for 1–3 years. In laboratory tests, all filtrate samples had $<$1 CFU/100 mL *E. coli* ($>$99.99999% reduction). In natural surface waters, all filtrate samples had $\leq$1 MPN/100 mL *E. coli* ($\geq$99.5% reduction). In households, filtrate samples had geometric mean 5.1 MPN/100 mL *E. coli* (90% reduction), with only 30% of filtrate samples complying with international standards of undetectable *E. coli*. Total coliform presence in natural water filtrate varied for both new and household filters. The discrepancy between laboratory and household results and premature filter failure are not well understood. Further research is recommended to understand this performance disparity and determine filter failure mechanisms in households.

Key words | drinking water, hollow fiber membrane, household water treatment, microbiological effectiveness, microfiltration, point-of-use

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doi: 10.2166/washdev.2017.156

INTRODUCTION

Worldwide, an estimated 663 million people drink water from unimproved sources (WHO/UNICEF 2015) and an estimated 1.2 billion more drink contaminated water from improved sources (Onda *et al.* 2012). Providing reliable, safely managed, piped water to every household is the ultimate goal (WHO/UNICEF 2014), but the World Health Organization (WHO) also supports incremental water supply improvements – such as household water treatment and safe storage (HWTS) options – to accelerate the heath gains associated with safer drinking water for those with unsafe supplies (WHO 2011a). A growing body of evidence demonstrates that the use of HWTS options improves the microbiological quality of household water and reduces the burden of diarrheal disease among users (Fewtrell *et al.* 2005; Waddington *et al.* 2009; Clasen *et al.* 2015).

HWTS options are evaluated using laboratory efficacy testing, health impact trials, and field effectiveness testing. In the laboratory, product efficacy at removing organisms of concern (bacteria, viruses, and protozoa) from test waters is evaluated. Randomized, controlled trials in developing country communities measure a product's ability to reduce diarrheal disease among users. Field effectiveness is evaluated to measure a HWTS product's ability to reduce indicator organisms such as *Escherichia coli* (*E. coli*) or thermotolerant coliforms in drinking water in actual users' homes.

WHO guidance includes tiered, health-based targets that classify HWTS products according to laboratory efficacy performance as: 'Highly protective' (4-log bacteria and protozoa reduction and 5-log virus reduction in laboratory settings), 'Protective' (2-log bacteria and protozoa reduction and 3-log virus reduction), or 'Interim' (achieving 2-star target for two pathogen classes and having epidemiological evidence demonstrating disease reduction in health impact trials) (WHO 2011b). These targets have since been termed '3-star,' '2-star,' and '1-star' performance classifications, respectively (WHO 2016). WHO guidelines also categorize diarrheal disease risk based on indicator organism levels in users' drinking water (WHO 1997).

One recently-promoted HWTS option is the Sawyer PointONE™ Filter, a hollow fiber membrane microfilter with 0.1 μm pore size. The PointONE™ filter is distributed with an assembly kit with fittings to attach the filter to a five-gallon bucket (Figure 1). To use the filter, water is poured into this source water bucket and the filter head is lowered, allowing water to flow by gravity through a delivery tube and the hollow fiber membrane, and into a secondary storage container. Users are instructed to backwash the filter when flow slows, using clean water and a syringe provided with the filter. PointONE™ filters have an advertised lifespan of up to 10 years, and have been distributed in over 70 countries (Sawyer Products 2014; Sawyer Products n.d.).

The PointONE™ filter has been shown to be efficacious in the laboratory at removing bacteria (>6-log reduction) and protozoan cysts (>5-log reduction) (Hydreion 2005; Erikson *et al.* 2013). Virus removal has not been evaluated, as most viruses are smaller than the PointONE™'s pore size and high removal is not expected. Additionally, one study demonstrated a reduction in diarrheal disease prevalence among users under 5 years old over a short, three-month follow-up in a controlled study setting (Lindquist *et al.* 2014). This evidence – all conducted under highly

Figure 1 | Sawyer PointONE™ Filter bucket assembly (secondary storage container not shown).

controlled conditions with new filters – suggests that the PointONE™ filter could potentially meet the requirements of the WHO 1-star performance target, although actual classification would require testing by an external independent laboratory.

