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Diarrhoeal diseases cause an estimated 1.87 million child deaths per year. Point-of-use filtration using locally made ceramic filters improves microbiological quality of stored drinking water and prevents diarrhoeal disease. Scaling-up ceramic filtration is inhibited by lack of universal quality control standards. We investigated filter production variables to determine their affect on microbiological removal during 5–6 weeks of simulated normal use. Decreases in the clay:sawdust ratio and changes in the burnable decreased effectiveness of the filter. Method of silver application and shape of filter did not impact filter effectiveness. A maximum flow rate of 1.7 l^{-hr} was established as a potential quality control measure for one particular filter to ensure 99% (2- log_{10}) removal of total coliforms. Further research is indicated to determine additional production variables associated with filter effectiveness and develop standardized filter production procedures prior to scaling-up.

Keywords: ceramic filtration; developing countries; household water treatment; point-of-use treatment; quality control

Introduction

Point-of-use water treatment and ceramic filtration

An estimated 1.1 billion people do not have access to improved water supplies (WHO/UNICEF 2004), and hundreds of millions more drink water contaminated during collection, transport, and storage (Clasen and Bastable 2003). Diarrhoea, one health consequence of unsafe drinking water, accounts for 1.87 million (19%) childhood deaths each year (Boschi-Pinto et al. 2008). Five household water treatment and safe storage (HWTS) interventions – chlorination, flocculation/chlorination, solar disinfection, biosand filtration, and ceramic filtration – have been shown to improve water quality and reduce diarrhoeal disease incidence in users in developing countries (Fewtrell and Colford 2005; Clasen et al. 2007; Sobsey et al. 2008). Household water treatment options can accelerate the health gains associated

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with improved water until the longer-term goal of universal access to piped, treated water is achieved. By preventing disease, HWTS practices can contribute to poverty alleviation and development. Their widespread use, in conjunction with hygiene education and sanitation, could save millions of lives until the infrastructure to reliably deliver safe water to the entire world population has been created.

Ceramic filters have traditionally been used to treat household water in many countries, and are commonly available for purchase in both developed and developing countries. Currently, the most widely available locally-produced household ceramic filters are based on a design developed in 1981 by the Guatemalan industrial research institute ICAITI (Lantagne 2006). In the mid-1990s, this filter was redesigned and promoted by the US-based non-governmental organization (NGO) Potters for Peace (PFP), and has subsequently been adopted in over 20 countries. PFP provides technical support to organizations implementing ceramic filter production and programs. The ICAITI/PFP filter design is flowerpot shaped, holds about 8 litres of water, and sits inside a plastic or ceramic receptacle fitted with a tap (Figure 1). To purify water, users simply pour water into the filter, wait for water to flow through the filter into the receptacle, and dispense water from the tap. The filters are produced locally at ceramics facilities, and impregnated with colloidal silver to ensure complete removal of bacteria in treated water and to prevent growth of bacteria within the filter itself (Oyanedel-Craver and Smith 2008).

Research has been conducted on ceramic filter efficacy in developing countries. In Bolivia, a trial using imported high-quality Katadyn® (Katadyn Produkte AG, Zurich, Switzerland) ceramic candle filters demonstrated improvements in the microbiological quality of stored household water and a 70% reduction in diarrhoeal disease incidence in ceramic filter users (Clasen et al. 2004). Each ceramic filter system costs US$25, which is higher than the respondents' willingness to pay by a mean of US$9.25. A second study (Clasen et al. 2005) using the same filter system in three conflict-affected areas in Columbia documented a 60% reduction in diarrhoeal disease incidence and a 75.3% reduction in faecal coliform in stored household water compared to controls, although performance varied across the study communities, indicating regional and sociological determinants of performance. A follow-up study of a similar design using imported Brazilian filters (Ceramica Stefani, Sao Paulo, Brazil) during an emergency documented almost half of 115 intervention households

Figure 1. The PFP filter.

in seven communities still had working filters 16 months after distribution (Clasen and Boisson 2006), and 23 (20%) of these 115 households had stored water free of faecal coliforms.

The studies presented above used high-quality, imported ceramic filters. During the course of an 18-week field study in Cambodia (Brown et al. 2008) using a locally-made PFP-style filter, *Escherichia coli* was reduced by a mean of 96% in stored water among intervention households, and diarrhoeal disease incidence was reduced by 42–49% in intervention group members. A retrospective study (Brown et al. 2007) of filters distributed in Cambodia from two local filter factories also found: (1) 50% of people had functional filters 18 months after distribution, and 20% had functional filters 36 months after distribution; (2) the geometric mean reduction of *E. coli* in filtered water was 98% and of total coliform was 94%; and (3) a 46% reduction of diarrhoeal disease incidence was documented in the population using ceramic filters.

Based on the successes documented above, it has been suggested that "ceramic and biosand household water filters are identified as most effective according to the evaluation criteria applied and as having the greatest potential to become widely used and sustainable for improving household water quality to reduce waterborne disease and death" (Sobsey et al. 2008). This conclusion was challenged by a group of HWTS experts (Lantagne et al. 2009); however, although ceramic filters are a promising HWTS option, critical research questions remain to be addressed.

One topic relevant to locally-made ceramic filters not currently addressed in the literature is how to maintain quality control standards in decentralized production processes. Experience from another locally-produced HWTS option, liquid sodium hypochlorite, has highlighted the importance of ongoing, stringent production and quality control standards to ensure that the sodium hypochlorite is the correct concentration and stabilized properly to ensure adequate water treatment at the user level (Point-of-Use Water Disinfection and Zinc Treatment [POUZN] 2007). The production of ceramic filters is more complex than mixing sodium hypochlorite. Locally-made ceramic filters are made by mixing clay with a burnable material ("burnable"), pressing the product into shape, allowing the filter to dry, firing the product to burn out the burnable which creates the pores, and measuring the flow rate for quality control. In addition, silver is added as a bactericide. Some variables involved in this process include : (1) type and composition of the clay; (2) type and composition of the burnable material; (3) sieve size used to screen the burnable; (4) clay:burnable ratio; (5) press method; (6) filter shape; (7) firing temperature and time; (8) amount of silver added and method of silver application (painted on/dipped before or after firing); and (9) flow rate considered acceptable and manner in which the flow rate is measured.

