Ceramic ‘Pot’ Water Filters:

Investigations into Manufacturing and Performance

A dissertation submitted by

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Abstract

Ceramic 'pot' water filters (CWF) are widely used to improve the microbiological quality of drinking water at the point of use. CWFs are manufactured at >50 filter factories worldwide by pressing a mixture of clay and a burn-out material into the filter shape, which is then fired to a ceramic state. Silver is added during this process as a bactericide. In 2011, the Ceramics Manufacturing Working Group (CMWG) developed recommendations to, "provide guidance to assist filter factories in producing the lowest-cost, most-effective ceramic filters possible". The focus of this dissertation was to further this aim. Specifically, to: 1) investigate the effects of silver type, silver concentration, and input materials on CWF performance; 2) evaluate filter distribution programs; 3) develop a framework for evaluating manufacturing quality control protocols; and 4) synthesize research findings through a systematic literature review. Overall, results suggest that in households filtered water quality meets the low-risk guideline and filter use has been associated with a reduction in diarrheal disease. However, local context, including source water quality, time in use and supply chain access, likely influence long-term filter use and can affect in situ technology performance evaluation. Results from laboratory investigations and the systematic review demonstrate filters can achieve ≥2 log reduction in bacteria; however, silver should not be relied on as a principal treatment mechanism for long-term filter performance. Thus, it is recommended that filters be tested for bacteria removal prior to silver application. Burn-out material particle size and clay content (<2μm) are associated with bacteria removal by the porous matrix. Lastly, with participation from factories, a framework for evaluating quality control protocols was developed. CWFs are widely manufactured, promoted and used; thus, there is a need to continue supporting factories in manufacturing high-quality filters and to broadly disseminate research findings.

Dedication

This work is dedicated to Ron Rivera, the 'Filter Pot Man'. Without his vision, dedication and words of encouragement, this work would not have been completed.

Acknowledgements

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Acronyms

Ag^+	Silver ions
$AgNO^3$	Silver nitrate
ASSLHA	L'Association Saint-Luc d'Haiti
C	Celsius
CDC	US Centers for Disease Control and Prevention
CFU	Colony Forming Units
cm	Centimeters
CMWG	Ceramic Manufacturing Working Group
CWF	Ceramic Water Filter
CWH	Clean Water for Haiti
E. coli	*Escherichia coli*
FCR	Free Chlorine Residual
g	Gram
hr	Hour
HA	Humic acid
HWT	Household Water Treatment
HWTS	Household Water Treatment and Safe Storage
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
L	Liter
LRV	Log_{10} Reduction Value
m-FC	Media for Fecal Coliform detection
Max	Maximum
MCL	Micro Contaminant Level
MF	Membrane Filtration

mg	Milligram
Min	Minimum
min	Minute
mL	Milliliter
mm	Millimeter
MPN	Most Probable Number
nAg	Silver nanoparticles
NTU	Nephelometric Turbidity Units
P/A	Presence/Absence
PFP	Potters for Peace
pH	Potential of hydrogen
PPM	Parts per Million
PWW	Pure Water for the World
TC	Total Coliform
TTC	Thermotolerant Coliform
USEPA	US Environmental Protection Agency
WHO	World Health Organization
µm	Micrometers
UV	Ultraviolet

Ceramic ‘Pot’ Water Filters:

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1 Introduction

1.1 The global burden of diarrheal disease

Diarrheal disease is preventable and treatable, yet it remains a leading cause of morbidity and mortality (Collaborators 2017). While death rates from diarrheal diseases have fallen by nearly 21% from 2005 to 2015; in 2015, an estimated 1.3 million deaths were attributed to diarrheal diseases and diarrheal diseases were estimated to cause 8.6% of deaths in children less than 5 years of age (Feigin 2016). Diarrheal disease is also a leading cause of morbidity, and contributed to an estimated 71.6 million disability-adjusted life years (DALYs) in 2015 (Collaborators 2017).

Diarrheal diseases are primarily transmitted through the fecal–oral route. Unsafe water and sanitation is a leading risk factor for diarrhea (Collaborators 2017). Worldwide in 2015, approximately 884 million people lack access to a basic drinking water service (WHO and UNICEF 2017) and an estimated 159 million people collect drinking water from surface water sources (WHO and UNICEF 2017).

1.2 Household water treatment

Household water treatment (HWT) can be a cost effective way of improving the microbiological quality of drinking water (Clasen, Cairncross, et al. 2007) and reducing diarrheal disease where access to safely managed water and sanitation infrastructure is limited (Clasen 2015, Fewtrell et al. 2005, Clasen, Schmidt, et al. 2007, Waddington et al. 2009) and is thus recommended as part of a comprehensive strategy to prevent diarrheal disease transmission through drinking water (UNICEF/WHO 2011). An estimated 1.1 billion people report treating their drinking water at the household level (Rosa and Clasen 2010).

HWT methods have technological differences and practical advantages and disadvantages. Different treatment methods might be more or less suitable depending on the pathogens of concern (WHO 2011b), water characteristics, technology availability, personal preference, ease of use, etc. Methods for treating drinking water at the household level apply similar processes to centralized water treatment and include: 1) chemical disinfection (e.g. chlorine); 2) filtration (e.g. ceramic, sand, or cloth filters); 3) solar disinfection (e.g. SODIS, which relies on heat and ultraviolet (UV) radiation); 4) sedimentation/coagulation (e.g. simple sedimentation or through the addition of a natural or chemical coagulant to increase the rate of sedimentation); and, 5) thermal treatment (e.g. boiling).

There are three main classes of pathogens that cause diarrheal disease: bacteria, viruses and parasites, each with variable susceptibility to water treatment processes (WHO 2011b). Both the intrinsic resistance of microorganisms and environmental conditions (e.g. water temperature) can affect water treatment effectiveness. For example, chlorine is not effective at inactivating oocysts of the protozoa *Cryptosporidium* and a higher dose is needed for turbid water. Many filtration methods on the other hand, are effective at removing larger organisms (protozoa), but removal of viruses by gravity filtration is a challenge due to their small size. Ideally, water treatment methods are combined, for example filtration with subsequent disinfection.

1.3 HWT evaluation

HWT technologies are assessed for their ability to inactivate or remove pathogens from water in laboratory evaluations under controlled conditions using water spiked with high concentrations of surrogates that represent the classes of pathogens of interest (WHO 2011a). Performance is then quantified by the $\log_{10}$ reduction, which corresponds to the difference between the test organism concentration in untreated and treated samples calculated on a base 10 logarithmic scale.

The World Health Organization (WHO) has set health-based performance targets for evaluating HWT technologies based on quantitative microbial risk assessment (QMRA) modeling. These performance targets are based on the predicted probability of infection associated with pathogen exposure in drinking water and associated risk reduction with regards to different classes of pathogens (WHO 2011a). According to the WHO classification, the performance target for “highly protective” HWT technologies (‘three star’ performance classification) is a 4-log reduction for bacteria and protozoa and a 5-log reduction for viruses. Technologies that meet this target have the potential to avert 1 x 10^6 DALYs per person per year (Table 1). The performance target for “protective” technologies (‘two-star’ performance classification) is a 2-log reduction for bacteria and protozoa and a 3-log reduction for viruses. Technologies that meet this target have the potential to avert 1 x 10^4 DALYs per person per year. A third classification, ‘one star’ is included for technologies that meet “protective” levels for at least two classes of pathogens (e.g. chlorine or some filtration technologies), with the recognition that the use of these technologies may result in substantial health gains (WHO 2011a).

Table 1: WHO health-based performance targets for HWT technology performance classification

Performance classification	Bacteria (log_{10} reduction required)	Virus (log_{10} reduction required)	Protozoa (log_{10} reduction required)	Interpretation (assuming correct and consistent use)
★ ★ ★	≥4	≥5	≥4	Comprehensive protection (very high pathogen removal)
★ ★	≥2	≥3	≥2	Comprehensive protection (high pathogen removal)
★	Meets at least 2-star criteria for two classes of pathogens			Targeted protection
---	Fails to meet WHO performance criteria			Little or no protection

Figure adapted from (WHO 2011a)

1.4 Water quality monitoring

Drinking water quality can be monitored at the point of use and HWT technologies can be evaluated during use by testing water quality before and after treatment. Due to the difficulty of monitoring water for specific pathogens, water is often tested for the presence of indicator organisms. The bacteria *E. coli* is a widely accepted indicator of fecal contamination (WHO 2011b), though the absence of *E. coli* does not mean water is free from pathogens.

Water quality can range widely over time - due to the use of alternate sources, an emergency, or seasonality (Kostyla et al. 2015). While the log reduction in test organisms is easy to evaluate in a laboratory setting, this metric is limited for evaluations in situ given the variable and sometimes low concentrations of indicator organisms in raw water samples. Thus, the WHO has introduced a classification system to assess risk. While <1 *E. coli* CFU/100mL conforms to guideline values, 1-10 *E. coli* CFU/100 mL is classified as low risk, 11-100 *E. coli* CFU/100mL is classified as medium risk, 101-1000 *E. coli* CFU/100mL is classified as high risk and >1000 *E. coli* CFU/100mL is classified as very high risk (Table 2) (WHO 2011a).

Table 2: WHO drinking water quality risk classification

E. coli CFU/100mL	Classification
<1	Conforms
1-10	Low risk
11-100	Medium risk
101-1000	High risk
>1000	Very high risk

To maximize health gains, a technology that works must also be used consistently to improve drinking water quality (Brown and Clasen 2012). Metrics used to evaluate the potential impact of HWT technologies include reported use, confirmed use and effective use (Lantagne and Clasen 2012). Reported use is calculated as the percentage of the surveyed population that provides a drinking water sample and self-reports it was treated. Confirmed use is the percentage of the surveyed population that reports and demonstrates use (i.e. technology is observed or disinfectant residual is measured in the treated water), and effective use is the percentage of the surveyed population that meets reported use criteria and uses HWT to improve untreated water from ≥1 *E. coli* coliform forming units (CFU)/100mL to <1 *E. coli* CFU/100mL in treated drinking water. Effective use can also be calculated using 10 *E. coli* CFU/100mL as a low-risk metric (WHO 2011a). Personal preference and local supply chain characteristics are important factors in HWT selection and use.