Microbiological field effectiveness data has identified bacterial contamination in 18–54% of tested PointONE™ filter direct filtrate and 51–70% of stored, filtered water in studies where filters were used for between three months and three years (Brune *et al.* 2013; Goeb 2013a, 2013b; Kohlitz *et al.* 2013). However, only one of these studies was peer reviewed, and results were limited by the use of a semi-quantitative method of identifying bacterial contamination, lack of source water quality testing, and small sample size (24 filtrate samples and 37 stored water samples) (Kohlitz *et al.* 2013). To our knowledge, no quantitative microbiological field effectiveness data on the PointONE™ filter has been published in peer-reviewed format to date.

Pure Water for the World (PWW) is a non-governmental organization that provides safe drinking water, sanitation, and hygiene education to communities in developing countries. PWW installed over 250 PointONE™ filters in six rural Honduran communities between 2010 and 2013. Beneficiaries were trained in filter use and maintenance upon installation, and again during household follow-up visits approximately three months after installation. In follow-up evaluations by PWW, usage rates ranged from 50 to 95% 9–13 months after distribution in some communities, and 66–68% 23 months after distribution in others. Reported reasons for filter disuse included: broken casings, clogged filters, broken or missing syringes, damaged hoses, casings which had been opened by users, and filters abandoned by users (Goeb 2013a, 2013b, 2013c). Additionally, an analysis of PointONE™ filters installed by PWW and used for almost two years identified membrane fouling as a challenge to long-term filter performance (Murray *et al.* 2015). Because of these unexpectedly high rates of disuse documented by PWW and the lack of available robust field effectiveness data, we sought to further understand the microbiological performance of PointONE™ filters used in the field over the long term, in addition to performance at removing organisms of concern in controlled environments.

In this research, we evaluated the microbiological performance of the Sawyer PointONE™ filter by investigating: (1) microbiological efficacy of new filters in the laboratory, (2) microbiological efficacy of new filters in a controlled field environment, and (3) microbiological effectiveness of PointONE™ filters known to be used in household settings at least one year after distribution.

METHODS

Laboratory efficacy testing

In March 2014, a new PointONE™ filter assembly was purchased from a distributor and fitted to a plastic 5-gallon bucket for laboratory testing at the University of Maine. The filter assembly was identical to the assembly employed in users' homes in Honduras. *E. coli* was grown in tryptic soy broth and then inoculated into 1.2 L of sterile deionized water at three doses: 10^7, 10^8, and 10^9 colony forming units (CFU)/100 mL. Each spiked water dose was poured into the filter source bucket and gravity-flowed through the PointONE™ filter. The first 100 mL of water was collected aseptically from the filter outlet in sterile bottles, and 100-mL samples were also collected after 500 and 1,000 mL of flow. The filter was backwashed three times with deionized water before each challenge test, and the sampling procedure was repeated with increasing *E. coli* concentrations.

Samples were processed immediately using the membrane filtration method (APHA/AWWA/WEF 2005) with m-ColiBlue24® media (Hach Company, Loveland, CO). Samples were diluted appropriately with sterile deionized water, vacuum filtered aseptically through a 45-micron filter (EMD Millipore, Billerica, MA), placed in a plastic petri dish with a media-soaked pad, and incubated for 24 hours at 35 °C before counting colonies. A negative control PointONE™ filter assembly was run in parallel with deionized water, and positive control *E. coli* plates were processed alongside laboratory samples.

Field efficacy testing

In August 2014, one new PointONE™ filter was purchased and assembled as above for controlled microbiological efficacy testing with natural surface waters in Maine and Honduras. In Maine, five different locations along an urban stream were tested. Before each test, the filter was backwashed three times with deionized water, and the source bucket was rinsed three times and filled with stream water. This source water was gravity-flowed through the filter for at least 1 minute, and then a 100-mL filtrate sample was collected aseptically directly from the filter outlet in a sterile plastic bottle. A water sample was also collected aseptically from the source bucket. Samples were placed on ice and analyzed within 8 hours using the most probable number (MPN) method (APHA/AWWA/WEF 2005) for simultaneous detection of total coliform and *E. coli* using IDEXX Quanti-Tray® 2000 and Colilert® media (IDEXX Laboratories Inc., Westbrook, ME). Trays were incubated for 24 hours at 35 °C, and then positive wells were counted.