As one example, at the Cambodian factory whose filters were used in the Cambodian health impact study referenced above, "locally sourced unfired clay bricks are milled and mixed with finely ground rice husks, press moulded, and fired to cone 012 ($\sim$870°C) in a scrap wood-fuelled masonry kiln. After flow testing to ensure that the flow rate is within the optimal range (1.5–3 l per hour at maximum head), the porous filters are painted with a 0.00215 molar reagent-grade (99.999%) silver nitrate solution" (Brown et al. 2008). The burnable material, the acceptable flow rate range, and the type of silver added (silver nitrate) all differ from the PFP design, which is described in the methods section.

As of 2007, PFP had started filter factories in 17 countries, with eight countries producing filters, and nine countries with discontinued projects (Lantagne 2006).

In 2007–8, factories were built in another eight countries (PFP 2008). Currently, there is interest from 23 more locations to begin a project. Very few other factories have the type of ongoing research and quality control seen in Nicaragua, Cambodia, or the Dominican Republic. Given the large demand for filter factories, but the lack of standardized production variables, it is imperative to understand which production variables affect the microbiological efficacy of the filter in order to responsibly scale-up filter production worldwide. The only research identified relevant to this work detailed that: (1) hydraulic conductivity and pore size varied significantly based on the type of clay used; and (2) dipping the filter in colloidal silver after firing (as compared to painting it on) was more effective, although both were significantly more effective at reducing bacterial transport through the filter than those filters without silver (Oyanedel-Craver and Smith 2008).

Methods

This research was conducted concurrently in the laboratories of the Department of Civil and Environmental Engineering at Lehigh University in Bethlehem, PA, USA, and at the Aqua Pure Filter Factory in Higuerito, Moca, Dominican Republic.

Filter production

At the Nicaragua factory, cast-off clay from a local factory is broken-up manually and pulverized using a hammer mill (PFP 2008). Milled clay is mixed with sawdust screened using a sieve at a ratio of 1:1.5 (by volume). A cement mixer at 60 rpm is used to mix the clay and sawdust for 20 min, with water added halfway through the mixing process. The mixture is moulded into balls manually, and a 12-ton automatic truck jack is used to press the mixture into a flat-bottomed mould. The filter is removed, stamped with a number, and dried before firing at 890°C for 8–9 h. After cooling, the filters are immersed in water. Flow rate is measured after filling the wet filter with water. Two ml of 3.2% Microdyn colloidal silver (marketed as colloidal silver although it is understood there could be silver nitrate contamination) is added to 300 ml of distilled water, and the mixture is painted on the inside and outside of each individual filter with an acceptable flow rate of 1–2 l^{-hr}.

At the Dominican Republic factory, the independent NGO Aqua Pure has modified the PFP production procedure based on research and technical advice. The major modifications include: (1) making the filter round-bottomed to strengthen the filter and reduce breakage; and (2) adding a larger amount of colloidal silver into the mixture before firing. These modifications have led to questions about whether the filter is effective by NGOs considering purchasing the product. In the Aqua Pure production process, the clay and sawdust are pulverized in a hammer mill and filtered through a 0.25 and 0.30 micron screen sieve, respectively, to remove impurities and ensure the burnout material size leaves a standardized pore size. A cement mixer is then used to mix the clay and sawdust homogenously at a ratio of 5:4.5 (by volume). Colloidal silver obtained from a high-quality laboratory source is dispersed evenly into water before adding to the homogenous mix. The amount of silver added is proprietary, but it is significantly higher than that recommended by PFP. Filters are fired at 900°C. Because of the standardization of the mixing process, only two filters from each batch are evaluated for bacterial effectiveness and flow rate is not evaluated.

Lehigh University Laboratory

At the Lehigh University Laboratory, we analyzed flow rate, turbidity reduction, and total coliform and *E. coli* reduction in new design (round-bottomed, fired-in silver) Aqua Pure Dominican Republic filters compared to standard designed (flat-bottomed, painted on after firing silver) and modified design (flat-bottomed, fired-in silver) Nicaragua factory PFP filters. All filters met respective factory quality control criteria, with measured flow rates in country of the Nicaragua filters between 1–2 l^{-hr} and Aqua Pure filters not measured for flow rate, but produced according to their standardized production methods. Aqua Pure and PFP filters were shipped to the Lehigh University Laboratory. After arrival, all filters were scrubbed and flushed with creek water for six days before testing. Due to the differences in the holding capacities of the two filters, approximately 48 litres and 36 litres of creek water were flushed through the PFP and Aqua Pure filters, respectively.

For six weeks, approximately 50 l of water was collected daily or every other day from Saucon Creek, Bethlehem, PA, and 8 l per day was added to each of the six filters – two each of the Aqua Pure, PFP, and modified PFP filters. Water quality testing occurred twice each week in each of the six filters. On a water quality testing day, 8 l of creek water was obtained for each filter, and the turbidity was measured in triplicate using a Hach 2100P portable turbidimeter (Loveland, CO, USA). All testing was conducted at 30 Nephelometric Turbidity Units (NTU), as this turbidity is representative of surface water sources in developing countries, and not too high (above 70–100 NTU) to require pre-treatment prior to ceramic filtration. If the turbidity was less than 30 NTU, creek sediments were added as necessary to each batch of influent water to obtain 30 NTU. Conversely, if the turbidity of the influent water was greater than 30 NTU, some creek water was removed and Millipore water was added until 30 NTU was achieved. The influent water was also spiked with *E. coli* (American Type Culture Collection® #11775, Manassas, VA) to obtain 1.25×10^6 colony forming units per litre (CFU^{-L}). Before the start of testing, individual *E. coli* colonies were isolated from the stock solution via the streak plate method on LB agar plates; these clonal plates were stored at 4°C and used for several weeks before replacing. The day before a water quality test day, LB agar broth was inoculated with a single colony from the clonal plate and incubated at 37°C for 24 h. The *E. coli* concentration of the broth was estimated by measuring the absorbance at 600 nm with a GeneQuant pro RNA/DNA calculator (GE Healthcare, Piscataway, NJ, USA), and the required volume of broth to obtain 1.25×10^6 colony forming units was calculated. The required inoculated broth volume was added to each 8-l influent batch and mixed for 15 min. An influent sample was taken to confirm the *E. coli* concentration by plate count.

