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Efficacy of a ceramic siphon household water filter for removal of pathogenic microorganisms: lifespan volume test

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ABSTRACT

Treatment of drinking water at the point of use (POU) has demonstrated health benefits for people who have access only to microbially contaminated drinking water. In this work, the ceramic siphon POU water filter was evaluated for its ability to reduce indicator microorganisms in test waters. During batch challenge tests, the filter reduced *Escherichia coli* in filtered water by 7 log_{10} (99.999987%) and bacteriophage MS2 by 0.12 log_{10} (24.0%). Next, a novel continuous flow dosing system allowing sewage-amended feed water to constantly pass through the filters allowed for determination of changes in microbial reductions over time and total volume of water filtered. *E. coli B*, MS2 and fluorescent microspheres (as a surrogate for *Cryptosporidium* oocysts) were seeded into test water and dosed to filters at 10, 25 and 50% of the filter's volume lifespan. Microbial removal efficacy decreased as the volume of water filtered increased and test filters did not achieve their volume lifespan before physically failing. The ceramic siphon household water filter is effective in reducing *E. coli* and surrogates for *Cryptosporidium* in water, but filter modifications may be needed to achieve acceptable levels of virus removal and to reach the target 7,000 L volume lifespan of the filter.

Key words | ceramic siphon water filter, diarrhoeal diseases, *E. coli*, MS2, point of use

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ABBREVIATIONS

CFU	colony-forming units
DOFW	de-ionized organic-free water
ND	not detected
NTU	nephelometric turbidity units
ppb	parts per billion
PFU	plaque-forming units
POU	point of use
TOC	total organic carbon
UNICEF	The United Nations Children's Fund
USEPA	United States Environmental Protection Agency
V/V	volume to volume
WHO	World Health Organization

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INTRODUCTION

Unsafe drinking water

Unsafe drinking water affects millions of people worldwide, with those living in the most underserved regions in developing countries often being the most affected populations. Over 1.6 million people, most of whom are children, die each year from diseases related to unsafe water, inadequate sanitation and poor hygiene (UNICEF/WHO 2009). Waterborne illnesses, such as diarrhoeal diseases, enteric fevers and hepatitis A, are transmitted through the ingestion of pathogens in drinking water (WHO 2008). Although the ideal solution to this problem would be increased infrastructure providing universal access to safe, pathogen-free and reliable piped water, this solution is not feasible for many developing countries due to high capital costs of water infrastructure construction and maintenance.

Point of use drinking water treatment technologies

Treatment of drinking water at the point of use (POU) has demonstrated improvements in microbial as well as chemical and physical water quality and health benefits for people who have access only to microbially contaminated drinking water sources. POU treatments may include chlorine disinfection, UV irradiation, boiling or filtration using ceramic pots or other types of filters. Limitations of some of these treatment options have led to a search for alternative methods for POU treatment of drinking water.

Ceramic siphon filter

The ceramic siphon household water filter is one option in water filtration technology. A candle element composed of diatomaceous earth and nanosilver particles is designed to reduce microbes in water, by both chemical inactivation and physical removal. The siphon design allows for faster flow rates than gravity-fed filters (4–6 vs. 1–3 L h^{-1} (Sobsey *et al.* 2008)) and the small size of the filter eliminates the need for integrating large plastic filtration containers into the device design, although a safe water storage container is still needed.

The siphon filter consists of the candle filter element, plastic housing, plastic hose, siphon bulb and siphon valve. The filter is placed at the bottom of a bucket or other container as seen in Figure 1. The siphon bulb is squeezed 2–3 times to create negative pressure to draw water through the filter and the filtrate is collected in a separate receptacle.