Following this testing, the filter was disassembled and the membrane was backwashed three times, placed in a new plastic zipper storage bag, transported to Honduras, and then reassembled with a new source bucket. Efficacy testing was repeated, as above, with the same PointONE™ filter in five locations along a river in one Honduran community.

Household effectiveness testing

Household selection and survey methods

Two Honduran communities located in the Trojes region of Honduras were selected for study inclusion because they: (1) had at least 40 filter assemblies distributed in each, and (2) represented a variety of times since filter training and distribution. In Community 1, PointONE™ filters were distributed to 45 households in August 2011, three years prior to this study. PWW provided the research team with a list of the 23 households known to be using filters in this community, based on a follow-up visit completed in July 2013. All of these homes were visited as part of this research in August 2014. In Community 2, PointONE™ filters were distributed to 65 households in August 2013, one year prior to this study. PWW provided the research team with a list of all 65 beneficiary households. In August of 2014, the research team visited 27 of these homes, which were selected based on availability at the time of the announced visit, being a current PointONE™ filter user, and ease of access for the study team.

Household surveys were written in English, and then translated into and administered in Spanish to an adult household member after obtaining oral consent. Surveys included 20 questions on filter use and habits, as well as respondent demonstration of the backwashing maintenance procedure and observation of filter condition. All household visits were unannounced. The study protocol was approved by the University of Maine Institutional Review Board.

Household water quality testing

At each household, the PointONE™ filter was backwashed at least three times by the user. The filter source bucket was then filled with untreated household source water, which was allowed to gravity-flow through the filter for at least 1 minute before a 100-mL filtrate sample was collected aseptically directly from the filter outlet in a sterile plastic bottle. A source water sample was also collected aseptically from the source bucket. Samples were placed on ice and analyzed within 8 hours by the IDEXX MPN method, as described above. At each household, source and filtrate turbidities were measured in duplicate with a Hach portable 2000P turbidity meter, and filter flow rate was measured.

Water quality data analysis

Data were entered into Microsoft Excel (Microsoft Corporation, Redmond, WA) and analyzed in R 3.0.1 (R Foundation for Statistical Computing, Vienna, Austria). For all statistical tests, *p*-values <0.05 were considered statistically significant.

E. coli, total coliform, and turbidity reductions between source and filtrate were calculated two ways: (1) the percent reduction in geometric mean of the parameter, and (2) the median percent reduction for the set of filters. In all cases, duplicate water quality measurements were averaged, and *E. coli* and total coliform values at the lower detection limit (<1 MPN/100 mL) were replaced with 0.5 MPN/100 mL, and values at the upper detection limit (>2,420 MPN/100 mL) were replaced with 2,420 MPN/100 mL. In calculating median percent reductions, values at the upper detection limit were removed to minimize bias. Water quality parameters were also compared using paired t-tests on log-transformed values.

Source and filtrate samples were categorized by WHO disease risk guidelines for *E. coli* results as: in conformity (<1 MPN/100 mL); low risk (1–10 MPN/100 mL); intermediate risk (11–100 MPN/10 mL); high risk (101–1,000 MPN/100 mL); and very high risk (>1,000 MPN/100 mL) (WHO 1997). Fisher's exact test was used to determine if these category distributions differed between source and filtrate samples.

Bivariate analyses were performed to compare median filter *E. coli*, total coliform, and turbidity reductions based on: time since distribution (one year or three years); observed filter casing cracks (yes or no); and users' demonstration of filter backwashing procedure (correct or incorrect) using a Wilcoxon rank-sum test. A multiple logistic regression on the dichotomous outcome of filter *E. coli* reduction of ≥90% was also performed with the same three independent variables.

RESULTS AND DISCUSSION

Laboratory efficacy testing

Filtrate from spiked laboratory efficacy tests was negative for *E. coli* presence for all *E. coli* doses and all sample times (Table 1). This represents up to >9-log *E. coli* removal efficiency. Results are consistent with other spiked water laboratory tests that demonstrated >9-log bacteria removal within the first liter of flow through new PointONE™ filters (Erikson *et al.* 2013).