Thirty minutes after addition of the water, when the filter was saturated, the flow rate of each filter was measured. Disposable aluminium pans sitting on a removable shelf were used to collect the filtrate for a measured time period, typically between 30 and 45 min (Figure 2). The collection time was monitored via stopwatch and the collected volume was measured using a graduated cylinder.

After water was filtered through the filters for 6 h, the effluent water was thoroughly mixed, and a sample was collected aseptically using the spigot in the clean receptacle container and an autoclaved beaker or flask. The effluent samples were analyzed in triplicate for turbidity. *E. coli* and total coliforms were also measured by filtering water aseptically through a 45-micron filter, placing the filter in a Petri dish with an mColiBlue24 (Billerica, MA, USA) media-soaked pad, and incubating for 24 h at 35°C following Standard Methods (APHA/AWWA/WEF 1998). Each sample was tested undiluted and at 1:10 dilution and 1:100 dilution with pH-buffered Millipore water (Hach Company, Loveland, CO, USA). Results between 1 and 200 CFU/100 ml were averaged for final *E. coli* and total coliform values. One negative control was included before each sample.

Dominican Republic filter factory

In the field-based studies, we analyzed turbidity reduction, flow rate, and total coliform and *E. coli* reduction in Aqua Pure Dominican Republic filters made with different clay:burnable ratios (40:60, 45:55, 50:50, 53:47, and 60:40), burnable materials (sawdust, coffee husks, and risk husks), and screen sizes (0.3 and 0.45 μm) (Table 1). Three filters of each of the eight specifications were produced at the factory, for a total of 24 filters. Six control filters, meeting all factory specifications, were also used in the study. To sterilize the filters before testing, river water was

Figure 2. Laboratory set-up for filter testing at Lehigh University.

Table 1. Characteristics of filters tested in the Dominican Republic.

Filter (number)	Clay:burnable %/%	Burnable material	Sieve size
1	50/50	Sawdust	0.30
2	55/45	Sawdust	0.30
3	60/40	Sawdust	0.30
4	45/55	Sawdust	0.30
Control 1	53/47	Sawdust	0.30
5	40/60	Sawdust	0.30
6	53/47	Sawdust	0.45
7	53/47	Coffee husks	0.30
8	53/47	Rice husks	0.30
Control 2	53/47	Sawdust	0.30

passed daily through the filters for two weeks, followed by heating the filters in a kiln at 400°C for 1–2 h. The study was broken up into two segments due to laboratory limitations – with the three filters of each of the first four specifications (12 filters total) tested against the first three control filters for five weeks, and then the three filters of the second four specifications (12 additional filters total) tested against the second three control filters for 5 weeks. Thus, the study lasted a total of 10 weeks. Six days a week, between 2 and 12 l of Yaque del Norte River water was filtered through each filter being tested.

Water quality testing occurred once each week per filter, with half the filters (6) and controls (3) being tested on one day and the remaining filters (6) and controls (3) on another. On a water quality testing day, river water turbidity was measured using a Lamotte 2020e portable turbidimeter (Chestertown, MD, USA). Flow rate was calculated for each filter by using a 16 ounce cup to directly capture the total volume of water that passed through the filter in the 10 min (timed using a stopwatch) immediately after it was filled, when hydraulic head was greatest. This water was also used to measure effluent turbidity. Effluent water samples were collected using sterile technique in 100 ml WhirlPak bags or sterile 120 ml sample cups with thiosulphate and stored for processing within 1 h of collection. Samples were analyzed using the Colilert Quantitray® 2000 system (IDEXX Laboratories Inc., Westbrook, ME, USA). Media reagent was added to the water sample, shaken until dissolved, poured into the Colilert Quantitray® 2000 culture tray, sealed, and incubated at 35°C for 24 h. The tray wells were then analyzed for color change and fluorescence, and based on the positive well number; a most probable number table was used for quantification of *E. coli* and total coliform. Treated water was analyzed undiluted, and untreated water was tested at dilutions at 1:10 and 1:100 with boiled water. To determine the final total coliform value, all replicate results from tests with 15–85 positive wells were averaged. A negative control with boiled water was included within each daily run. Twenty percent of all microbiogical samples were duplicated. Data from the triplicate filters were averaged for analytical purposes.

Statistics

All data was entered into Microsoft Excel for Mac 2001, and analyzed using standard Excel functions. Percent reduction was calculated by subtracting the final value from the initial, dividing by initial, and multiplying by 100. Log reduction was calculated by subtracting the $\log_{10}$ of final concentration from $\log_{10}$ of initial. Statistical significance ($p < 0.05$) was assessed using the *t*-test function for samples sized greater than 15.

Results

Lehigh University Laboratory

The initial flow rates with the 30 NTU water were 1.03–1.69 l^{-hr} ($n = 2$) for the PFP flat-bottom silver-after firing filters; 0.84–1.22 l^{-hr} ($n = 2$) for the PFP flat-bottom silver-before firing filters; and 0.46–0.53 l^{-hr} ($n = 2$) for the Aqua Pure round-bottom, silver-before firing filters (Figure 3). Flow rates in the PFP filters declined over the 6 weeks of filtering 30 NTU water, falling to 0.78–1.28 l^{-hr} and 0.43–0.70 l^{-hr}, respectively. Flow rates in the Aqua Pure filters increased slightly over the 6-week time period, ending at 0.57–0.64 l^{-hr}.