There are limited data on the microbial removal effectiveness of the ceramic siphon filter to date. One laboratory test has been reported, in which the removal efficiency of *Escherichia coli* in silver-impregnated ceramic siphon filters was tested over an expedited (compressed time) lifespan, with water run through the filter continuously to simulate ongoing household use. Results showed a decline in *E. coli* removal efficiency over a lifespan of 7,000 L (Wubbels *et al.* 2008). However, this test used

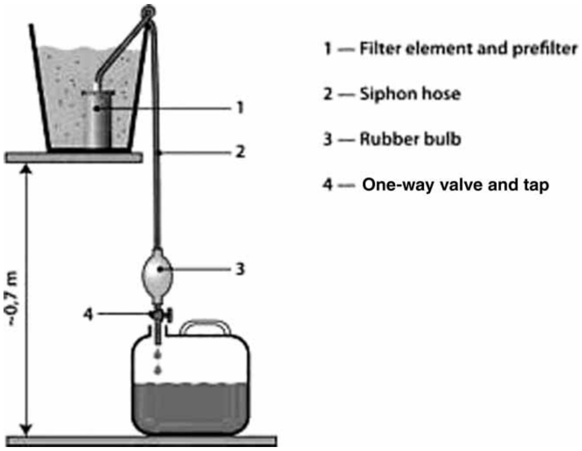

Figure 1 | Schematic layout for ceramic siphon filter (modified from Safe Water Today).

highly treated water, which is not representative of the drinking water sources used in most developing countries, and may not accurately reflect effects of variables such as organic matter content and turbidity on filter performance.

Forthcoming guidance on evaluation of POU technologies by the World Health Organization (WHO) suggests that it is important to test POU treatment technologies using conditions that simulate actual use conditions (WHO 2011). For the ceramic siphon filter, this includes the use of test waters that model faecally contaminated ground and surface water that is often the source for drinking water in developing countries, as well as the use of declining head water surface levels that model the siphon action during real world use. Additionally, it is important to evaluate changes in filter performance over the lifespan of the unit. It is well known for other technologies, such as the biosand filter, that technology performance changes over time and with the volume of water filtered (Stauber *et al.* 2006). However, this remains an unexplored area for ceramic filter technologies. The purpose of this research is to measure microbial removal efficiency and flow rate of a ceramic siphon filter over its water volume lifespan (estimated at 7,000 L) using test water and test conditions similar to those experienced under actual use conditions in developing countries. Faecally contaminated test waters were used in a continuous flow test to measure the $\log_{10}$ reductions of the three key classes of waterborne microbes, bacteria (*E. coli*), viruses (F + coliphage MS2) and protozoans, for which fluorescent microspheres were used as a surrogate for *Cryptosporidium* oocysts, over the volume lifespan of the ceramic siphon filter.

METHODS

E. coli, the WHO recommended indicator of microbial water quality, was used to measure bacterial removal (WHO 2008). Bacteriophage MS2 was chosen as a viral indicator due to its similarities to human enteric viruses and because it is recommended as a challenge virus by NSF International (2003). Fluorescent microspheres (3 μm, specific gravity 1.05) were used as surrogates for *Cryptosporidium parvum* oocysts due to the cost and biosafety concerns associated with the large quantities of oocysts that would be required for lifespan testing and because they are recommended as a challenge parasite surrogate by NSF International (2003). Previous studies have shown that the use of microspheres to mimic *Cryptosporidium parvum* oocysts can provide a conservative estimate of oocyst removal in filters (Dai & Hozalski 2003).

Batch tests

Batch tests of 10-L volumes were performed in triplicate to determine baseline $\log_{10}$ reductions of *E. coli* and MS2 coliphage. *E. coli* B (ATCC #11303) was grown to log phase in tryptic soy broth and purified by centrifugation at 7,277× *g* and 4 °C for 10 minutes (RC-3B Refrigerated Centrifuge, Sorvall Instruments). Pellets were resuspended in 10 mL of phosphate buffered saline, and added to 10 L of laboratory reagent grade water treated by reverse osmosis and UV light (Dracor, Durham NC) to give an initial *E. coli* concentration of about 1.6×10^5 colony-forming units (CFU)/mL. Bacteriophage MS2 was grown in tryptic soy broth containing host *E. coli* F_{amp}, purified by extraction with 1/2 volume of chloroform followed by centrifugation at 7,277 × **g** and 4 °C for 10 min, and storage at −80 °C. The titre of the stock was 2.2×10^{11} plaque-forming units (PFU) mL^{-1}. One-millilitre aliquots of the stock were dosed into 10 L of feed water to give an initial concentration of about 2.2×10^7 PFU mL^{-1}.