Field efficacy testing

The new control PointONE™ filter demonstrated geometric mean 99.7% *E. coli* reduction and >99.98% total coliform reduction across all five Maine efficacy tests (with all filtrate *E. coli* and total coliform samples having <1 MPN/100 mL). In Honduras tests, the filter removed geometric mean 99.5% *E. coli* (with all filtrate samples having ≤1 MPN/100 mL). Total coliform reduction ranged from 0 to 49% in all five tests (source: >2,420 MPN/100 mL; filtrate: 1,300 to >2,420 MPN/100 mL), though exact total coliform reductions could not be calculated from values at the detection limit (Table 1).

Household effectiveness testing

Survey results

Surveys were completed with 23 households (51% of filter recipients) in Community 1, where filters were distributed

Table 1 | Water quality test results for Sawyer PointONE™ filter performance in the laboratory (laboratory efficacy), controlled field testing (field efficacy) in Maine and Honduras, and in Honduran homes (field effectiveness)

Water source	Parameter	Source geometric mean (95% CI)	Filtrate geometric mean (95% CI)	% Reduction in geometric mean	*p*-value[a]
Laboratory spiked water	*E. coli* (CFU/100 mL)[b]	10^7–10^9	<1	>99.99999%	–
Urban stream in Maine (*n* = 5)	*E. coli* (MPN/100 mL)	186 (139, 249)	<1	>99.7%	<0.001
	Total coliform (MPN/100 mL)	>2,420[c]	<1	>99.98%	<0.001
	Turbidity (NTU)[d]	–	–	–	–
River water in Honduras (*n* = 5)	*E. coli* (MPN/100 mL)	124 (79.9, 192)	0.57 (0.44, 0.75)	99.5%	<0.001
	Total coliform (MPN/100 mL)	>2,420	1,921 (1,530, 2,414)	–[e]	0.12
	Turbidity (NTU)	5.9 (5.0, 8.8)	0.33 (0.24, 0.45)	94.3%	0.001
Honduran households (*n* = 50)	*E. coli* (MPN/100 mL)	48.9 (32.7, 72.9)	5.1 (2.9, 9.0)	89.5%	<0.001
	Total coliform (MPN/100 mL)	1,677 (1,382, 2,036)	539 (352, 824)	67.9%	<0.001
	Turbidity (NTU)	5.4 (3.7, 8.0)	0.60 (0.46, 0.79)	88.9%	<0.001

CFU, Colony forming unit; MPN, Most probable number; NTU, Nephelometric turbidity units.

[a]*p*-values calculated with paired t-tests on log-transformed values.

[b]Spiked tests at 10^7, 10^8, 10^9 CFU/100 mL. Filtrate samples collected at three times (first 100 mL, after 500 mL, after 1,000 mL of flow).

[c]Upper detection limit: 2,420 MPN/100 mL.

[d]No turbidity data available for Maine control testing.

[e]Total coliform percent reductions limited by test results at the upper detection limit.

three years prior. This is believed to be all households currently using PointONE™ filters. Surveys were completed with 27 households (42% of filter recipients) in Community 2, where filters were distributed one year prior. In both communities, the source water used was primarily river water.

Overall, 80% of respondents reported using the PointONE™ filter within the previous day, and 64% of respondents reported treating water with the filter at least daily. When asked 'what do you think of the filter?' 91% of respondents reported that it was 'very good.' When asked if they perceived a change in the family's health, all but one respondent (98%) reported an improvement in health. Over half of respondents (54%) reported that filters had blocked or had reduced flow in the past, and 81% of those who estimated the frequency of flow blockage reported that it happened once a month or less. Most respondents (94%) reported that they used a container other than the clean storage container to collect source water before treating, and 71% of respondents demonstrated the full, correct backwashing procedure (using a clean syringe with filtered water to backwash the filter 3–4 times in the correct direction). Seven filters (14%) had observable cracks or damage to the filter casing, and one filter had a leak in the tubing on the inlet end (Table 2).

Household water quality results

The geometric mean filter flow rate was 77.2 mL/min (95% CI: 61.8, 96.4). The estimated average flow rate according to filter product literature is 719 mL/min (Sawyer Products, n.d.).