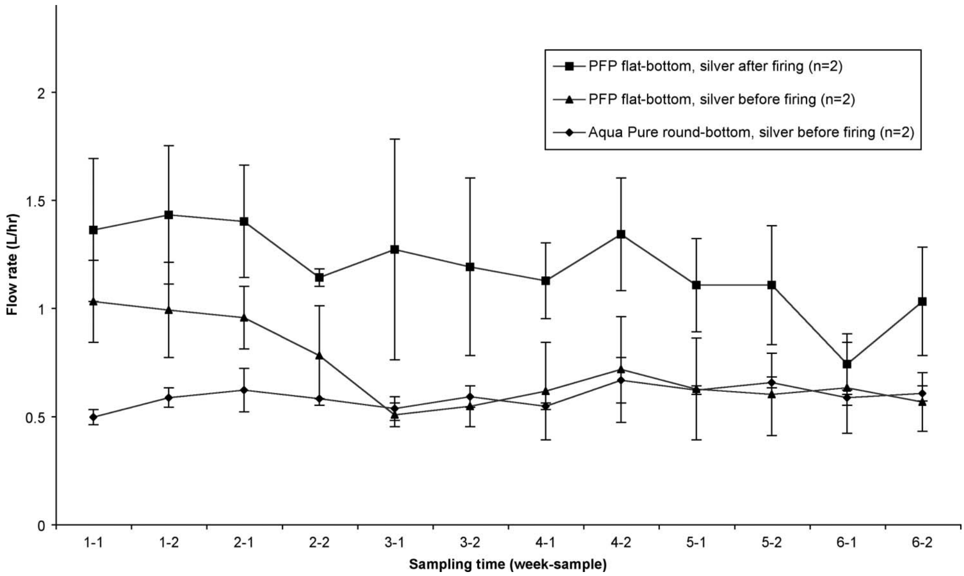

Figure 3. Flow rate in six filters of three types over 6 weeks.

The average percent error of the influent water triplicate samples (>25 NTU, $n = 72$) was 3.6% (min = 0.3, max = 16.0, standard deviation [SD] = 2.7). The average percent error of the effluent water triplicate samples ($\leq$3 NTU, $n = 72$) was 15.2% (min = 0.0, max = 104.7, SD = 14.8). The average percentage error for all samples ($n = 144$) was 9.4% (min = 0.0, max = 104.7, SD = 12.1).

The average influent water turbidity across all sampling days was 30.4 NTU ($n = 72$, min = 25.1, max = 35.8, SD = 2.3). The average influent waters tested each day was 30.4 NTU ($n = 3$, min = 27.5, max = 32.1, SD = 1.1) with no trend across time noted. Average effluent water turbidity across all sampling days was 1.2 NTU ($n = 72$, min = 0.2, max = 3.0, SD = 0.6). The average effluent water turbidity for the PFP flat-bottomed, silver after firing filter was 1.1 NTU ($n = 24$, min = 0.3, max = 2.0, SD = 0.5), for the PFP flat-bottomed, silver before firing filter was 1.2 NTU ($n = 24$, min = 0.3, max = 2.5, SD = 0.6), and for the Aqua Pure round-bottomed, silver after firing filter was 1.3 NTU ($n = 24$, min = 0.5, max = 2.6, SD = 0.6).

Percentage turbidity reduction was calculated for each filter on each sampling day, and duplicate results were averaged (Figure 4). For the PFP flat-bottom, silver-after filter, the percent turbidity reduction began at 95.6% at the week 1 first sampling, and increased to 98.3% (average = 96.3, min = 93.9, max = 98.7) at the second sampling in week 6. Percentage turbidity reduction began at 92.6% at the first sampling and increased to 98.0% at the last sampling (average = 95.9, min = 92.6, max = 98.4) for the PFP flat-bottom, silver-before filter. For the Aqua Pure round-bottom, silver-before filter, the percent turbidity reduction was 96.1% at the first sampling, and 97.9% at the last sampling (average = 95.7%, min = 92.2%, max = 97.9%). No significant differences were identified in efficacy of the three filter types in this data.

Influent water into all filters was spiked with *E. coli* before filtration, with an average of 4.29×10^5 CFU/100 ml (min = 0, max = 1.3×10^6, SD = 3.89×10^5).

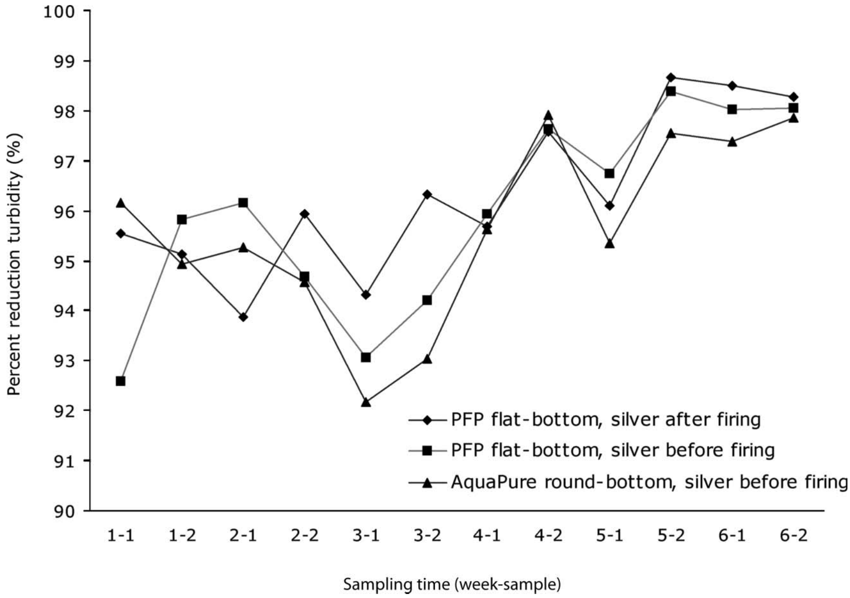

Figure 4. Percentage turbidity reduction of three filter types over 6 weeks. (Note: $n = 6$ for each sample (duplicate filters with triplicate turbidity measured.) Errors bars not presented because y-axis is percent reduction, not NTU).