Microbes were dispersed by continuous stirring for 15 min. Influent samples were collected before filtration. The filter was placed in the bucket containing the feed water and siphon flow was initiated. Filtered water was collected in a sterile carboy. The time it took to filter all 10 L (minus a minimal amount of feed water left in the bottom of the bucket) was recorded.

Continuous flow setup

Feed water contained 1% volume to volume (V/V) pre-filtered (5-μm mesh) primary sewage effluent from the local wastewater treatment plant (Orange County Water and Sewage Authority (OWASA), Chapel Hill, NC), which was mixed in-line with dechlorinated, activated carbon-filtered municipal tap water. An automated water feed system continuously delivered water through three new filters running in parallel with a declining head water level mode. Water-level sensors in buckets containing the filters triggered water to flow and refill the bucket when the water level reached a low-level sensor. Feed water stopped flowing into the bucket when water reached a top-level sensor. To ensure that primary effluent was properly mixed in-line with feed water, there was a 15-s flow of water to a waste drain before an outflow valve closed and the feed water mixture was routed to filter buckets. Flow meters at water outlet collection points measured flow rate, and data were transferred to a laptop computer for later analysis. The overall system was controlled by a Programmable Logic Controller unit (Model Click C0-00DR-D, Automation Direct, Inc., Atlanta, GA). About 70–120 L of water flowed through each filter daily.

Design of microbial challenge studies

Projected filter lifespan was suggested by the manufacturer to be approximately 7,000 L. Microbial challenge tests were scheduled to occur at 10%, 25%, 50%, 75% and 100% of the volume lifespan. Microbial challenges used *E. coli*, bacteriophage MS2 and fluorescent microspheres (as surrogate for *Cryptosporidium* oocysts) in test water at concentrations that allowed determination of 5 to 7 $\log_{10}$ reduction of test microbes. Filtered water collected for analysis was held at 4 °C until analysed.

For microbial challenges at the pre-determined volume points, a separate container of 10 L of microbe-seeded test water was prepared. *E. coli* and bacteriophage MS2 were spiked into feed water using the same method as previous batch tests. In addition, 1-ml aliquots of fluorescent microsphere stock were dosed into the 10 L of feed water to give an initial concentration of about 1.0×10^7 PFU mL^{-1}. Following the addition of challenge microbes into the continuously flowing feed water, influent samples were collected and turbidity, pH, silver concentration and total organic carbon (TOC) were measured. Flow rate was monitored throughout challenge tests.

Microbial analyses

E. coli concentrations in influent and filtered water were quantified by the spread plate and membrane filtration methods (USEPA 2002b) using BBL™ MacConkey Agar (Catalog #211387, Becton Dickinson and Company, Sparks, MD) or BioRad RAPID *E. coli* 2 Agar (Catalog #356-4024, Bio-Rad Laboratories Inc., Hercules, CA). Concentrations were expressed as CFU mL^{-1}.

MS2 in influent and filtered water was assayed using the double agar layer method (USEPA 2001) on host *E. coli* F_{amp}. Concentrations were expressed as CFU mL^{-1}.

Carboxylate fluorescent microspheres (Catalog #17147-5, Polysciences Inc., Warrington, PA) with a 3 μm diameter and specific gravity of 1.05 were used as a surrogate for *Cryptosporidium* oocysts. The feed water contained 10^7 microspheres in 10 L to allow for detection of up to 5 $\log_{10}$ reduction in filtered effluent. Influent and filtered water samples were shaken vigorously by hand or on a shaker to resuspend microspheres that may have settled while in storage. Sample volumes of 100 ml were filtered through a 2.0 μm pore size Nuclepore Track-Etch Membrane (Whatman, Banbury, UK). The membrane was then mounted on a 3″ × 1″ clean glass microscope slide using DABCO with glycerol. PBS was applied to the centre of the filter, and a 25 mm square glass cover slip was placed on top. Microspheres were enumerated using an epifluorescent microscope.

Cleaning of filters

Filters were cleaned according to manufacturers' instructions. Scrubber pads were used to gently clean the ceramic filter element, followed by rinsing with clean water. Once a week, filters were backwashed by removing the filter from the water, removing the outer container, closing the tap and gently squeezing the rubber bulb two to three times. The diameter of the candle element was measured weekly with callipers near the top, at the middle and near the bottom.