Between source and filtrate samples, geometric mean *E. coli* reduction was 90%, geometric mean total coliform reduction was 68%, and geometric mean turbidity reduction was 89% (Table 1). Median percent reductions for the set of all filters were 87% for *E. coli* ($n = 50$), 65% for total coliform ($n = 19$, excluding all readings at the upper detection limit), and 91% for turbidity ($n = 50$). These median reductions for the set of filters are consistent with percent

Table 2 | Sawyer PointONE™ filter household user survey results ($n = 50$)

		n	%
Last used filter ($n = 49$)	Today or yesterday	39	80%
	Within the past week	9	18%
	>One month ago	1	2%
How often filter water ($n = 47$)	>Once a day	12	26%
	Once a day	18	38%
	2–3 times per week	15	32%
	Once a week or less	2	4%
Respondent impression of filter ($n = 44$)	Very good	40	91%
	Standard	3	7%
	Bad	1	2%
Change in family health since started using filter ($n = 48$)	Better	47	98%
	No Change	1	2%
Filter has ever blocked up in the past ($n = 48$)	Yes	22	46%
	No	26	54%
How often has the filter flow been reduced or blocked ($n = 42$)	Never	26	62%
	Once a day	1	2%
	Once a week	2	5%
	Once a month	6	14%
	Every six months or less	7	17%
Container used to collect water ($n = 50$)	Different container	47	94%
	Same container	3	6%
Observation of backwash procedure ($n = 49$)	Correct	35	71%
	Incorrect	14	29%
Observed cracks in filter casing ($n = 50$)	Yes	7	14%
	No	43	86%

reductions in geometric means from source water to filtrate, and all three water quality parameters were statistically significantly lower in filtrate than in source water ($p < 0.001$). Seven filters (18%) had higher *E. coli* concentrations in filtrate than in source water; the *E. coli* concentration increase was modest in two of the seven filters (7.4–8.1 MPN/100 mL and 66–73 MPN/100 mL), and greater in five filters, which had an average increase of 87.4 MPN/100 mL *E. coli* from source to filtrate. Of these seven filters, none had observable filter damage, and five users demonstrated correct backwashing.

When categorized by WHO risk levels based on *E. coli* concentrations, no source water was in conformity with the WHO guideline of <1 MPN/100 mL (Figure 2). Among source water samples, 12% were considered low risk, 62% intermediate risk, 24% high risk, and 2% very high risk. Among filtrate samples, the distribution was 30% in conformity, 32% low risk, 32% intermediate risk, 6% high risk, and none very high risk. The categorical distribution was significantly different between source and filtrate samples ($p < 0.001$). These results showing 30% of filtrate with no detectable indicator bacteria are consistent with previously-published PointONE™ filter effectiveness data (Kohlitz *et al.* 2013).

No statistically significant differences were found in bivariate analyses comparing microbiological performance based on time since distribution, observed filter casing cracks, or demonstrated backwashing procedure. Comparing filters in homes for one and three years, the newer filters had higher median *E. coli* reduction (94 vs. 85%, $n = 50$, $p = 0.08$), lower median total coliform reduction (54 vs. 75%, $n = 19$, $p = 0.69$), and higher median turbidity reduction (93 vs. 88%, $n = 50$, $p = 0.21$). Comparing filters with visible casing cracks to those without, cracked filters had lower median *E. coli* reduction (67 vs. 91%, $n = 50$, $p = 0.23$), lower median total coliform reduction (44 vs. 68%, $n = 19$, $p = 0.96$), and higher turbidity reduction (97 vs. 90%, $n = 50$, $p = 0.91$). Filters in homes of users who demonstrated correct backwashing had higher median *E. coli* reduction (89 vs. 79%, $n = 50$, $p = 0.42$), higher median total coliform reduction (71 vs. 21%, $n = 19$, $p = 0.41$), and lower median turbidity reduction (88 vs. 92%, $n = 50$, $p = 0.72$) than those in homes where users did not demonstrate the full, correct procedure.

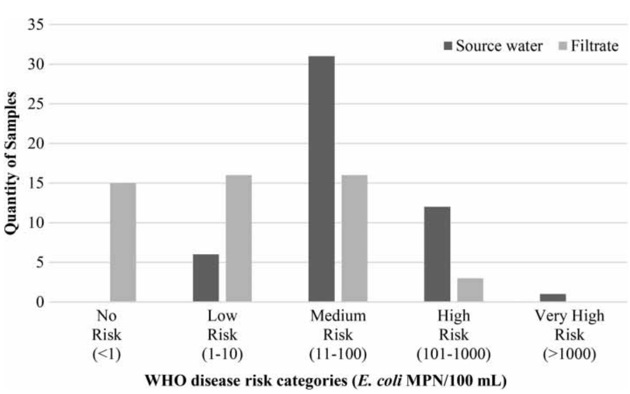

Figure 2 | Classification of source water and filtrate from Sawyer PointONE™ filters in households according to WHO disease risk categories ($n = 50$).