All but two effluent water samples tested in both rounds of testing had no *E. coli* present. For the PFP flat-bottom, silver-after filter, the *E. coli* $\log_{10}$ reduction ranged from 4.1–6.1. The $\log_{10}$ reduction ranged from 3.1–6.0 for the PFP flat-bottom, silver-before filter. For the Aqua Pure round-bottom, silver-before filter, the $\log_{10}$ reduction ranged from 3.6–6.0. Please note that due to variation in the *E. coli* concentration in the spiking, no temporal evaluation or comparison between filters can be conducted.

Dominican Republic filter factory

Source water total coliform concentrations varied between $5.35 \times 10^2 - 1.1567 \times 10^3$ MPN/100 ml ($n = 10$ conducted at multiple dilutions and averaged, average = 4.61×10^3, SD = 4.036×10^3) over the course of the 10-week study. *E. coli* was not consistently obtained from river water samples, and this parameter was dropped from further analysis. Because of influent water variation in total coliform concentration, percentage reduction was used instead of $\log_{10}$ reduction values in subsequent analysis. Duplicate sampling was conducted in 24 (19.7%) of 122 total coliform tests. Results for original and duplicate water samples were highly correlated for total coliform ($R^2 = 0.973$). Nine (90%) of 10 negative controls tested at 0 MPN/100 ml, with the tenth at 1.1 MPN/100 ml.

Source water turbidity varied between 1.16–4.80 NTU ($n = 10$, average = 2.97, SD = 1.05). Due to the low influent turbidity values, turbidity reduction data is not presented or included in subsequent analysis.

The average first week flow rates for the five clay:sawdust ratio testing filters ($n = 3$ filters per ratio) varied from 0.25–4.24 $\mathrm{l}^{-\mathrm{hr}}$ (Figure 5a), with higher

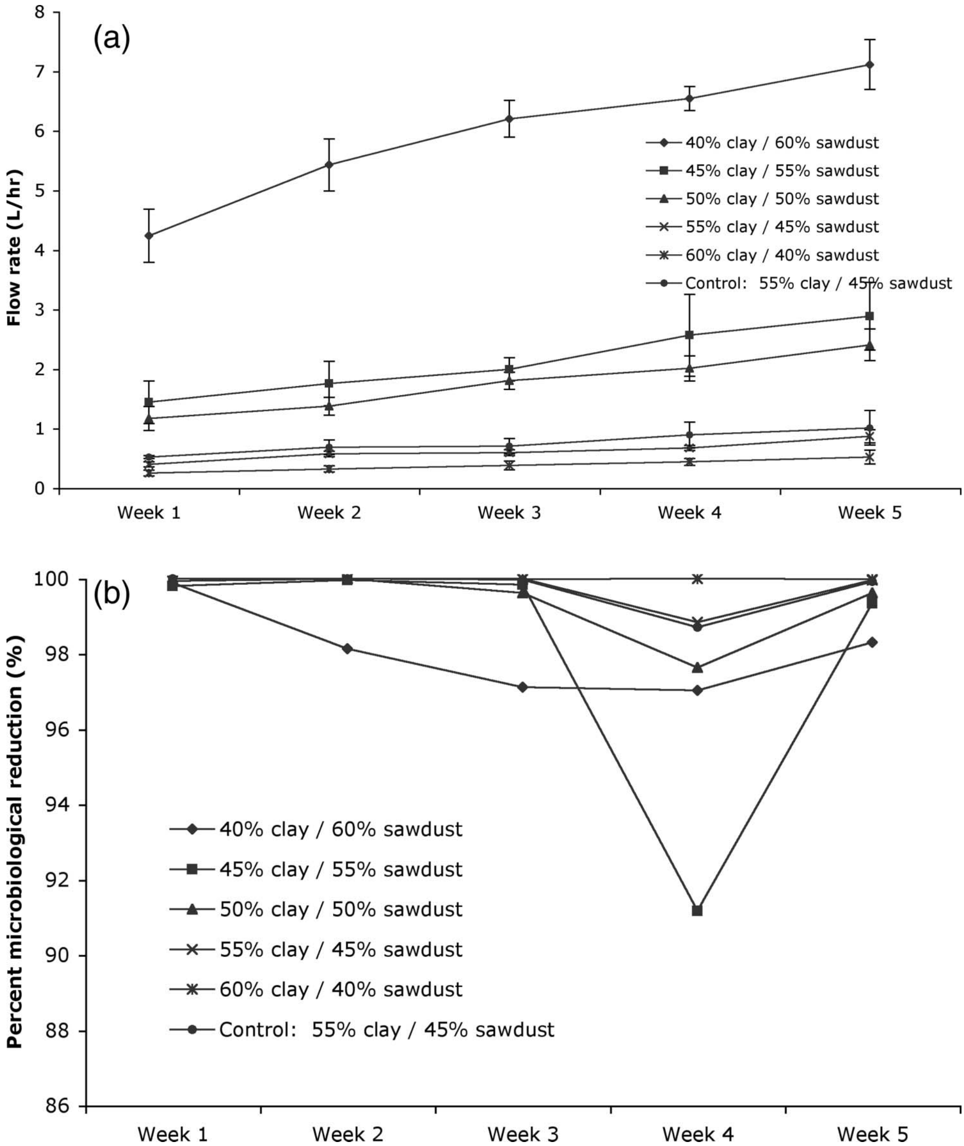

Figure 5. (a) and (b) Flow rate and total coliform percentage reduction in clay:sawdust ratio testing filters. Note: Results presented are averages of triplicate samples.

percentage sawdust leading to higher flow rate. Flow rate increased over the course of the 5-week testing period in all clay:sawdust ratio testing filters, with final week flow rates of 0.52–7.1 l^{-hr}.

Average flow rates in the burnable testing filters were 10.2 and 3.7 l^{-hr} in the coffee husk and rice husk filters ($n = 3$ filters per burnable type), respectively, during the first week of testing, and 9.6 and 6.7 l^{-hr} in the fifth week of testing. The flow rate increased in the rice husk filters, but not the coffee husk filters (Figure 6). In the sieve testing filters ($n = 3$), the flow rate increased from 0.65 l^{-hr} in the first week of testing to 1.6 in the fifth week (Figure 7).