Water quality parameters

Total organic carbon was measured on a Shimadzu TOC 5000 Analyzer fitted with an ASI 5000 autosampler (Shimadzu Corporation, Atlanta, GA) according to the High Temperature Combustion Method (APHA/AWWA/WEF/WPCF 1998). Turbidity was measured using a turbidimeter (Model 2100N, Hach, Loveland, CO). Silver concentration in filtered water samples was measured using the RapidSilver™ Test Kit (Hach Company, Loveland, CO).

Flow rates

Water flow rates were measured using DigiFlow flow meters (Model DFS-2W, DigiFlow Systems, Mansfield, OH). Flow meters were connected to a USB data acquisition system (Model OMB-DAQ-56, Omega, Stamford, CT), which relayed information to a laptop computer. Flow data were collected using the Omega Personal DaqView program (Omega, Stamford, CT), and readings were taken every 32 s.

RESULTS AND DISCUSSION

Batch tests

Initial batch challenge experiments using laboratory reagent-grade water showed a mean reduction of 7.02 $\log_{10}$ (99.999987%) for *E. coli* (95% confidence interval: 6.49, 7.55 $\log_{10}$). There was almost no reduction of MS2 by the filter (mean $\log_{10}$ reduction 0.12 $\log_{10}$ (24.0%), 95% confidence interval: 0.08, 0.16 $\log_{10}$).

There were within-filter variations in reductions of *E. coli* and MS2. *E. coli* reduction in batch testing was higher than previously reported by other investigators for the siphon filter with a mean reduction of 7 $\log_{10}$ in this study versus a 6 $\log_{10}$ reduction in previous studies (Wubbels *et al.* 2008).

Lifetime volume studies

Filter longevity and microbial reductions over lifespan volume challenge tests

None of the filters reached the manufacturer's projected lifespan of 7,000 L, due to breakage. Therefore, data were collected from 10% (700 L) and 25% (1,750 L) volume life span for filter 1, and 10, 25 and 50% (700, 1,750 and 3,500 L) volume life span for filters 2 and 3. Filter 1 broke at the earliest time point, 42.2% (2,954 L) of volume lifespan, during routine cleaning. Filter 2 broke at 49.2% (3,444 L) volume lifespan, immediately following the 50% challenge test while the bulb was being squeezed to re-initiate water flow. Filter 3 lasted the longest, at 64.6% (4,522 L) of its volume lifespan, when it broke during routine cleaning.

E. coli removal decreased over time and increasing water volume, from 6.7 mean $\log_{10}$ reduction at 700 L filtered to 2.86 mean $\log_{10}$ at 3,500 L filtered (Figure 2a). MS2 reductions were $<1 \log_{10}$ throughout the lifespan of the filters, similar to those observed in batch testing. There appeared to be a trend of declining virus reductions with increased volume filtered but initial virus reductions were so low that this decline in performance is difficult to document (Figure 2b). Reductions of fluorescent microspheres ranged from 3.7 $\log_{10}$ to 5.00 $\log_{10}$ (Figure 2c); again, there was a trend of decreasing removal as volume filtered increased.