1.5 Ceramic water filters

Locally manufactured ceramic 'pot' water filters (CWFs) are an effective HWT technology (Sobsey et al. 2008). The success of CWFs is largely attributed to their being an easy to use, durable product. CWFs are comprised of an ~10L capacity, silver-treated ceramic filter element that suspends in a lidded receptacle. Water is poured into the filter, gravity fed into a safe storage container and dispensed through a tap (Figure 1).

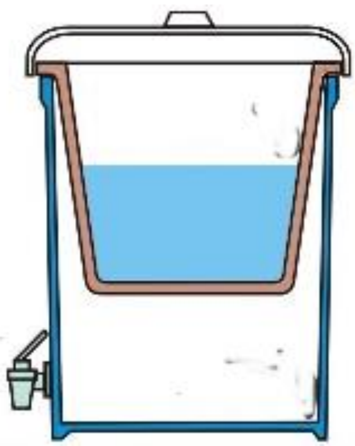

Figure 1: CWF schematic (Potters for Peace)

The technology was invented in 1981 by Lic. Fernando Mazariegos with the aim of developing a household drinking water filter manufactured by local artisans and using locally available materials; thus, it was designed to accommodate variability in materials during manufacture (ICAITI 1980). Originally thrown on a potter's wheel, in 1999 the manufacturing process was mechanized and promoted worldwide by the non-governmental organization Potters for Peace.

Filters are typically manufactured by pressing a pre-determined ratio of locally-sourced clay and burn-out material, such as sawdust or rice husk, into the filter shape. The burn-out material is sieved to control the particle size and during firing, it combusts, thus leaving a porous matrix. After filters are pressed, dried and fired to a ceramic state (~800-900°C) they are tested for quality control. The primary quality control check is a falling-head flow rate test where the volume of water that filters from a full, water-saturated filter in the first hour is measured and expressed as liters per hour (L/hr). Filters that meet factory established flow rate criteria are coated with silver, a known antimicrobial agent, and packaged for sale or distribution (Figure 2-Figure 6, images taken by the author).

The filter mixture ratio is determined by manufacturing batches of filters with different clay to burn-out material ratios. The filters are tested for flow rate and filters from the batch that meet the factory-established flow rate range (typically 1-3 L/hr) are tested for bacteria reduction. The specific recipe of the batch that meets both flow rate and bacteria reduction criteria is then used in production. Since it is not practical to test every filter for bacteria reduction, flow rate is the most commonly used indicator of production consistency (CMWG 2011). Originally, the flow rate guideline of 1-2 L/hr was established as theoretically this would provide the required contact time between the water and silver for disinfection during filtration (Lantagne 2001b). The minimum flow rate is to achieve a minimum rate of water treatment to meet a household's drinking water needs. Currently, the maximum flow rate is a topic of research and debate (CMWG 2011).

Figure 2: Clay and burn-out material processing

Figure 3: Mixing and pressing

Figure 4: Trimming and drying

Figure 5: Firing and flow rate testing

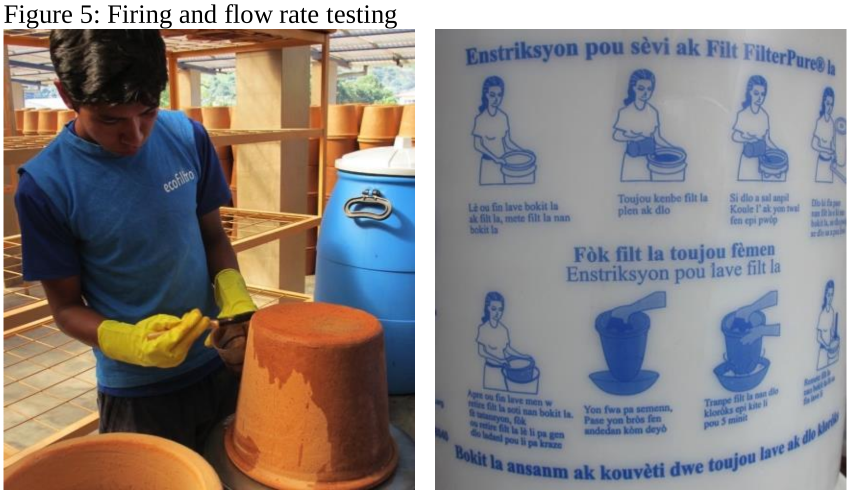

Figure 6: Silver application and receptacle with instructions

In laboratory investigations, CWFs have demonstrated ≥2 log reduction value (LRV) of protozoa and protozoan-sized particles (Lantagne 2001b, Van Halem et al. 2007) and 2-7 LRV of bacterial organisms from drinking water (Lantagne 2001b, Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al. 2007). Virus reduction remains a challenge, with results ranging from <1-2 LRV (Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al. 2007). Thus, CWFs are expected to meet the WHO HWT ‘one star’ performance target as they meet “protective” levels for at least two classes of pathogens.

In situ, water treated by CWFs is often improved to the WHO’s low-risk classification (60-93% of filtered samples) (Brown, Sobsey, and Loomis 2008, Kallman, Oyanedel-Craver, and Smith 2011) of <10 CFU *E. coli* /100 mL (WHO 1997) and filter use has been associated with 49-80% reduction in diarrheal disease (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014).

Ceramic filters are thought to work through a variety of mechanisms. Physical screening, or pore size exclusion, is when the pores in the filter act as a physical barrier to pathogens, organic material and turbidity in the influent water. Filters with smaller pores have a higher removal rate of bacteria (Oyanedel-Craver and Smith 2008); however, filters have been successful at removing micro-organisms smaller than the measured pores; therefore, in addition to screening, mechanisms such as, diffusion, sedimentation and adsorption have been proposed (Van Halem et al. 2007). These processes are influenced by the morphology of the porous matrix, such as the relative distribution of different pore types (Figure 7) and the 'tortuosity' – that creates the actual path the water takes through the porous matrix.

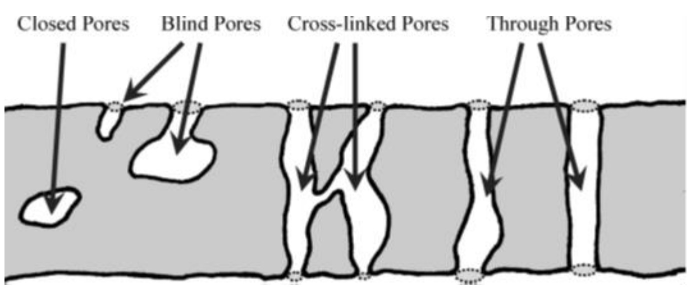

Figure 7: Pore types
(Giesche 2006)

Additionally, silver added to ceramic filters contributes to the microbiological removal effectiveness (Van Halem et al. 2007, Oyanedel-Craver and Smith 2008) by disinfection (Oyanedel-Craver and Smith 2008) and may also inhibit biological growth from forming on the filters and in the water storage containers (receptacles) (Bloem et al. 2009).

Over the past decades, locally produced CWFs have gained recognition and popularity as an appropriate technology for HWT and are currently manufactured at >50 independently run factories (Rayner, Skinner, and Lantagne 2013). The findings of a survey of filter factories found that manufacturing and quality control protocols vary widely both between and within factories, including: 1) criteria for modifying filter mixture ratio; 2) flow rate criteria and test protocols; 3) amount and type of silver applied; and, 4) bacteria reduction test protocols (Rayner, Skinner, and Lantagne 2013). These findings, in combination with reports of poor quality filters reaching households (Kallman, Oyanedel-Craver, and Smith 2011, Lemons et al. 2016) lead to concerns about the consistency of filter quality.

The Ceramics Manufacturing Working Group (CMWG), comprised of members of government, academia, non-governmental organizations and filter manufacturers, was formed in 2009 in response to recommendations by attendees of the first International Conference on Ceramic Pot Filters in Atlanta, GA, USA that minimum standards in filter production be established. The overarching objective of the working group is to, "provide guidance to assist filter factories in producing the lowest-cost, most-effective ceramic filters possible". The output was a set of consensus-based manufacturing guidelines: *Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment* (CMWG 2011). In addition to manufacturing guidelines, the CMWG identified needs for research to fill knowledge gaps.

1.6 Research objectives

The overarching objective of this research was to address previously identified research needs (CMWG 2011), to further guide manufacturing recommendations and to facilitate and support the consistent production of high quality filters. To achieve this, five research projects were carried out, which comprise of chapters 2-6 of this dissertation, and are described briefly below.

Chapter 2 - *Laboratory investigation into the effect of silver application on the bacterial removal efficacy of filter material for use on locally-produced ceramic water filters for household drinking water treatment*

This laboratory study evaluated the performance of different silver types and different silver concentrations applied to ceramic disks manufactured with different clays and burn-out materials and with different influent water chemistries.

Chapter 3 - *The effects of input materials on ceramic water filter efficacy for household drinking water treatment*

This laboratory study was an exploratory investigation into the influence of input materials such as clay, burn-out type, burn-out processing and filter mixture ratio on filter characteristics, flow rate and bacteria LRV.

Chapter 4 - *Evaluation of household drinking water filter distributions in Haiti*

This field research evaluated five programs that distributed biosand, ceramic, or Sawyer filters in Haiti after the 2010 earthquake and cholera outbreak. Two of the filter programs distributed CWFs manufactured at different factories.

Chapter 5 - *Developing a Framework to Evaluate Quality Control Protocols of Ceramic Filter Factories*

A framework for evaluating quality control protocols in CWF manufacturing was developed by developing assessment tools, visiting factories, observing and documenting production and testing filters for flow rate and *E. coli* $\log_{10}$ reduction value.

Chapter 6 - *A Systematic Review of Ceramic 'Pot' Filter Effectiveness for Drinking Water Treatment*

A systematic review of the CWF literature was carried out to synthesize research findings on CWF effectiveness with regards to laboratory efficacy, effectiveness during use and health impact, with a specific focus on materials and manufacturing processes during production.

Each of these projects are presented in the subsequent chapters of the dissertation. The dissertation concludes with a discussion and conclusions section.