Associations in the multiple logistic regression model were also not statistically significant. Filters that were distributed one year prior had 1.22 times the odds of demonstrating ≥90% *E. coli* removal than did filters distributed three years prior, after correcting for backwashing and cracked status (95% CI: 0.90, 1.66; $p = 0.20$). Filters with visible cracks had 0.88 times the odds of demonstrating ≥90% *E. coli* removal than did filters without visible cracks, when adjusting for filter age and backwashing (95% CI: 0.57, 1.35; $p = 0.57$). Filters from users who demonstrated the correct backwashing procedure had the same odds of having ≥90% *E. coli* removal as those from users who did not, after correcting for filter age and cracking (OR = 1.00, 95% CI: 0.72, 1.37; $p = 0.98$).

We hypothesized that filters would have better microbiological performance if they were newer, not visibly damaged, and their users correctly demonstrated knowledge of backwashing maintenance. Median *E. coli* reduction was higher among filters that fit these criteria in bivariate analyses, and filters were more likely to have ≥90% *E. coli* reductions in a multivariate regression model if they were newer and not visibly damaged. These trends support our hypotheses; however, the small sample size limited our ability to detect statistically significant differences.

Summary

In household microbiological effectiveness testing of PointONE™ filters still in use in homes after one or three years, most filters significantly improved drinking water quality. However, only 30% of filtrate samples complied with WHO microbiological guidelines, and 18% of samples had *more E. coli* in the filtered water than in source water. Additionally, up to half of distributed filters were no longer in use in these communities. These household-level results are in contrast to those of a newly-purchased filter, which removed all *E. coli* (>9-log) in spiked laboratory waters, and nearly all *E. coli* in controlled testing of both Maine and Honduran surface waters, data which supports that the PointONE™ could potentially achieve the WHO 1-star classification based on laboratory efficacy at removing both bacteria and protozoa. These results, where laboratory efficacy is higher than household effectiveness and disuse is high, have been seen with other HWTS options (Reller *et al.* 2003; Brown *et al.* 2008; Boisson *et al.* 2009, 2013; Stauber *et al.* 2009; Levy *et al.* 2014).

Average *E. coli* reduction in households (90%) is consistent with published data for locally-produced filters such as biosand filters (Stauber *et al.* 2012, 2006). When compared to household performance of other commercially-produced membrane filters used for six months to two years, these PointONE™ filter results are consistent with the Nerox™ (A-Aqua, Oppegaard, Norway) flat-sheet 0.28 μm membrane filter (80–93% thermotolerant coliform reduction) (Ensink *et al.* 2015). However, they are lower than the household performance of the 0.02 μm hollow fiber membrane Lifestraw® Family Filter (Vestergaard Frandsen, Lausanne, Switzerland), which has demonstrated a 98–99.9% reduction in indicator organisms (Boisson *et al.* 2010; Peletz *et al.* 2012, 2013; Rosa *et al.* 2014), and a prototype household filter developed by the Swiss Federal Institute of Aquatic Science and Technology which utilizes a BIO-CEL® (MICRODYN-NADIR, Wiesbaden, Germany) 0.04 μm flat-sheet membrane (98% reduction) (Perron 2012). Similarly to the PointONE™ filter, all of these household filters are intended for long term household use. Comparative published quantitative data was not located for either the Sawyer PointONE™ or other 0.1 μm hollow fiber microfilters in household settings.

Total coliform reduction was lower than expected in household effectiveness testing. Interestingly, in controlled field efficacy testing, the new filter removed all total coliform in the Maine water, but only a partial amount in Honduran water (Table 1). The cause of this discrepancy is unknown, but some possible explanations are that: (1) different sizes of coliform species in the Honduran test water were not excluded by the 0.1 μm pore size; or (2) bacterial growth within the membrane persisted even after backwashing, and these bacteria recontaminated filtered water.