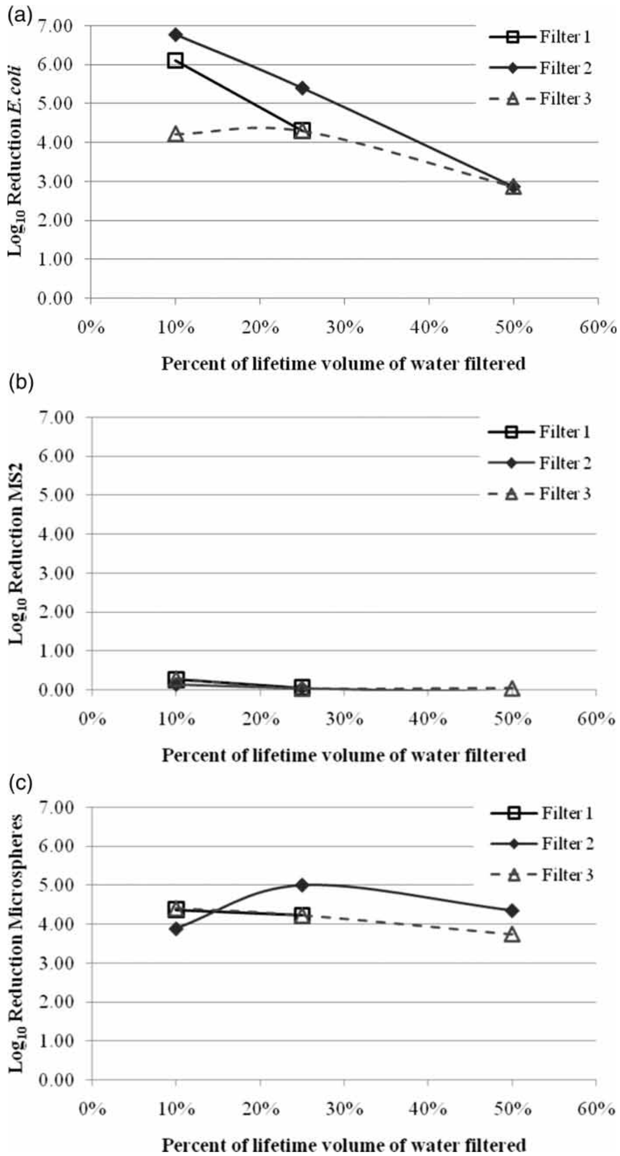

Figure 2 | $\log_{10}$ reductions in microbes during challenge tests: *E. coli* (a), coliphage MS2 (b) and fluorescent microspheres (c).

Water quality parameters

Turbidity measurements showed a decrease in turbidity of water following filtration (Table 1).

In addition, the percent reductions in turbidity increased as volume of water and time increased. Even when feed water turbidity was high (>5 NTU), turbidity was consistently reduced by the ceramic siphon filter to below 1 NTU in filtered water.

Silver concentration in filter effluent appeared to decrease with increasing flow volume (Table 2). At the 10% volume point (700 L), where the highest leaching of silver would be expected, the silver concentration of 25 parts per billion (ppb) in filtered water was below the United States Environmental Protection Agency (USEPA) (2002a) standard of 100 ppb and it was only 5 ppb at the 25 and 50% volume points. Therefore, silver leaching from the filter into feed water does not appear to reach concentrations of human health concern.

Total organic carbon measurements did not indicate removal of TOC by filtration (Table 3). The lack of TOC reduction by the filter was expected because the filter pore size is relatively large compared to that of the mostly soluble organic matter in the challenge water.

Table 1 | Turbidity levels of test waters and their reductions before and after challenge tests

Filter	Volume (time) point (%)	Influent turbidity	Effluent turbidity	% turbidity reduction
1	10	1.20	0.291	75.8
1	25	1.71	0.466	72.8
1	50	N/A	N/A	N/A
2	10	1.33	0.554	58.4
2	25	2.15	0.273	87.3
2	50	13.1	0.517	96.1
3	10	1.36	0.752	44.7
3	25	1.78	0.350	80.3
3	50	8.43	0.525	93.8

Table 2 | Silver concentration in filtered water

Filter	Time point (%)	Silver concentration Effluent (ppb)
1	10	25
1	25	0
1	50	N/A
2	10	25
2	25	5
2	50	5
3	10	25
3	25	5
3	50	5

Table 3 | TOC levels at 10, 25 and 50% volume lifespan

Time point (%)	Mean influent TOC (mg L^{-1})	Mean effluent TOC (mg L^{-1})
10	80.97	74.32
25	18.54	20.63
50	13.80	ND

Flow rates

Initial flow rate experiments using constant head water level and laboratory reagent-grade water gave flow rates between 6.2 and 6.4 L h^{-1}. Water flow rates varied between filters and over time for individual filters during the continuous flow experiment. Figure 3 shows the flow rates of all three filters over the duration of the experiment. Flow rates were similar for the first five days of testing, and then dropped to less than 1/3 of initial flow rate. The inclusion of primary sewage in the test water is the likely cause of the reduced flow rates. Reduced flow rates were potentially caused by the feed water particles clogging the pores of the filter, or formation on the filter surface of a biofilm.