2 Laboratory investigation into the effect of silver application on the bacterial removal efficacy of filter material for use on locally-produced ceramic water filters for household drinking water treatment

2.1 Abstract

Locally produced ceramic water filters (CWF) are an effective technology to treat pathogen-contaminated drinking water at the household level. CWF manufacturers apply silver to filters during production; although the silver type and concentration vary and evidence-based silver application guidelines have not been established. We evaluated the effects of three concentrations of two silver species on effluent silver concentration, *E. coli* removal and viable bacteria retained on the surface and contained in the pores of ceramic disks manufactured with clay imported from three CWF factories using sawdust as the burn-out material. Additionally, we evaluated performance using water with three chemistry characteristics (Na^+-NaCl, Ca^{2+}-$CaCl_2$ and humic acid as natural organic matter) of disks made from the different clays using either sawdust or rice husk as burn-out material. Results showed: 1) silver desorption from disks coated with silver nitrate (Ag^+) was greater than desorption of silver nanoparticles (nAg) for all disks; 2) effluent concentration, *E. coli* removal and viable bacteria retained in disk formation inside the disks were dose-dependent on the amount of silver applied; and, 3) neither water chemistry conditions (inorganic or organic compounds) nor burn-out material showed an effect on any of the parameters evaluated at the silver concentration tested. The recommendation for filter manufacturers to use only nAg and at a higher concentration than currently recommended is discussed.

2.2 Introduction

Worldwide, an estimated 783 million people do not have access to an improved water source (WHO/UNICEF 2012), and hundreds of millions more drink water that is contaminated at the source or during collection, transport or storage (Clasen and Bastable 2003). Drinking water contaminated by pathogenic microorganisms causes gastrointestinal infections, which account for 1.87 million childhood deaths each year, mostly in developing countries (Boschi-Pinto, Velebit, and Shibuya 2008). Potters for Peace (PFP) style ceramic water filters (CWF) are a low-cost technology produced at independently owned factories in developing countries by pressing a mixture of clay and an organic (burn-out) material into the filter shape and then firing it to a ceramic state. Combustion of the burn-out material during the firing process creates the porous structure. CWFs remove pathogens from water by retaining them on the surface or trapping them within the filter pores.

CWFs are effective at removing more than 99% of protozoan (Lantagne 2001b, Van Halem et al. 2007) and 90-99.99% of bacterial organisms from drinking water (Brown and Sobsey 2010); however, the removal of viruses remains a challenge. In the field, water treated by CWFs is often improved to the World Health Organization's (WHO) low-risk classification (WHO 1997) of fewer than 10 CFU *E. coli* /100 mL, (Brown and Sobsey 2010, Roberts 2004) and filter use has been associated with a reduction in diarrheal disease among users (Brown, Sobsey, and Loomis 2008).

Silver nanoparticles (nAg) and silver nitrate ($AgNO^3$, Ag^+) are known anti-microbial agents, and are added to filters at all factories, mostly after the firing process (Oyanedel-Craver and Smith 2008). Reported *E. coli* log reduction values (LRVs) by CWFs coated with nAg range from 2.5 to 4.56. (Kallman, Oyanedel-Craver, and Smith 2011, Oyanedel-Craver and Smith 2008) LRVs of 2.1 to 2.4 of *E. coli* have been measured using filters coated with Ag^+; however, in the same study similar LRVs were also measured in CWFs without Ag^+ application (Brown and Sobsey 2010).

In production, 83% of factories use nAg and 17% use Ag^+ (Rayner, Skinner, and Lantagne 2013). Some factories use Ag^+ because it is cheaper than nAg and/or it is locally available. The concentration of silver applied at each factory varies. Reported nAg concentrations range from 107 to 288 ppm (Rayner, Skinner, and Lantagne 2013), excluding probable outliers. The silver solution is applied to fired filters by brushing or dipping. When applied with a brush, the volume and concentration of silver can be measured, whereas when filters are dipped, the amount of silver absorbed by the filter is not controlled. Factories reported applying from 32 to 96 mg of nAg per filter when applied by brushing. The current guideline, which is experiential rather than evidence based, is 64 mg of nAg per filter (CMWG 2011).

A variety of water sources are used at factories to prepare silver solutions, from untreated surface water to treated water (Rayner, Skinner, and Lantagne 2013). Water characteristics at the filter user's home will also vary. Previous studies have reported a reduction in antibacterial properties of nAg with increased size of the nanoparticle clusters due to aggregation in the presence of divalent ions such as Ca^+ and magnesium ions (Mg^+) (Zhang and Oyanedel-Craver 2011, Zhang, Smith, and Oyanedel-Craver 2012). In addition, water can contain organic compounds, such as humic acid (HA). These can rapidly coat the nanoparticle surfaces creating a physical barrier that prevents interaction between nanoparticles and bacteria (Zhang and Oyanedel-Craver 2011, Zhang, Smith, and Oyanedel-Craver 2012, Fabrega et al. 2009). While previous studies have reported that different water chemistry conditions can impact the disinfection performance of nAg in the aqueous phase, these parameters have not been evaluated on CWFs either in the field or in laboratory tests.

Desorption of silver from coated CWFs has been reported during the first flushes of water (Oyanedel-Craver and Smith 2008). A study using phosphate buffer as influent solution reported a decrease in silver concentration in effluent from nAg-impregnated CWFs to below the United States Environmental Protection Agency (USEPA) maximum contaminant level (MCL) for silver in drinking water (0.1 mg/L or 100 ppb) (USEPA 2011) within a few flushes (Oyanedel-Craver and Smith 2008). To our knowledge, no comprehensive study has evaluated desorption of either nAg or Ag^+ from CWFs using different clays and water chemistry conditions.

This research aimed to address some of the silver-related research needs outlined in the *Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment* (CMWG 2011). The objective was to develop evidence-based recommendations for silver type, concentration and dilution water characteristics that take into consideration variation in local material characteristics and potential silver exposure for filter users. In this study, we evaluated the performance of ceramic disks manufactured with clays from three different factories and two types of burn-out material, sawdust and rice husks. In Phase I, disks manufactured with the different clays and sawdust were coated with three different concentrations of either nAg or Ag^+ and evaluated for: 1) effluent silver concentration and silver retention; 2) *E. coli* removal; and, 3) viable bacteria retained in disks. In Phase II, the influence of three water chemistries (Na^+-NaCl, Ca^{2+}-$CaCl_2$ and humic acid as natural organic matter) on nAg and Ag^+ were evaluated on disks manufactured with each of the clays and each of the burn-out materials against the same outcome parameters.

2.3 Methods

2.3.1 Disk manufacturing and pretreatment

While PFP-style filters are ~10-liter capacity filter pots, in this study 10-cm diameter disks were manufactured to simplify manufacturing, transport and testing. Disks were manufactured at Advanced Ceramics Manufacturing (Tucson, AZ) with clay imported from filter factories in Indonesia (Indo), Tanzania (Tanz) and Nicaragua (Nica). Factories were selected for geographical distribution, variation in manufacturing methods and willingness to ship clay (Rayner, Skinner, and Lantagne 2013). The burn-out material, either saw dust or rice husk as they are the primary burn-out materials used at factories (Rayner, Skinner, and Lantagne 2013), was purchased in Arizona and processed between U.S. sieve numbers 16 and 30 (1.19-mm and 0.595-mm openings, respectively). It comprised 15%, burn-out to clay ratio by weight, of the filter mixture. Disks were pressed at 3.58 PSI and air-dried. In order to achieve sufficient strength for testing, the Indonesian clay disks were fired to 800°C peak firing temperature held for 180 minutes (800°C/180min), Tanzanian to 950°C/60min and Nicaraguan to 1085°C/60min. Fired disk thickness was ~1.5 cm. Once fired, disks were boiled in water for one hour and the percent porosity of each disk was calculated by dividing the difference between saturated weight and dry weight by the geometric disk volume.

Disks were shipped to the University of Rhode Island (URI) where they were cut to 3.8cm diameter to fit filter holders. To eliminate any possible microbiological contamination, disks were heat treated to 550°C /30min, then allowed to cool at room temperature. The sides of the disks were sealed with silicone, allowed to dry and then sealed in the filter holders with silicone. All tests were performed in duplicate.

2.3.2 Disk characterization

Tracer experiments were conducted to determine the intrinsic characteristics of the disks and to identify possible anomalies in the porous matrix. Tracer tests and the subsequent determination of the advection and dispersion coefficients were performed using the procedure described in Oyanedel-Craver et al. (2008) but with NaCl as conservative tracer instead of tritiated water.

2.3.3 Study phases

This study was carried out in two phases. In both phases, tests were conducted in duplicate, using two disks of each recipe. In Phase I, the effects of different concentrations of each type of silver on disks manufactured with sawdust and each of the clays was evaluated using a phosphate buffer solution. This was selected to minimize natural decay of bacteria during the test period. Only disks manufactured with sawdust were tested in Phase I due to limited availability of rice husk disks.

In Phase II, the influence of three water chemistries, selected to mimic the ionic strength and organic carbon content in natural water, was evaluated with each of the silver types on disks manufactured with each of the clays and each of the burn-out materials (Table 3). In Phase II, disks manufactured with sawdust or rice husk and each of the clays were tested. The silver concentration was selected to minimize the effect of residual silver, on bacteria deactivation.

Table 3: Experimental conditions

Study Phase	Burn-out Material	Silver (nAg* or Ag^{+}**) concentration (mg/g***)	Water characteristics
I	Sawdust	0.003	10% phosphate buffer solution
		0.03	
		0.3	
II	Sawdust or rice husk	0.003	150 mg/L Na^{+}-NaCl
		0.003	150 mg/L Ca^{2+}-NaCl
		0.003	5 mg/L humic acid as total organic carbon

*Silver nanoparticles, **ionic silver and *** milligrams of silver per gram of disk

2.3.4 Silver release and retention

Suspended silver nanoparticles (nAg) (70 % silver) was purchased from Laboratorios Argenol and dissolved silver (Ag^{+}) from Sigma Aldrich. The majority of CWF factories use Argenol silver nanoparticles (CMWG 2011). The few factories that use Ag^{+} purchase it from a variety of sources. Silver was applied by brushing each disk with a specific concentration of either nAg or Ag^{+} in the appropriate electrolyte solution according to the procedure described in Oyanedel-Craver et al (Oyanedel-Craver and Smith 2008). Physicochemical characterization details of nAg using the different water chemistry conditions are presented in section 2.6 in the supporting information. These results are similar to results from other studies performed by the authors and other researchers (Huynh and Chen 2011, Thio, Zhou, and Keller 2011, Hotze, Phenrat, and Lowry 2010, Zhang and Oyanedel-Craver 2011), and show the impact that divalent ions have on the stability of nanoparticles suspensions. When Ca^{2+} was used as electrolyte solution the nanoparticles aggregated, forming clusters with an average hydrodynamic diameter three times greater than in the other solutions.