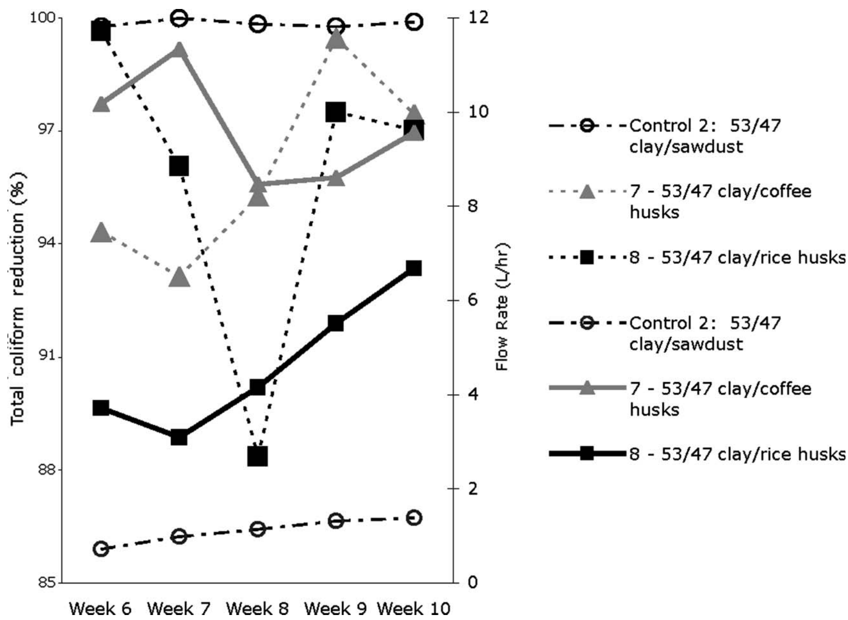

Figure 6. Flow rate and total coliform percentage reduction in burnable testing filters. Note: Dotted lines are total coliform reduction, solid flow rate, dashed control filters. Results presented are averages of triplicate samples.

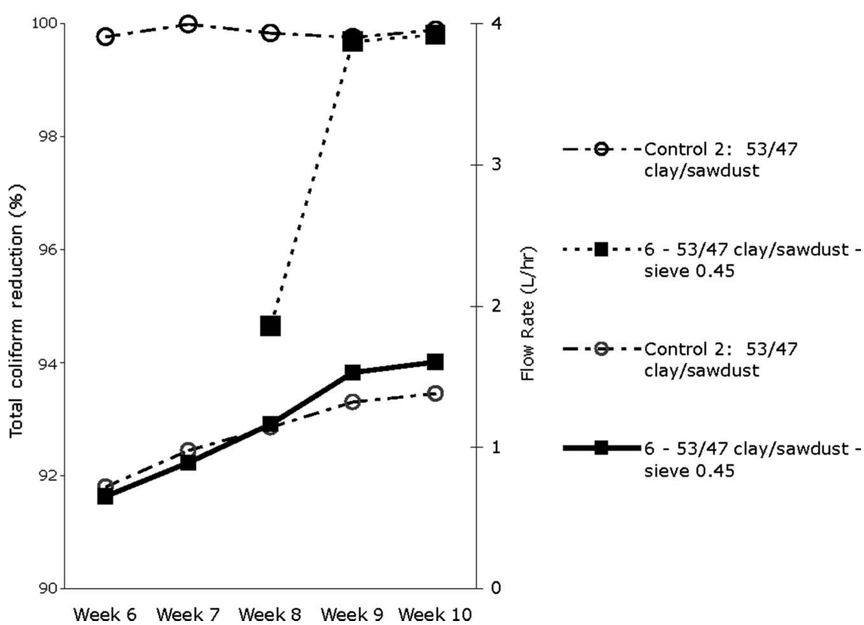

Figure 7. Flow rate and total coliform percentage reduction in sieve testing filters. Note: Dotted lines are total coliform reduction, solid flow rate, dashed control filters. Results presented are averages of triplicate samples.

A >99% average reduction in total coliform was seen only in the 60/40 clay:sawdust ratio filters ($n = 3$) and the second control filters ($n = 3$) across all five weeks of testing (Figure 5b). The first control filters ($n = 3$) and the 55/45 clay:sawdust ratio filters ($n = 3$) achieved averages of 98.7% and 98.9% reduction of total coliform, respectively, during the fourth week of testing, but otherwise achieved 99% reduction. The 50/50 ($n = 3$) and 45/50 ($n = 3$) clay:sawdust ratio filters dropped below 99% reduction of total coliform during the fourth week of testing as well, at 91.2% and 97.5% reduction. The 40/60 clay:sawdust ratio filters ($n = 3$) achieved greater than 99% average reduction only during the first week of sampling.

In the burnable testing regime, the rice husk filters ($n = 3$) reduced total coliform on average between 88.4 and 99.7% over the course of the five-week sampling, and the coffee husk filters ($n = 3$) reduced average total coliform 93.1–99.5% (Figure 6). Both sets of filters removed greater than 99% average total coliform on one sampling day only. For the first two weeks of sieve testing, three of the four tests had more *E. coli* in the effluent water than influent water, indicating contamination in the filters itself that resolved over time (Figure 7).

Flow rate and percentage total coliform appeared to have some correlation when data from all 10 filters tested for each of the five weeks ($n = 50$) was graphed, although the R^2 was not significant (0.28) due to outliers ($R^2 = 0.68$ without outliers) (Figure 8). A correlation was observed when the average percent reduction and initial flow rate over the 5-week period for each filter (10 data points) was graphed, with flow rate predicting 77% of the variance of percentage reduction ($R^2 = 0.77$). The calculated flow rate from the regression equation for a 99% reduction of total coliform is 1.71 l^{-hr}.