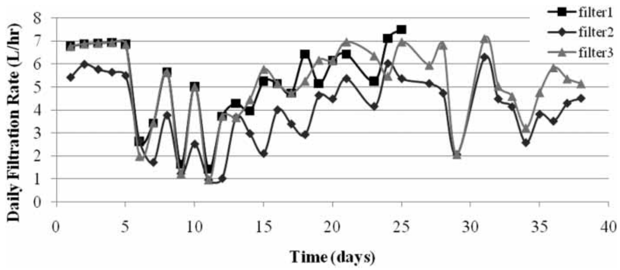

Figure 3 | Daily flow rates of filters 1, 2 and 3 during continuous flow experiment.

Flow rates declined in all three filters as the water head level dropped. As more sewage-amended test water passed through the filters, they clogged, typically reducing the flow rates by about 80%. Following cleaning, flow rates increased, and then gradually decreased again with more volume filtered. This trend can be seen throughout the lifespan of the filters. There appears to be unit-to-unit variation in flow rates, sometimes differing by >3 L h^{-1}. Average flow rates of the three filters over the course of their volume lifespans were 5.2, 3.9 and 5.1 L h^{-1} for filters 1, 2 and 3, respectively.

Effect of cleaning on filter diameter and longevity

Percent decreases in filter diameter over time are shown in Table 4. The filters were cleaned after every 70–120 L of water filtered, due to decreasing flow rates. Measured flow rates decreased by >80% within 24 hours after each cleaning and therefore daily cleaning was necessary. Assuming a typical household filters between 10 and 20 L of water per day, the cleaning schedule was equivalent to weekly cleaning with normal use filter dosing rates.

Regular cleaning of the siphon filter in response to decreasing flow rates resulted in a filter lifespan of about 50% of the manufacturer suggested lifespan when faecally contaminated test water with sewage organic matter was used. Scrubbing with an abrasive pad as recommended by the manufacturer causes progressive thinning of the ceramic

Table 4 | Percent decrease in filter diameter measurements

		% decrease in diameter		
Filter	**Time point (%)**	**Top**	**Middle**	**Bottom**
1	29.5	14.3	14.0	18.3
1	42.2	24.1	N/A	N/A
2	16.4	4.5	6.8	9.6
2	30.6	8.2	9.7	16.9
2	41.4	8.7	13.1	17.4
2	49.2	8.7	23.8	20.8
3	29.1	6.5	8.3	12.2
3	42.0	14.2	15.7	19.1
3	54.9	14.6	19.7	22.0
3	64.6	14.7	24.8	25.1

candle element. The appreciable decreases in filter diameter, reaching approximately 25% in all three filters, indicates a continued decline in filter wall thickness over time with regular filter surface cleaning to restore the filter flow rates. Eventually, the candle elements became so thin that they cracked during normal handling.

With regular cleaning to maintain flow rate near initial levels, the ceramic siphon filter lasted about 50% of the manufacturers' suggested lifespan of 7,000 L in a continuous-flow lifespan volume test. Bacterial reductions in challenge water decreased over the lifespan of the filter. Initially, *E. coli* reductions exceeded the 6 $\log_{10}$ bacteria reduction target of the USEPA and NSF International at the initial challenge point of 700 L filtered. However, the *E. coli* reductions declined to about 3 $\log_{10}$ before the filters failed due to breakage at about 50% of their volume lifespan or about 3,500 L. Other types of ceramic filters, such as the ceramic pot filter, show a maximum of 6 $\log_{10}$ reduction of *E. coli* under laboratory testing conditions, similar to the performance of the siphon filter in batch tests. The results of this study suggest that the performance of the siphon filter may exceed that of pot filters for bacterial removal from volumes <3,500 L.

Consistent with reported results of ceramic pot filter challenge studies, the siphon produced little to no reduction of F^+ coliphage MS2, a surrogate for human enteric viruses. Porous ceramic media filter microbes from drinking water by size exclusion (Sobsey *et al.* 2008). Pore size for the ceramic pot filter can be made as small as 0.2 μm, which can effectively trap bacteria and protozoa, but viruses are smaller, and thus capable of passing through the filter (Brown *et al.* 2007). Efforts to increase virus retention in porous ceramic filters by incorporating positively charged media such as iron oxides into the ceramic material have been reported, but such amendment of the ceramic material has not been reported for the ceramic siphon filter (Brown & Sobsey 2009).