Disks were then flushed with a bacteria-free solution for 24 hours. After preserving samples by adding 2% nitric acid, effluent silver concentration was measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES) after 100 minutes, 200 minutes, 300 minutes, and at 24 hours. Percent retention of silver was calculated by dividing the difference between the mass of silver applied and the mass of silver released by the initial amount of silver added to the disk and then multiplying by 100 to obtain the percent value.

2.3.5 Bacterial removal performance

After 24 hours of flushing with a bacteria free solution, a concentration of 10^6 CFU/mL *E. coli* was prepared in water of the same chemical composition as used during the flushing stage (i.e., deionized water with a buffer solution, electrolytes, or humic acid) and continuously fed to the disks at a flow rate of 0.5 mL/min using a peristaltic pump. A fresh solution of bacteria was prepared daily for both Phase I and Phase II testing. Samples were taken daily for 10 days and LRVs were calculated. The concentration of bacteria in the influent and effluent were measured using membrane separation followed by an incubation period in m-FC, specific substrate media (Millipore, Inc) and colonies were counted after 24 hrs. A more detailed description of the procedure (Vigeant et al. 2002) is presented in the supporting information.

At a feed of 0.5 mL/min for 10 days, the total throughput for each disk over the study period was ~7.2 L, which equates to ~1300 L through a full-sized filter. This was calculated by multiplying the flow rate per cm^2 of the filter disk by the area of a full-sized Nicaraguan filter using filter dimensions presented in van Halem (Van Halem et al. 2007). Using this calculation, the 10 day test period simulated approximately four months of a filter treating 10 L of water per day.

2.3.6 Bacteria retention

After completing the bacterial removal tests, the concentration of viable bacteria retained on the surface and contained in the pores of the disks was determined. The disks were ground and 10 grams were transferred to a 50-ml flask. The bacteria were dispersed in the buffer solution by gentle sonication for 15 minutes to detach the bacteria from the ceramic material. The concentration of bacteria was determined using Vigeant et al. (2002) as described above (additional method details are provided in the supporting information).

2.4 Results

2.4.1 Disks characterization

A total of 144 disks were tested, including 30 each of Indo-sawdust, Tanz-sawdust and Nica-sawdust, and 18 each of Indo-rice husk, Tanz-rice husk and Nica-rice husk. The average advection (v) (directly proportional to the fluid velocity) and dispersion (D) (directly proportional to the effective porosity) coefficients and geometric porosity values for the ceramic disks manufactured from the same recipe were similar (Table 4). Results from disks manufactured with Indonesian and Tanzanian clays were also similar; however, disks manufactured with the Nicaraguan clay had higher advection and dispersion coefficients, indicating that the solute spread fastest through the Nicaraguan disks. For each of the clay groups, disks manufactured with rice husk had slightly lower porosities than disks manufactured with sawdust. This is likely because rice husk is denser than sawdust, so the same mass would result in a smaller volume ratio.

Table 4: Physical properties of ceramic disks

Clay source & Burn-out material	Firing temp. & soak (°C/min)	Advection coefficient (cm/min)	Dispersion coefficient (cm^2/min)	Geometric Porosity (%)
Indonesia-sawdust	800/180	0.06±0.01	0.01±0.01	57±1.5
Tanzania-sawdust	950/60	0.06±0.01	0.01±0.00	59±1.8
Nicaragua-sawdust	1085/60	0.09±0.01	0.05±0.03	54±1.5
Indonesia-rice husk	800/180	0.05±0.01	0.01±0.00	54±0.5
Tanzania-rice husk	950/60	0.06±0.01	0.01±0.00	54±1.3
Nicaragua-rice husk	1085/60	0.10±0.01	0.09±0.05	49±1.6

2.4.2 Phase I

2.4.2.1 Silver release and retention

For both types of silver and regardless of clay type, a higher concentration of silver was measured in effluent from disks coated with higher concentrations of silver (Figure 8). With the exception of 0.003 mg/g of silver, for each of the silver concentrations applied a higher effluent concentration of Ag^+ was measured in comparison with nAg. Silver concentration in the effluent reduced with solution throughput regardless of silver type. Effluent silver concentration from nAg-coated disks was below the USEPA MCL after 24 hours in all but one case (disks made with Nicaraguan clay and impregnated with 0.3 mg/g nAg). After 24 hours, the effluent concentration from disks impregnated with 0.3 mg/g Ag^+ exceeded the USEPA's MCL in all cases and ranged from 797 ppb to 2,697 ppb. Specific effluent values are presented in the supporting information in section 2.6.

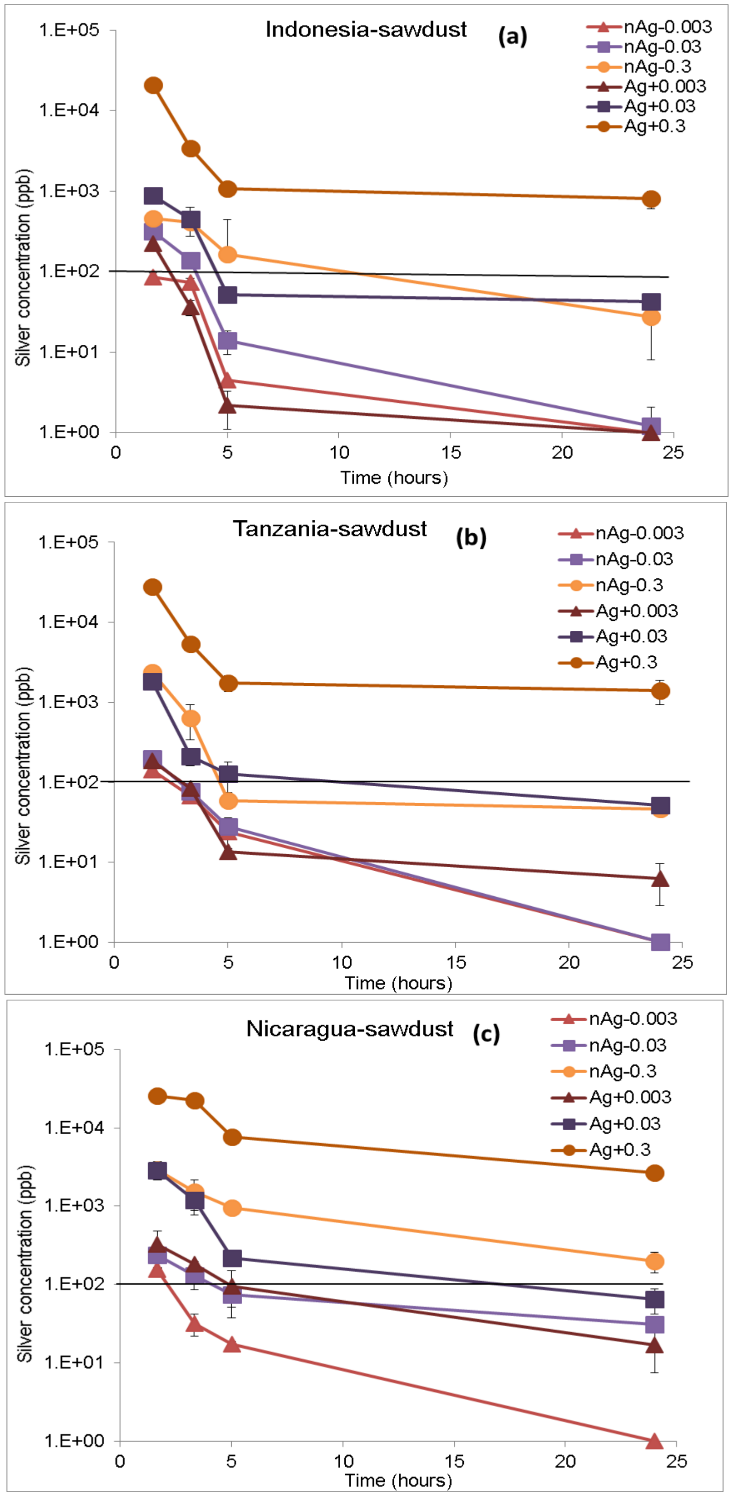

Figure 8: Silver concentration in effluent from disks manufactured with Indonesian (a), Tanzanian (b), or Nicaraguan (c) clay and sawdust (with standard error bars), coated with different concentrations (mg/g) of either nAg or Ag^{+} (horizontal line at 1.E+02 represents USEPA MCL for silver)

An increased concentration of silver resulted in increased silver retention in disks coated with nAg regardless of clay type (Figure 9). nAg retention did not vary widely between disks made with different clays. A greater percentage of nAg was retained in disks in comparison with Ag^+, most notably in disks made with Nicaraguan clay. A greater difference in Ag^+ retention between the different clays was observed. An increase in Ag^+ concentration from 0.003 mg/g to 0.03 mg/g resulted in increased retention; however, the highest concentration of Ag^+ 0.3 mg/g resulted in the lowest percent retention.