Discussion

In laboratory-based testing, with 30 NTU water at study initiation, only three (75%) of the four PFP filters met factory quality control standards (1–2 l^{-hr}). In addition, variability was seen in the flow rates of filters made at the same production facility over time (Figure 3). These results show the variability that can occur: (1) between filters; and/or (2) when conducting flow testing with waters of different turbidities in different environments. The PFP filters showed a steady decline in flow rate over the six-week time period in the laboratory, which has been widely documented due to the build-up of organic material in the filter, and can be partially, but not sustainably, alleviated by teaching users to scrub the filter when the flow rate is unacceptably slow (Lantagne 2001a, 2001b; van Halem 2006). Flow rates in the Aqua Pure filters increased slightly over the six weeks of laboratory testing and almost doubled during the five-week testing in the Dominican Republic, possibly due to combustible material flowing out of the filter during the initial uses. Note the Aqua Pure filters are not tested for flow rate prior to distribution and Aqua Pure does not have a recommended flow rate, thus the filters with the lower initial flow rate were acceptable to include in the study.

Despite the variation in flow rates, all three filter designs effectively reduced turbidity in the laboratory setting between 92.6 and 98.7%. No significant differences were identified in the efficacy of the three filter types in these data. In addition, all three filter designs effectively removed bacteria from challenge water, with all but two (3%) of 72 individual challenge tests (two filters of each of three designs tested twice per week for six weeks) removing all spiked *E. coli* and achieving $\log_{10}$

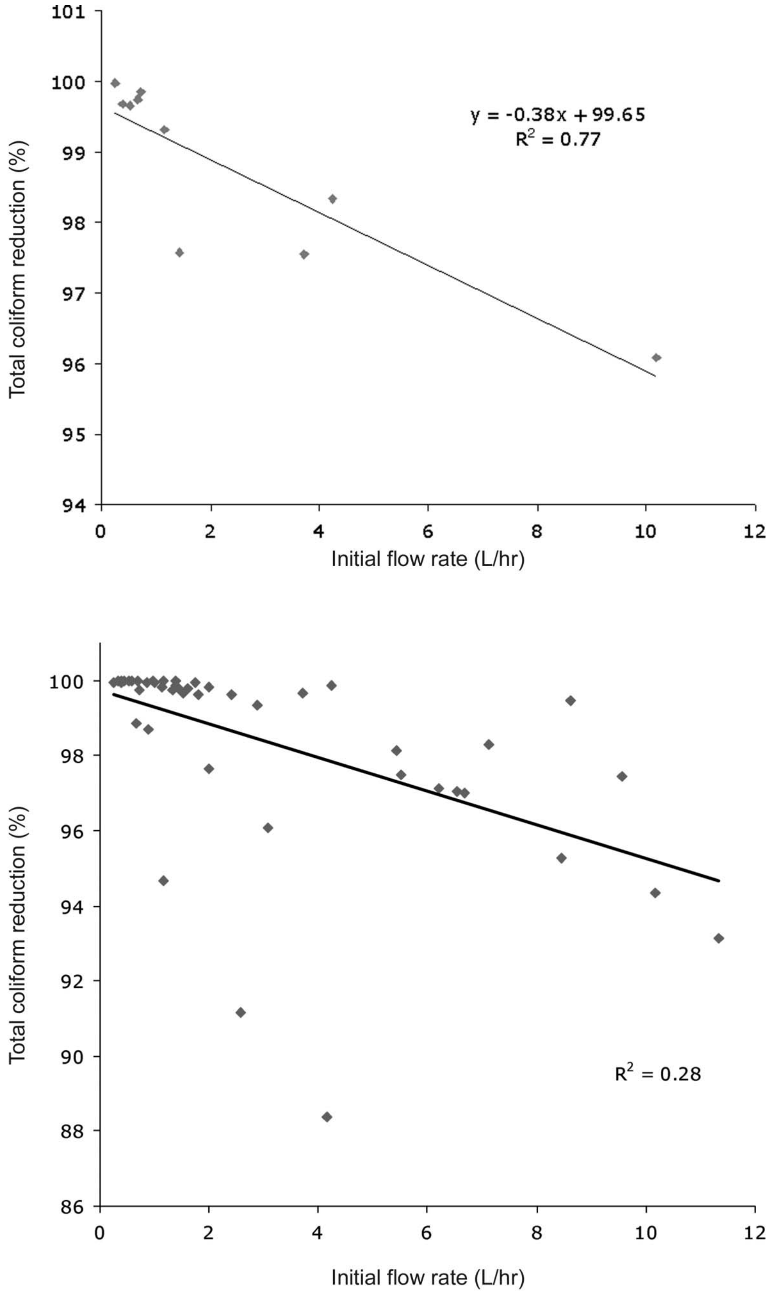

Figure 8. Regression analysis – percentage total coliform removal and flow rate (weekly per filter type [50 data points] and study average per filter type [10 data points]).

reduction values (LRVs) of 3.1–6.1. Both positive *E. coli* results (with LRVs of 4.5 and 3.1) were obtained from the modified PFP filter, which could potentially indicate that firing in the silver at the lower concentration is not as effective, although the data is not conclusive due to too few measurements, and further research is recommended with standardized *E. coli* spiking. The Aqua Pure and PFP control filters removed all spiked *E. coli* in all samples up to an LRV of 6.1 and 6.0, respectively, throughout the course of the 6-week study, indicating both are highly effective at removing bacteria during the initial phase of use. Based on this combined turbidity and microbiological data, the Aqua Pure filter should be considered an acceptable alternative to the PFP standard design. The modified silver-fired-in design for PFP needs more testing to determine if it is effective.

In the field studies conducted with the Aqua Pure filters in the Dominican Republic, three variables – clay:burnable ratio, burnable type, and sieve size – were investigated to determine how manufacturing differences affected filter performance and if flow rate could be increased to increase user acceptability without losing filter efficacy. Changing the flow rate by increasing the pores in the filter (i.e. by lowering the clay:sawdust ratio) led to gradually increasing flow rates until the proportion of sawdust reached 60% when the flow rate increased substantially and total coliform percent reduction was compromised. As the total coliform reduction was also slightly compromised at 55% and 50% sawdust, it is not recommended at this time to increase beyond the current 47% sawdust percentage in the filter.