No studies reported to date have tested protozoan parasite reduction by the ceramic siphon filter. The ceramic siphon filter achieved between 3.7 $\log_{10}$ and 5.00 $\log_{10}$ reduction of *Cryptosporidium parvum* oocyst surrogates, fluorescent microspheres. The ceramic pot filter has been reported to achieve similar reduction of protozoan parasites, with a *C. parvum* reduction of 4.3 $\log_{10}$ (Lantagne 2001b). The results of this study suggest that the ceramic siphon filter is capable of effectively reducing protozoan parasite surrogates at all volume lifespan points tested. The observed protozoan parasite surrogate particle reductions of the ceramic siphon filter observed in this study exceeded the 3 to 3.5 $\log_{10}$ protozoan parasite (or surrogate fluorescent particle) reduction performance target of the USEPA and NSF International (USEPA 1987; NSF 2003).

Turbidity in feed water varied from one volume challenge point to the next, making it difficult to observe trends in turbidity removal over the lifespan of the filter. However, regardless of the starting turbidity in feed water, which ranged from 1.2 to 13.1 NTU, turbidity in filtered water was consistently <1 NTU over the observed volume lifespan of the filter. These results suggest that although the ceramic siphon filter can reduce turbidity in filtered water to USEPA drinking water standards, turbidity removal is not a reliable surrogate indicator of microbial removal by the filter. The removal of turbidity by the filter may facilitate the incorporation of post-filtration chemical disinfection steps, such as treatment with hypochlorite, as a possible option for increasing bacteria and virus reductions in finished water.

The role that silver incorporated into the candle element of the ceramic siphon filter played in microbial reduction is still uncertain. It may have an effect on microbial reduction, which might account for the higher reductions that were seen at earlier challenge testing points in this volume lifetime experiment, where silver concentrations in filtered water were highest. The antimicrobial effect of colloidal silver content in the ceramic pot filter is inconsistent in the reported literature, with one study considering it necessary for optimal reduction of bacteria and bacterial indicators (Lantagne 2001a) and another study showing no effect on microbial reductions (Brown & Sobsey 2010). However, even when silver was detectable in ceramic siphon filtered water, viral reductions were still $<1\ log_{10}$, indicating that there is little or no inactivation of viruses by silver in the filter. Further research into the role of silver in the candle element of the ceramic siphon filter is necessary.

Frequent cleaning of the siphon filter led to a decreased lifespan, but was necessary to maintain flow rates when sewage-contaminated test water with organic matter was used. Filter flow rates decreased by over 80% within 24 hours after each cleaning. Slow flow rates may lead to user dissatisfaction with POU technologies, and users filtering 10–20 L of water a day may potentially clean the filter every week to maintain flow rate. The suggested cleaning method involves scrubbing the ceramic candle element with a scouring pad, and each consecutive cleaning causes small amounts of the filter element exterior surface to wear away. As a result, the effective life of the filter is reduced because it eventually becomes so thin that it is extremely vulnerable to breakage during routine use. The observed relationship between flow rates, cleaning and thinning of the element in this study suggests that if users adopt cleaning practices that keep the filter flow rate at levels of 10–20 L per day, the filter may need replacing more often than currently thought.

The results of this study suggest that testing ceramic filters with relatively low (10 L) volumes of water in batches may not provide adequate information about filter performance. Batch testing, which uses discrete volumes of water that are only a fraction of what would pass through a typical filter over its lifespan, is a standard method for the evaluation of many POU technologies. The comparison of batch and continuous flow test results suggest that using batch test data alone will give misleading results and lead to overestimation of filter efficacy for microbial reductions. Batch testing assumes that reductions do not fluctuate throughout the lifespan of the filter, but the results of this present study suggest this assumption is faulty. Therefore, challenge tests at various points in the volume lifespan of the filter should be conducted when testing filter performance for microbial reduction. It may be advisable to alter filter instructions to recommend using a second treatment option, such as chlorination, as the virus reduction efficiency of the filter is consistently inadequate ($<1\ log_{10}$) and as the bacterial removal efficacy of the filter decreases. It may also be necessary to lower the projected volume lifespan of the ceramic siphon filter; based on the results of this study it needs to be replaced more often than currently recommended, perhaps twice as often.