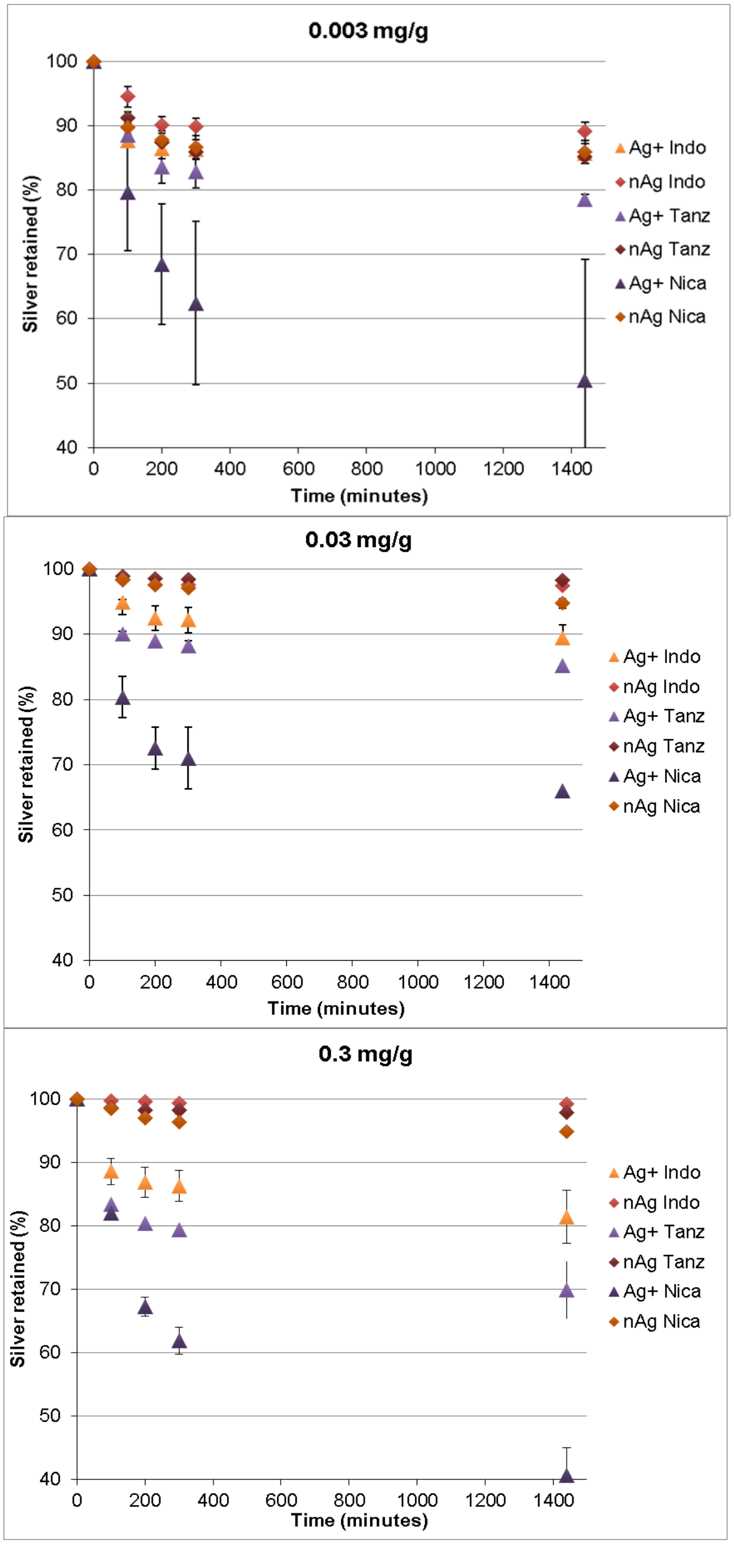

Figure 9: Percent silver retention and standard error over time in disks manufactured with different clays and sawdust coated with different silver species and concentrations (mg/g).

2.4.2.2 Bacterial removal performance

In all samples, a sharp reduction in LRV was observed from day one to four of continued 0.5 mL/min throughput (Figure 10), which would be the equivalent to 520L through a full-sized filter; however, the LRV leveled off from day five. Thus, the LRV performance comparison is based on an average of the results from the last six days (days 5-10) of testing, the equivalent to an additional 780L full-sized filter throughput.

Disks made with Indonesian and Tanzanian clays demonstrated an increased LRV with increased silver concentration, regardless of species applied (Figure 10). No change in LRV was measured from Nicaraguan disks regardless of silver species or concentration applied. LRVs were similar in terms of evolution as a function of time and magnitude between disks coated with nAg and Ag^+, with the exception of 0.3 mg/g Ag^+ which achieved the highest LRV in both Tanzanian and Indonesian disks.

Disks made with either Indonesian or Tanzanian clay and coated with 0.3 mg/g nAg achieved >4 LRV on the 10th day of testing (1-1.7 LRV improvement, respectively, over control disks without silver). A less than 1 LRV improvement was measured over the control disks with 0.03 mg/g of either silver. Disks coated with 0.003 mg/g of silver showed little or no improvement in LRV in comparison with the control disks by the 10th day of testing.

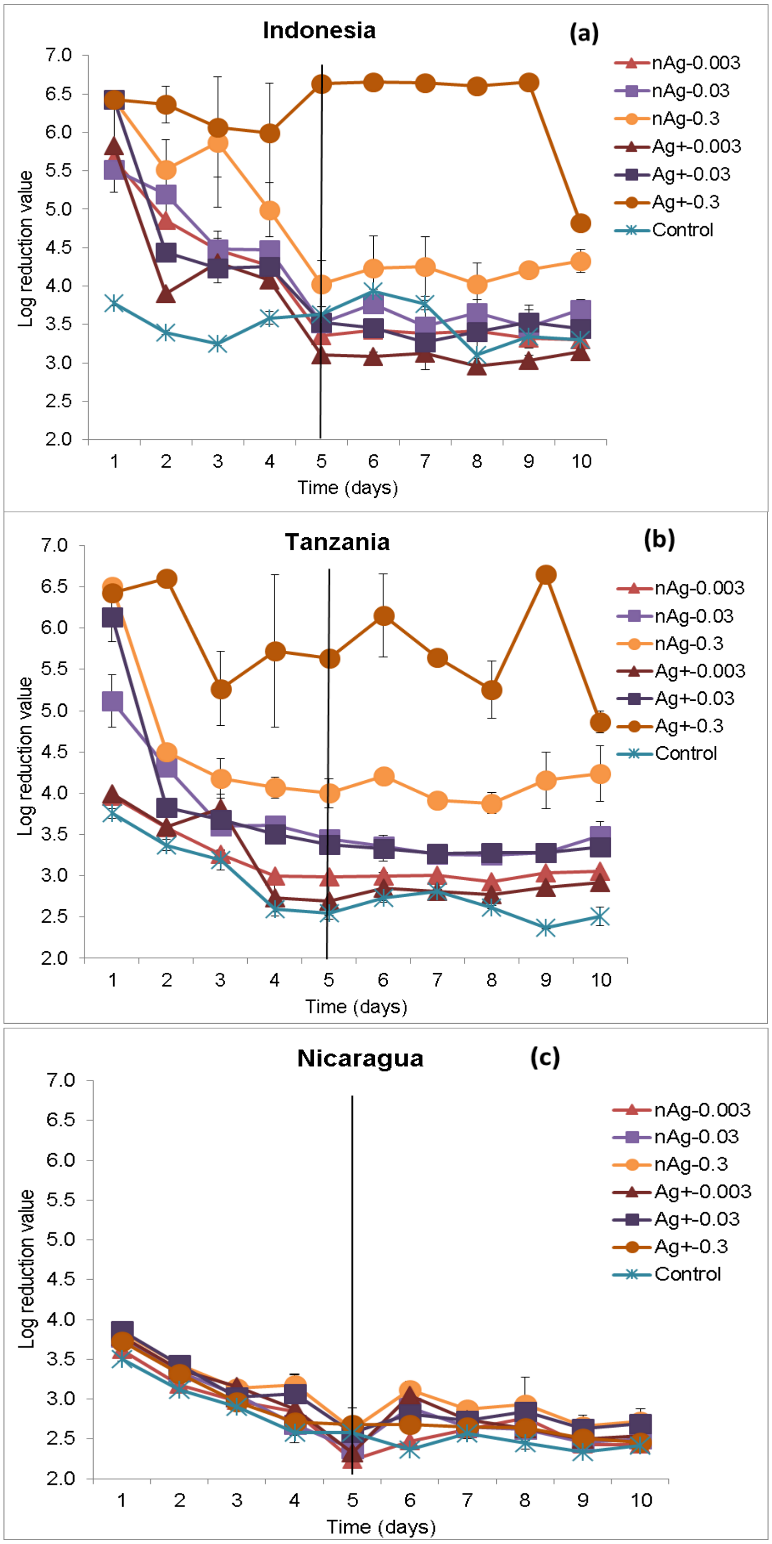

Figure 10: LRV of disks manufactured from Indonesian (a), Tanzanian (b) and Nicaraguan (c) clay (with standard error bars) and sawdust coated with varying amounts (mg/g) of either nAg or Ag^{+}. Vertical lines indicate the 5th day of operation.

2.4.2.3 Viable bacteria retention

The concentration of viable bacteria measured from the disks decreased with increased silver concentration of either nAg or Ag^+; however, disks made with Nicaraguan clay showed little difference (Figure 11). This could be a result of bacteria accumulation in the possibly larger pores in the Nicaraguan disks. Disks impregnated with either nAg or Ag^+ resulted in similar bacteria concentration reduction per silver concentration applied, although disks coated with 0.3 mg/g of nAg had fewer viable bacteria than Ag^+. Negligible changes were detected between the amount of viable bacteria remaining in disks coated with 0.003 mg/g of either silver species and the control groups (without silver application) regardless of clay type.

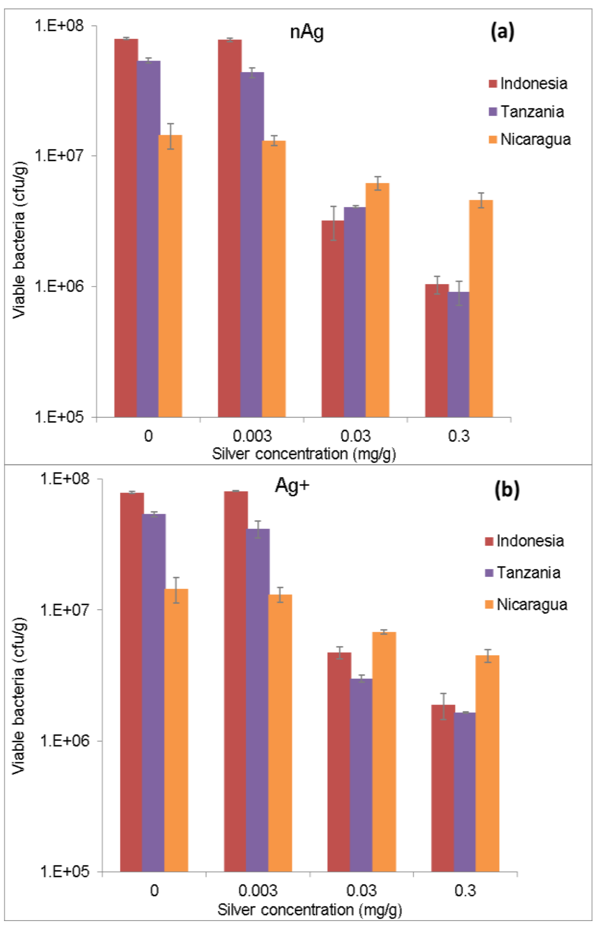

Figure 11: Viable bacteria detected in disks (with standard error bars) manufactured with sawdust coated with varying amounts of nAg (a) or Ag^+ (b)

2.4.3 Phase II

2.4.3.1 Effect of water chemical composition and burn-out material

Effluent concentration of silver from disks manufactured with rice husk or sawdust with 0.003 mg/g of either silver was below the MCL value of 100 ppb after 300 minutes of throughput with each water chemistry. See supporting information in section 2.6. Variation in influent water characteristics resulted in little difference in silver retention among disks treated with nAg (see supporting information in section 2.6). In disks coated with Ag^+, there was some variability in silver retention in disks manufactured with Tanzanian and Nicaraguan clays when HA was used as the influent solution. A difference in silver retention was not observed between disks manufactured with the same clay but different burn-out materials.