Backwashing is the only maintenance recommended by the PointONE™ filter manufacturer. While a demonstration of correct maintenance knowledge is an imperfect surrogate for actual user behavior, users in these communities reported relatively infrequent membrane blockage, or fouling, and most respondents (71%) correctly demonstrated how to backwash the filter. In household effectiveness testing, filters were backwashed prior to flow rate testing and water sample collection for microbiological analysis. The mean filter flow rate was only 11% of what would be expected of a new filter, which is consistent with previous research that identified that backwashing alone may be insufficient to clear severely fouled membranes (Murray *et al.* 2015).

Also, many filtrate samples contained *E. coli*. The hollow fiber membrane operates on the principle of size exclusion, so the reason for *E. coli* presence in filtrate is unknown. Possible explanations are that: (1) internal membrane fibers may have burst, allowing short-circuiting of unfiltered water; or (2) users may have backwashed the filter with contaminated water, and membranes were biofouled at the outlet side or on internal surfaces of hollow membrane fibers. Enumerators observed two users (4%) backwashing filters with unfiltered water during the survey. Despite users in these communities being trained on filter operation and maintenance and demonstrating proficiency at cleaning procedures, there was a high incidence of abandoned filters, and filters with slow flow rates and lower than expected microbiological performance.

This research is limited by selection bias, lack of household demographic data, small sample size, and variable microbiological methods. Households were not randomly selected, and those with nonworking or missing filters were excluded from selection, as a primary research objective was to test microbiological effectiveness of in-use filters. Overall, 45% of filter recipient homes were surveyed in the two communities, but not all homes were visited to determine if filters were in use. As such, the quantity of beneficiary households with nonworking or missing filters is unknown, and we should not extrapolate these results to estimate usage rates in this or other settings. Had non-filter-users been included, we would likely see a higher rate of broken filters and lower rates of satisfaction and recent filter usage. Also, the lack of demographic data collection did not allow us to analyze results controlled for variables such as socioeconomic status or water, sanitation, and hygiene behaviors that are often correlated with HWTS use (Figueroa & Kincaid 2010); however, these factors may not affect objective measures such as microbiological removal rates. Additionally, the small sample size is prohibitive in identifying differences in sub-analyses of the data. While some trends were seen in water quality data (such as better *E. coli* removal performance in newer filters and filters without visible damage), these differences were not statistically significant. Finally, different microbiological detection methods were used in the laboratory and in field testing, so there are potential limitations in directly comparing data collected with different methods.

To our knowledge, this is the first peer-reviewed quantitative field effectiveness data evaluating the PointONE™ filter. Comprehensive microbiological testing with rigorous methods and objective outcomes of filter performance evaluated household effectiveness as well as controlled laboratory and field efficacy. Further research is recommended to confirm microbiological field effectiveness results over long-term follow-up with a larger sample size. More research is also needed to understand the discrepancy between new and used filter performance, partial total coliform removal in controlled field efficacy testing, and possible PointONE™ filter failure mechanisms.

CONCLUSIONS

The PointONE™ filter is a HWTS option promoted worldwide. It has been shown to be efficacious in laboratory settings and to reduce diarrheal incidence in short-term follow-up, although limited available field effectiveness data has shown reduced microbiological performance when employed in users' homes. This evaluation confirmed high *E. coli* reductions in controlled efficacy testing of new PointONE™ filters with laboratory-spiked and natural waters. In field effectiveness testing of PointONE™ filters in two communities where many filters had already been abandoned after 1–3 years, most remaining filters improved household drinking water quality, yet 70% of filtrate contained *E. coli,* and filter flow rates were slow. Total coliform reduction was also lower than expected in field efficacy tests and in users' homes. The microbiological performance discrepancy between new and used filters and potential PointONE™ filter premature failure mechanisms are not well understood; future research on these topics, and future field effectiveness research with larger sample sizes, is recommended.

ACKNOWLEDGEMENTS

This research was supported by the Water For ME Foundation, and partially through NSF grant EEC-1444926. The authors gratefully acknowledge the use of facilities and equipment at the Department of Molecular and Biomedical Sciences at the University of Maine. The authors thank PWW health promoters and staff: Arlen Mejia, Fredy Rodriguez, Karla Vargas, Luis Zuniga, Ostilio Ramirez, Rony Quiñones, Maria Regina Inestroza, and Oscar Andino.

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First received 4 September 2015; accepted in revised form 28 December 2016. Available online 6 February 2017