The differences between batch and continuous flow testing are also important for benchmarking POU technologies of this type against performance standards. The USEPA sets current United States standards for POU water treatment at a minimum 6 log_{10} (99.9999%) reduction in bacteria, 4 log_{10} (99.99%) reduction in viruses and 3 log_{10} (99.9%) reduction in protozoan parasites (USEPA 1987; NSF 2003). Only two out of the three filters tested in this study met the USEPA standard for 6 log_{10} reduction of *E. coli* at the 10% volume lifespan point. At later volume lifespan points, all three filters failed to meet the USEPA performance standard for *E. coli*. In addition, based on the use of MS2, none of the filters met the USEPA 4 log_{10} reductions standard for viruses at any of the volume lifespan points. Results indicate that log_{10} reductions of protozoan parasites (as represented by fluorescent microspheres) met the USEPA standard of at least 3 log_{10} reductions at every challenge point throughout the lifespan of the filters.

This is the first study of its kind, in which the lifespan of the siphon filter was tested using water containing sewage effluent that is continuously flowing through the filters. The use of primary effluent modelled faecally contaminated surface water in developing countries. The effluent was filtered before addition to the feed water flow, to better model groundwater and surface water in which larger particles are either filtered out in the soil or can settle out, such as in reservoirs, lakes and ponds. Testing of the siphon filter using protocols that simulate real world use conditions suggests a need to reconsider filter design in order to address problems encountered when filtering turbid, faecally contaminated water. It may also be necessary to redesign or revise filter efficacy testing protocols to better reflect the actual performance of these types of filters over their lifespan. New POU performance evaluation guidelines to be released by the WHO suggest using higher concentrations of sewage or sewage effluent in feed water than was used in this study (WHO 2011). This would most likely cause even greater problems with clogging of the ceramic siphon filter than were observed in this study. Thus, filter design may need to be further altered to accommodate this type of water. Additionally, a redesigned pre-filter may be beneficial for reducing clogging of the ceramic filter element. There is a need for a standard protocol to be developed to test POU water treatment technologies for use in the developing world, perhaps with similar or modified standards to the USEPA POU standards or with the guidance performance targets to be recommended by the WHO.

CONCLUSIONS

This is the first effort to evaluate reductions of bacteria, viruses and protozoa by a ceramic siphon filter over its projected volume lifespan using test water designed to simulate faecally contaminated drinking water sources in developing countries. This study shows that reductions of *E. coli*, MS2 and fluorescent microsphere surrogates for protozoa decrease over the volume lifespan of the filter. Additionally, the use of sewage-contaminated water as feed to the filter leads to the need for routine cleaning to restore flow, which reduces the lifespan of the filter by thinning the ceramic filter element.

The ceramic siphon filter has the potential to be successful in producing acceptable drinking water at the POU. It can reduce *E. coli* and fluorescent microspheres (representing protozoan parasites) to levels that meet USEPA drinking water standards (USEPA 2006). However, it performs poorly in reducing viruses, with $<1 \log_{10}$ ($<90\%$) reduction. It has a faster flow rate (almost 3×) than that of the ceramic pot filter, and it performs similarly in reducing turbidity. It is also more compact than the ceramic pot filter, making it a potentially more appropriate technology for places where transportation is difficult. Both filters are priced similarly, ranging from $8–15, depending on the country (Sobsey 2008).

Following filtration, it is important that there be safe storage of water in order to prevent recontamination. Implementers need to stress hygienic handling of the filter, filter hose, spout and receiving receptacle of the filtered water to avoid recontamination. Furthermore, it might be necessary to alter the method of ceramic filter element cleaning to reduce the effects of cleaning on the filter diameter. It is recommended that changes in the filter composition be explored to reduce the amount of material that sloughs off during cleaning.

Perhaps the most promising method to improve performance would be the use of two successive POU treatments in order to ensure safe water. Future research is recommended to explore the use of chemical disinfection treatments to enhance the removal of turbidity and viruses in influent water, such as chemical coagulants like chitosan or adsorbents like goethite. Chemical disinfection of the filtered water would also further improve reduction of viruses and other microbes not removed by the filter and provide residual disinfectant as a barrier against recontamination.

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