For each clay, LRVs were in the same magnitude range regardless of influent water chemistry applied, the silver type or the burn-out material used (see supporting information in section 2.6). The amount of viable bacteria retained in disks coated with nAg or Ag^+ was within the same order of magnitude regardless of the influent water chemistry conditions or burn-out material (see supporting information in section 2.6). The amount of viable bacteria retained in disks manufactured with clay from Nicaragua was almost an order of magnitude less than disks made with either Indonesian or Tanzanian clays regardless of silver type or influent water chemistry.

2.5 Conclusions and Discussion

In this study, nAg and Ag^+ performance at varying concentrations in disks manufactured with clays from different filter factories was evaluated. Additionally, silver was evaluated using different water chemistries on disks manufactured with different clays and different burn-out materials. Disks were used as a model for full-sized filters due to space, time and laboratory constraints. The continuous flow rate was controlled at 0.5 mL/min to simulate four months of household use, which is possibly the longest lab-scale materials evaluation on CWFs to be carried out to date. The main difference between our manufacturing specifications and full-sized filter manufacturing was the criteria used. At CWF factories, filter mixture recipes are established by selecting a ratio and firing temperature that, using the locally available materials, result in filters that meet specific quality criteria such as flow rate, LRV and strength. In this study, rather than manufacture filter disks that met factory quality criteria, the ratio of clay to burn-out material was held constant regardless of the clay origin or burn-out type in order to control variables except for silver application. In order to achieve enough strength for testing however, the firing temperature was adjusted for each clay. A protocol for establishing or evaluating firing temperature at filter factories has not been developed and peak firing temperature ranges from 800°C-980°C. Little research has been carried out on the effects of firing temperature on filter characteristics and while its importance is recognized, firing temperature evaluation was beyond the scope of this research. Disks manufactured with the different clays likely varied in structure due to variability in the clay, burn-out material type and firing temperature.

Disks manufactured from Indonesian and Tanzanian clays had comparable advection and dispersion results and their porosity and strength were suitable for testing. The higher advection and dispersion coefficients in disks manufactured with Nicaraguan clay suggested the solute spread faster, possibly due to larger or more interconnected pores. The Nicaraguan clay was exceptionally challenging to work with during manufacturing and the firing temperature (1085°C) likely resulted in excessive vitrification (over-fired) in comparison with filters. A separate particle size analysis was carried out on samples of the raw clays used in this research by taking periodic density measurements of a soil and water suspension. The United States Department of Agriculture (USDA) particle size classification system was used to ascertain the relative sand, silt and clay content. Results showed that the material from Nicaragua had a very low clay (<2 micron) content in comparison with the Tanzanian and Indonesians clays (0.5%, 28.5% and 31%, respectively) (Duocastella and Morrill 2012). Results from the Nicaraguan disks should therefore be interpreted with caution in this study.

The results of our study showed: 1) increased desorption of Ag^+ compared with nAg; 2) a difference between effectiveness of nAg and Ag^+; 3) variation in LRV of *E. coli* depending upon silver concentration; 4) a difference in the amount of viable bacteria remaining in disks depending upon silver concentration; and, 4) at the concentrations tested, no impact of water chemistry on the efficacy of silver. These results are discussed in the following paragraphs.

Using phosphate buffer influent, disks retained nAg more efficiently that Ag^+. Desorption of nAg ranged from 5% to 10% for all disks tested, while for Ag^+, 10% to 30% desorbed from Tanzanian and Indonesian clay disks and 30% to 40% from Nicaraguan clay disks. This effect has been reported by other authors who evaluated sorption of silver species on unfired clays using batch systems with equilibrium time of 24 hours (Matsumura, Yoshikata, and Tsuchido 2003). Ag^+ can be displaced by cations with higher valence or higher charge density, while nAg are trapped in the nano- and micro- porous structure of the filter allowing for a slow release of silver ions as the surface of the nanoparticles is oxidized by the dissolved oxygen in water (Li, Lenhart, and Walker 2010). With the exception of disks manufactured with Nicaraguan clay, after 24 hours the concentration of nAg in filter effluent was below the EPA MCL for each concentration tested, therefore safer for users and compliant under the current drinking water recommendation. The concentrations released from nAg coated disks after 24 hrs of operation were similar to results presented in other laboratory studies using full-sized CWFs (Van Halem et al. 2007, Bielefeldt, Kowalski, and Summers 2009, Bielefeldt et al. 2010), with the exception of the 0.3mg/g dose that would require more flushing to achieve acceptable levels of silver in treated water.

A rough projection of how long silver could potentially last in filters if the same amount of silver measured in the effluent at 24 hours continued to release over time at the same rate was calculated. Since the concentration of silver after 24 hours of operation was used as end point of concentration released, these estimations of the time needed to exhaust the silver are conservative. Results are presented in the supporting information in section 2.6. At the application strength of 0.003 mg/g, nAg or Ag^{+} could last for less than 4 years in the filter regardless of influent characteristics. At 0.03 and 0.3 mg/g of nAg, the silver could last in filters for more than 8 years; whereas, the application of Ag^{+} at 0.03 and 0.3 mg/g could last for less than 1 year. The calculation methods and assumptions of this projection are presented in the supporting information.

While little change in LRV was measured regardless of the type or concentration of silver applied in Nicaraguan disks, with the Indonesian and Tanzanian clays, for either silver species, a dose-response relationship was observed: an increased concentration of silver resulted in increased LRV of *E. coli*. Disks coated with 0.3 mg/g Ag^{+} resulted in the highest LRV; however, this was likely the effect of the high concentration of silver in the effluent (one order of magnitude above the EPA MCL) and therefore bacteria deactivation was partially achieved by the high concentration of residual silver in the effluent rather than contact with the silver sorbed/trapped in the porous structure of the disks. With lower concentrations of silver, comparable bacterial reduction was achieved between nAg and Ag^{+}; however, less silver was measured in the effluent of disks coated with nAg. The application of high concentrations of Ag^+ in filters causes concern about: 1) the time that Ag^+ remains in the filter material, thus having implications on the length of time silver can impact filter efficacy; and, 2) potential health consequences associated with ingestion of elevated concentrations of Ag^+ by filter users.

The application of 0.003 mg/g of either silver did not demonstrate improved LRV over the control disks (without silver) after 10 days of testing (equivalent to 1300 L throughput in a full-sized filter). This data is consistent with another study that compared CWF performance with and without Ag^+ application (Brown and Sobsey 2010). In disks manufactured with Indonesian and Tanzanian clays, in comparison with the control group, 0.03 mg/g of nAg resulted in a 0.4 and 1.0 LRV improvement, and 0.3 mg/g of nAg resulted in a 1 and 1.7 LRV by the 10th day of testing, respectively. Disks made from Indonesian and Tanzanian clays coated with 0.3 mg/g achieved similar LRVs (>4) on the 10th day of testing. The application of nAg resulted in a slightly greater improvement in LRV for the Tanzanian disks than the Indonesian disks.

The viable bacteria quantification both on the surface and inside the disks supports and expands upon the LRV results. An increase in silver concentration resulted in reduced viable bacteria retained in disks; and, disks with a higher concentration of nAg retained fewer viable bacteria than disks with a higher concentration of Ag^+. The results of this study demonstrated that a silver coating reduces, by up to two orders of magnitude, the viable bacteria retention in disks. To our knowledge this is the first study providing quantitative information about viable bacteria retention inside ceramic filter material.

Phase II focused on evaluating the impact of: 1) inorganic and organic compounds present in natural water; and, 2) burn-out materials, on silver sorption, bacterial removal and viable bacteria retained in disks. The silver concentration (0.003 mg/g) used in this phase was selected to minimize the effect of residual silver (silver in the filtrate), either nAg or Ag^+, on bacteria deactivation. At the selected test conditions, a difference was not observed between the clays, burn-out material, or the silver species with the water chemistries evaluated in terms of silver retention, LRV or concentration of viable bacteria remaining in the disks. This could be due to the low concentration of silver used, as little impact was seen at this concentration using phosphate buffered water, and several other studies have shown the influence of the chemical characteristics of the solution on nAg aggregate size (Li, Lenhart, and Walker 2010, Zhang, Smith, and Oyanedel-Craver 2012). Based on current knowledge about the aggregation of nanoparticles in different electrolyte solutions, water containing a low concentration of divalent ions (soft water) should be used to prepare the silver solution used to coat filters. Additionally, the presence of natural organic matter, such as humic acids, can reduce the antimicrobial properties of nAg as they can interact with the surface of the nanoparticles, reduce silver ion release and prevent direct contact between the nanoparticles and the bacteria (Gao et al. 2009, Gao et al. 2012).

Recommendations resulting from this research include: 1) factories should use nAg rather than Ag^+ due to better silver retention. Ag^+ is not recommended for filter application as it can lead to silver concentrations that exceed guideline values in filtered water; 2) factories could increase the nAg concentration to 0.3 mg/g (approximately 640 mg/filter) to achieve improved microbiological performance without compromising the quality of filter effluent; and, 3) although this study did not show significant differences in terms of performance with water chemistry, evidence from other studies suggest that organic and inorganic compounds present in natural water can affect nAg performance and therefore, soft water should be used in silver solution preparation.