Changing the burnable increased the flow rates of the filter and compromised the total coliform reduction percentage, indicating that a new clay:burnable ratio should be developed for each burnable. Although the rice husks and coffee husks were sifted using the same size screen as the sawdust another variable in the combustible material other than size must influence pore characteristics in the finished filter. It could be possible that coffee or rice husks clump and are not able to mix with the clay as evenly as sawdust. It is also noted that the coffee husk filters were more fragile, with the rims of two of the three replicates breaking during the five-week study.

Although it was hypothesized that flow rate would increase by increasing the sieve size to 0.45 μm from 0.30 μm and potentially increasing the pore size in the filter, the results of the study did not support this, as almost no difference in flow rate between the control filter and higher sieve size filters was noted. However, it is difficult to make any comparisons between the two filters' abilities to reduce total coliform because of filter contamination and increased *E. coli* in filtered water compared to source in the first two weeks of testing. The fact these filters were contaminated highlights the individual variability that can occur in filters.

Despite all the variables investigated in this study, it is important to note that of the ten sets of filters tested over 5 weeks (48 microbiological data points, missing only the sieve filters from the first 2 weeks) only one (2%) removed less than 90% of total coliform bacteria, only four (8%) removed 90–<95%, 12 (25%) removed 95–<99%, and the majority, 31 (65%) removed > 99% of total coliform bacteria. A 99% (2 $\log_{10}$ reduction) of bacteria was established as the criteria for this setting because in resource-limited developing countries it is often not possible to spike samples with *E. coli* or find contaminated enough water to document a higher $\log_{10}$ reduction. Thus, the 99% criteria is one that local ceramic filter manufacturing facilities can verify with the resources available.

A maximum initial flow rate, below which filters consistently reduced total coliform bacteria by >99%, of 1.7 l^{-hr} for the Aqua Pure filter was identified. This information could have important implications for enforcing quality control in the field as flow rate could be a simple, inexpensive proxy for determining filter effectiveness without the need for microbiological testing. It is important to note that this maximum flow rate may only hold true as an average for the first 5 weeks of the filter's life. Due to the fact that flow rate increases over time, it is possible that effective filters will have a higher flow rate once consistently used in the field, or a lower flow rate due to clogging. One challenge to this regime is the fact that individual ceramic filters may have different results on different days, as highlighted by the outlying points in the regression modeling (Figure 8). It is also unknown if this flow rate value can be applied to other filters made in other local factories.

Filters without silver were not analyzed in this study because it is standard practice throughout industrial and local ceramic filter production to add silver as a bacteriocide to prevent growth of bacteria within the filter itself and subsequent added contamination to filtered water. At laboratory scale and under controlled conditions, there is some evidence that application of silver nanoparticles could increase microbiological removal efficacy (Lantagne 2001a) and some evidence showing no impact (Brown et al. 2007). At high spiked bacteria concentrations, filters impregnated with colloidal silver consistently have better performances than filters without it (Oyanedel-Craver and Smith 2008). While there is significant debate and variability as to whether silver presence increases filter microbiological effectiveness, the reality is that all correctly manufactured filters reduce microbiological contaminants significantly, and that silver is a necessary additive to the filter to prevent bacterial growth in the filter itself. Thus, in this study, there was no utility in testing no-silver filters. However, further research on the impacts of different amounts and types of silver on the production variables tested herein is indicated.

Currently, when a new filter factory is established, generally a Potters for Peace technical specialist works on site for 1–2 months to develop the appropriate filter mix (burnable, clay, silver, sieve) for each location. This process is iterative, and is considered complete when the mixture reliably produces filters with flow rates between 1 and 2 l^{-hr}. Sometimes some microbiological testing is conducted, but often either none is conducted or the quality or number of samples is low. Increased collaboration between the potters who design the filter process and researchers who investigate the linkages between microbiological reduction and health is needed. This process is beginning with the formation of a "Ceramics Filter Manufacturing Working Group" that is meeting via conference-call to develop "Minimum Standards for the production of locally-manufactured ceramic filters".

The importance of filter production quality control was highlighted recently in Arusha, Tanzania, where Aqua Pure is providing technical assistance to establish a new filter factory (Lemons 2009). Tanzanian potters received training from Aqua Pure staff in the Dominican Republic, returned to Tanzania, and made 50 ceramic filters for use in a research trial intended to assess user acceptability. Flow testing indicated the filters were highly variable, with an average flow rate of 3.8 l^{-hr} (min = 0.3; max = 10.8; SD = 2.5). A modified user acceptability and water quality study commenced, and water quality testing documented *E. coli* contamination in treated water from higher flow filters. It was recommended to ensure filters are high-quality before initiating distribution or user acceptability testing, as users might have a false sense of security about filtered water and data gained from user acceptability studies using poor-quality filters with high flow rates is not meaningful.

The limitations of this research are: (1) the small number of filters tested for each testing regime; and (2) that short duration of testing per filter. Longer-term testing of a larger sample of filters is indicated, although strategies to complete this testing while minimizing laboratory workload should be investigated. The work presented in this paper represents only a small portion of the research needed to establish production criteria for local production of ceramic filters worldwide. To fully understand the production variables further research is needed to: (1) develop a full list of all production processes for all existing filter factories; (2) conduct a review to hypothesize, and then test, which production variables are relevant; and (3) work in collaboration with industry to develop manuals for establishing high-quality local filter production. This type of research will require considerable laboratory and human resources to complete the necessary studies, as substantial effort is required to maintain daily use of the filters in the laboratory.

Conclusions

This study documented that changing some production variables, such as the clay:sawdust ratio and burnable used, led to decreased effectiveness of the filter in the first five weeks of use. Changing other production variables, such as the method of silver application and the shape of the filter, did not impact the effectiveness of the filter during the first 5–6 weeks of use. Thus, the Aqua Pure Dominican Republic filter is an acceptable alternative to the standard PFP design. A maximum flow rate of 1.7 litres per hour can be used as a preliminary quality control measure, provided the flow rate is accurately measured for each filter at the production factory. Further research is required to: (1) identify additional production variables associated with increased, decreased, or consistent filter effectiveness; and (2) develop standardized filter production procedures and quality control procedures.

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