We recognize that these results and recommendations will have an impact on factories. Ag^+ is locally available and significantly cheaper in some countries (however, in some cases information about quality or concentration may not be available); and, in some cases importing nAg can be a challenge. Therefore, the recommendation to use only nAg and to increase nAg concentration by 10 times the current recommendation will add a cost burden to the manufacturers. The cost of silver nanoparticles from Argenol Laboratorios has increased to €1,400.00/kg (70% total silver). Implementing this recommendation would result in an increase in cost from €0.13 to €1.30 per filter. The manufacture of high quality filter material will remain important in achieving high performing filters and while silver application improves bacteriological removal effectiveness, the lower concentrations showed little improvement over disks without silver.

We also note that previous research has not always documented sufficient detail required to compare research results including type of silver, silver concentration, dilution and throughput water characteristics. In some cases this may be attributable to a lack of documentation or information about silver type or concentration. Previous research should therefore be compared with caution, and future research should attempt to include these details.

The limitations in this study include the use of a controlled 5.4 L/hr flow rate, which is about 2-3 times the flow rate used in the field. This flow rate was selected to achieve throughput equivalent to represent long-term operation within a short period of time. The results could underestimate microbiological performance and either under or overestimate viable bacteria retention due to faster water velocity, constant pressure and reduced contact time between silver and bacteria. The same filter material subject to a slower (1-3 L/hr) flow rate would likely result in similar trends and possibly improved performance.

Extrapolation of results from disks to full-sized filters may be influenced as throughput per cm^2 of filter material may vary. While the volume of water fed through disk material was consistent per cm^2, at the household level continuous exposure to water at different heights in the filter will vary depending upon the pattern of use in each household. Additionally, if structural or hydraulic differences exist between filter base and sides, the disks are more likely similar to a filter base due to the amount and/or direction of pressure applied during manufacture. The flow rate through filter walls and base; however, is likely comparable as approximately 83% more water flowed through the sides than the bottom of two Nicaraguan experimental filters (Lantagne 2001b) and the surface area distribution of a Nicaraguan filter is approximately 81% and 19%, sides and base respectively.

This study identified several key parameters that require more detailed studies, such as silver concentration, the effects of various influent water characteristics and the nature of clay and other manufacturing variables. Future studies should include pressure and hydraulic conductivity measurements of filter material. Further research recommendations include: 1) evaluation of higher concentrations of nAg under a selection of water chemistry conditions to evaluate nanoparticle aggregation and silver particle size distribution in filter effluent; 2) evaluate effects of water characteristics both on silver dilution and filter use (influent solutions); 3) evaluate physicochemical interaction between clay and nAg or Ag^+ on silver sorption and LRV and the influence of these properties and the pore size distribution of the porous matrix; 4) carry out a pore-size comparison between disks with and without silver application; 5) investigate the influence of the amount and direction of pressure applied during manufacturing on pore structure and hydraulic properties to understand whether or how this may influence the extrapolation of results from disks to full-sized filters; 6) characterize the influence of manufacturing variables on pore structure and hydraulic properties, including pore formation resulting from firing temperature, burn-out material size and type and clay characteristics and the influence of these variables on filter criteria including flow rate, microbiological removal and strength; and, 7) work towards the identification of indicator(s) to classify and compare filter material.

2.6 Supporting Information

Table 5: Physicochemical properties of silver nanoparticles at different water chemistry conditions

	Hydrodynamic diameter (nm)	*Zeta potential (mV)*
Ca^{2+}	156 ± 16	-9 ± 2
Na^{+}	35 ± 3	-30 ± 5
HA	35 ± 4	-32 ± 4
Buffer	30 ± 7	-35 ± 6

E. coli growth procedure method description, as per Vigeant et al. (2002)

An aliquot of stock solution of E coli was thawed and used to inoculate 50 ml of autoclaved broth prepared with 10g of tryptone, 5g of NaCl and 1 liter of water. The solution was incubated in a shaker table at 30°C at 150 rpm until the mid-exponential phase of growth was reached. The bacteria were harvested in mid-exponential phase when the optical density of the culture was about 1.0, as measured at a wavelength of 590nm. The bacteria solution was rinsed with phosphate buffer three times. Then the bacteria concentration was determined using a membrane filtration method in order to prepare the appropriate solutions at the different conditions tested in phase I and II.

Phase I Silver concentration in effluent

Table 6: Silver concentration in effluent over time from disks coated with different concentrations of silver

Disk material	*Silver type*	*Concent-ration (mg/g)*	*Silver in effluent (ppb) over time (min) and estimated equivalent time (days) and throughput (Liters) in full-sized filter*			
			100 min <1 day 9 L	200 min <2 days 18 L	300 min ~2.5 days 27 L	1440 min ~12 days 130 L
Indonesia-Sawdust	nAg	0.003	86	73	4	ND
		0.03	314	139	14	1
		0.3	456	407	165	27
	Ag^+	0.003	223	36	2	ND
		0.03	887	449	52	42
		0.3	20935	3368	1063	797
Tanz-Sawdust	nAg	0.003	141	67	24	ND
		0.03	198	78	28	ND
		0.3	2377	634	59	46
	Ag^+	0.003	187	84	14	6
		0.03	1816	209	127	51
		0.3	27705	5404	1751	1414
Nica-Sawdust	nAg	0.003	155	32	17	ND
		0.03	236	130	75	31
		0.3	2927	1517	946	198
	Ag^+	0.003	181	323	94	17
		0.03	2842	1206	218	65
		0.3	25528	22321	7688	2698

ND: not detected

Phase II Silver concentration in effluent

Table 7: Silver concentration in effluent over time using different influent water characteristics

Disk material	*Silver type*	*Water characteristic*	*Silver in effluent (ppb) over time (min) and full-sized filter equivalent time (days) and throughput (L)*			
			100 min <1 day 9 L	200 min <2 days 18 L	300 min ~2.5 days 27 L	1440 min ~12 days 130 L
Indonesia-Sawdust	nAg	NaCl	109	48	10	4
		$CaCl_2$	121	31	6	ND
		HA	113	58	19	7
	Ag^+	NaCl	138	34	29	26
		$CaCl_2$	120	61	44	10
		HA	196	44	22	8
Tanzania-Sawdust	nAg	NaCl	132	34	22	ND
		$CaCl_2$	124	35	18	ND
		HA	171	49	22	2
	Ag^+	NaCl	189	52	16	ND
		$CaCl_2$	50	36	10	5
		HA	173	82	27	5
Nicaragua-Sawdust	nAg	NaCl	161	68	19	5
		$CaCl_2$	197	43	15	2
		HA	184	52	23	6
	Ag^+	NaCl	130	85	42	3
		$CaCl_2$	184	63	32	13
		HA	239	112	47	10
Indonesia - Rice husk	nAg	NaCl	103	65	41	5
		$CaCl_2$	141	29	14	8
		HA	160	33	26	3
	Ag^+	NaCl	141	45	4	4
		$CaCl_2$	118	66	10	8
		HA	110	49	36	16
Tanzania - Rice husk	nAg	NaCl	127	33	30	<1
		$CaCl_2$	103	54	46	9
		HA	135	49	32	ND
	Ag^+	NaCl	132	51	30	8
		$CaCl_2$	193	46	23	ND
		HA	234	114	40	5
Nicaragu-Rice husk	nAg	NaCl	152	80	30	8
		$CaCl_2$	147	78	40	11
		HA	133	90	57	ND
	Ag^+	NaCl	194	65	39	5
		$CaCl_2$	189	42	24	ND
		HA	263	160	25	19

ND: not detected

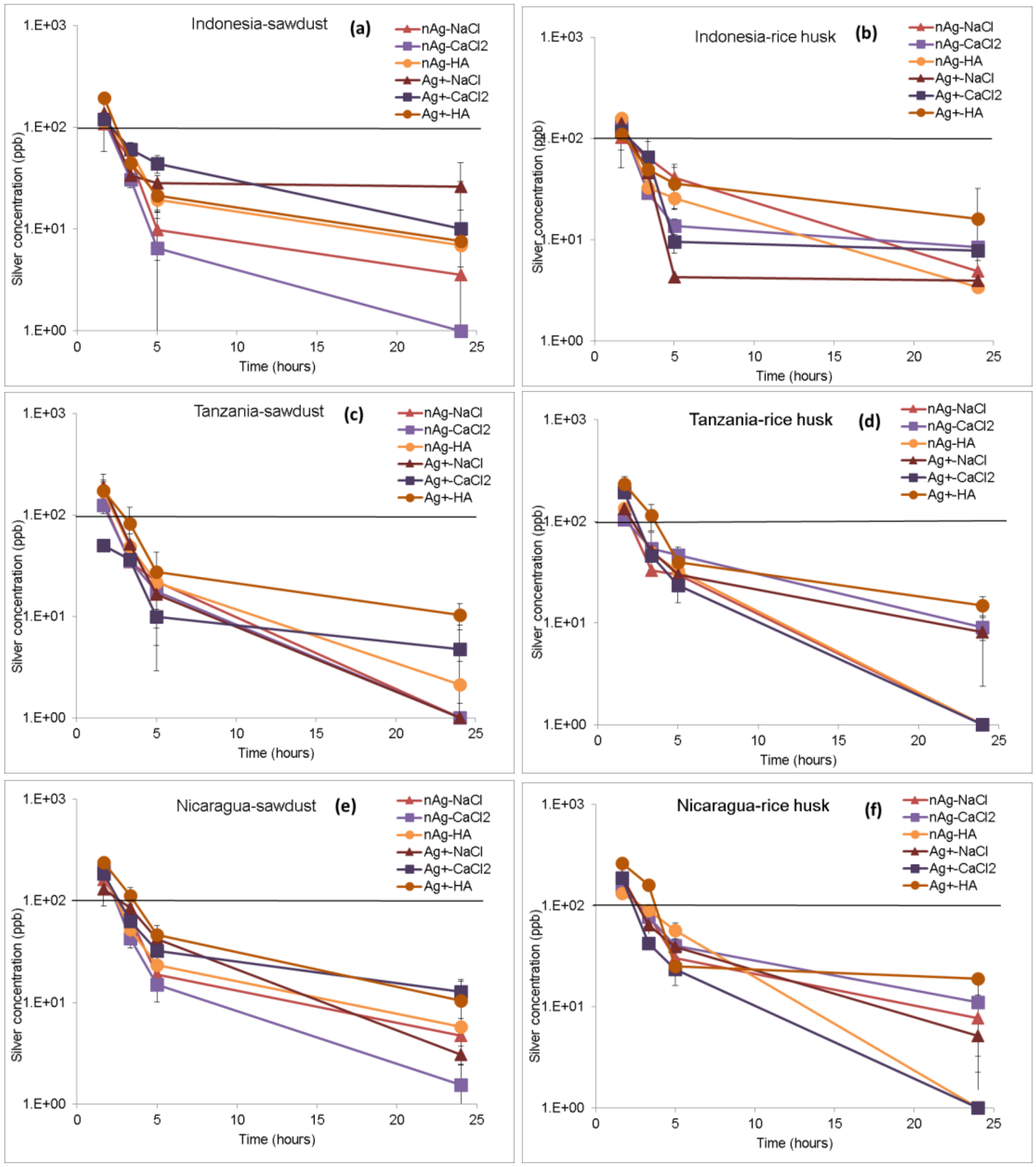

Figure 12: Concentration of silver in effluent (ppb) as a function of time (hours) from disks manufactured with Indonesian clay and sawdust (a) or rice husk (b), Tanzanian clay and sawdust (c) or rice husk (d) and Nicaraguan clay and sawdust (e) or rice husks (f) as burn-out material using different influent water chemistry conditions, with standard error bars.

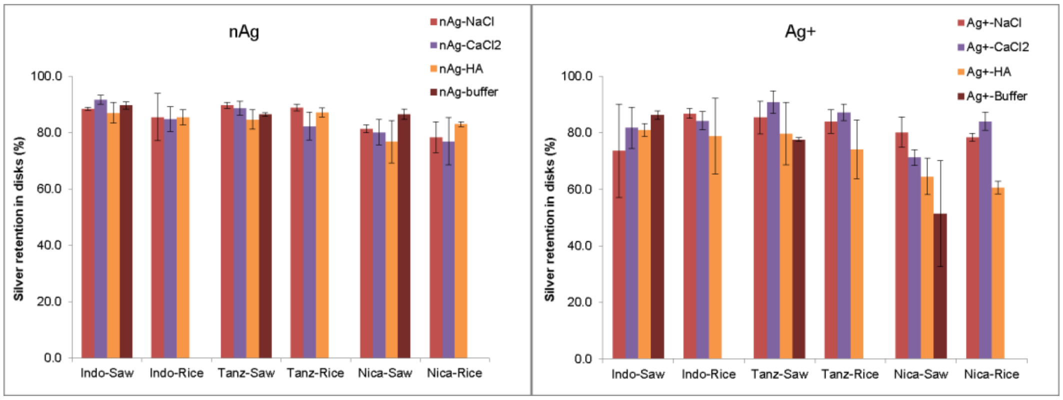

Figure 13: Percent silver retention, with standard error bars, after 24 hours of throughput, in disks manufactured with clay from Indonesia, Tanzania or Nicaragua and Sawdust (saw) or rice husk (rice) as burn-out material coated with 0.003 mg/g of nAg (a) or Ag^{+} (b) using different influent water chemistry conditions

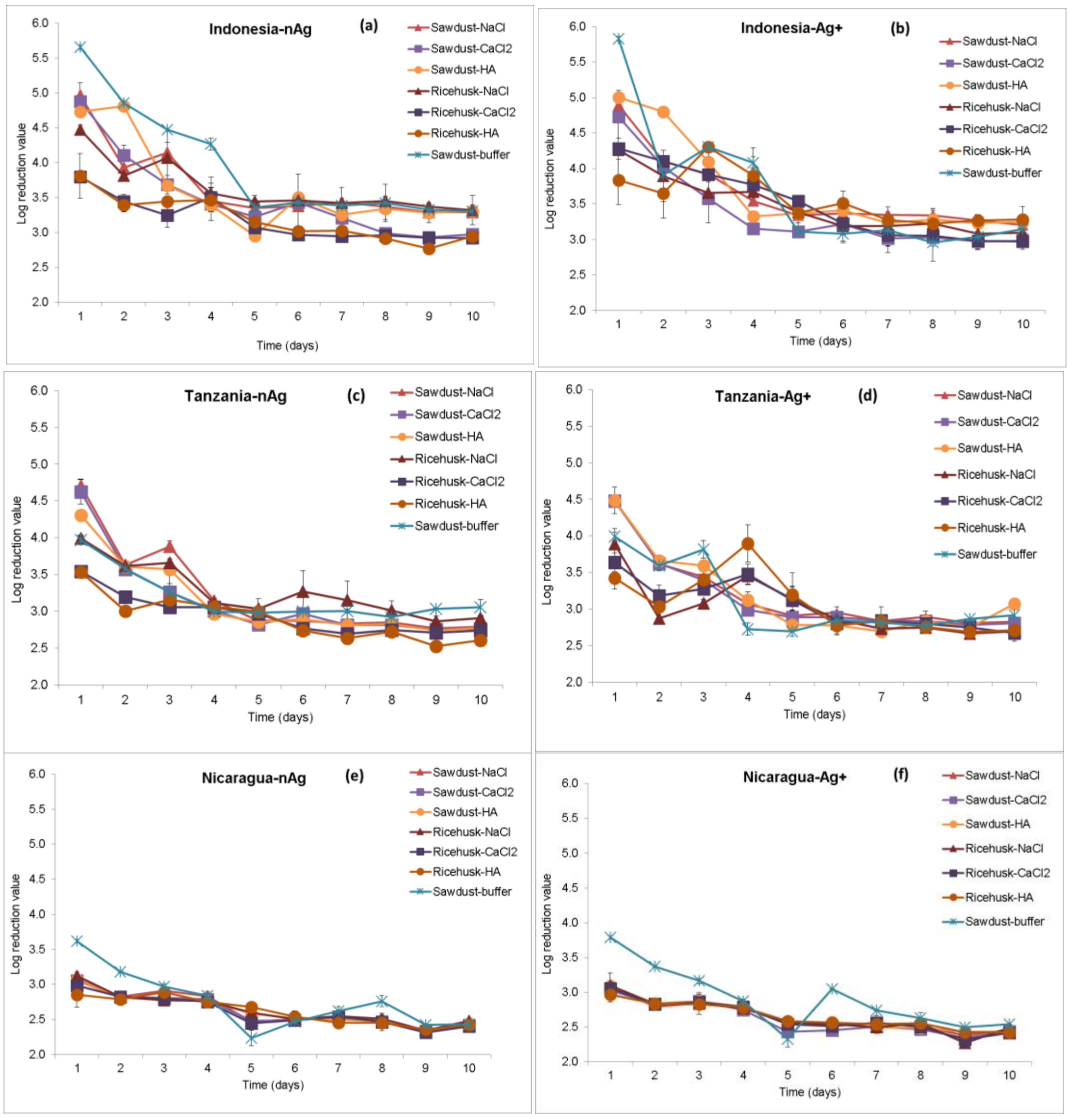

Figure 14: LRV of disks made with sawdust and Indonesian clay with nAg (a) or Ag^+ (b), Tanzanian clay with nAg (c) or Ag^+ (d) and Nicaraguan clay with nAg (e) or Ag^+ (f) using different influent water chemistry conditions, with standard error bars.

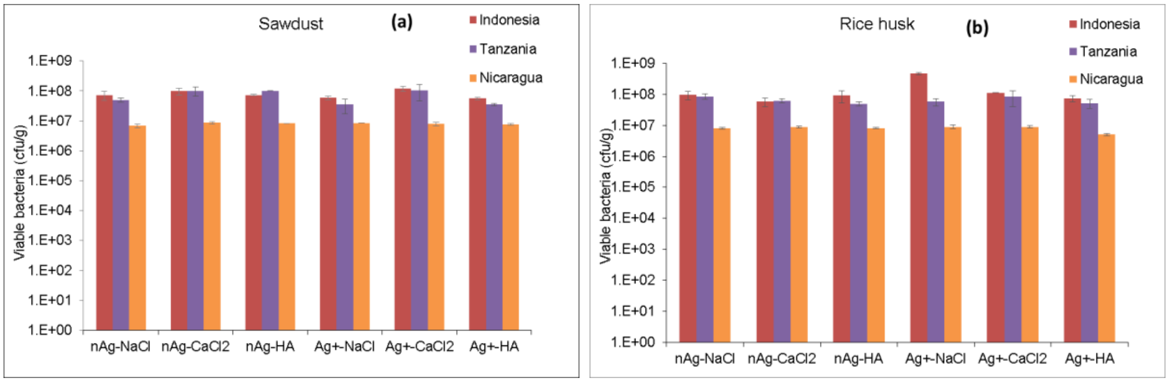

Figure 15: Viable bacteria detected in disks coated with 0.003 mg/g of nAg or Ag^{+} manufactured with various clays and sawdust (saw) (a) or (b) rice husk (rice) as burn-out material using different influent water chemistry conditions, with standard error bars.

Silver longevity estimation PHASE I & II

A rough projection of how long silver could potentially last in filters based on the amount of silver measured in the effluent after 24 hours of continued throughput under phase I (Figure 16) and phase II (Figure 17) conditions was calculated.

These results are based on the assumption that silver would continue to be released at this rate until depleted and therefore, this is a conservative estimate.Variability between duplicate samples in some cases was large and in some cases the concentration in the effluent was greater in the 4th than the 3rd measurement. Regardless, some trends can be noted. Other factors such as potential effects of scrubbing filters in the field and variation in water characteristics, which could potentially affect the effectiveness of the remaining silver or the rate of silver release, are not accounted for in this calculation.

Total mass of silver released was calculated as:

$$M_r = \frac{Q\left[\left(C_1 * T_1\right) + C_2 * \left(T_2 - T_1\right) + C_3 * \left(T_3 - T_2\right) + C_4 * \left(T_4 - T_3\right)\right]}{1000 * 1000}$$

Where:

M_r is total mass of silver released (mg)

Q is flow, 30 mL/hr

$C_1, C_2 ... C_4$ concentration of silver measured in the effluent (ppb)

$T_1, T_2 ... T_4$ Time in hours when effluent was measured (1.7 hours, 3.3 hours, 5 hours and 24 hours, respectively)

The amount of time silver could remain in the filters was projected by:

$$0 = \frac{M_a - (M_r + C_4 * T * Q)}{1000 * 1000}$$

M_a is Mass applied

M_r is Mass released after 24hrs calculated using four measurements.

C_4 Concentration measured at 24 hrs (assumed the silver will continue releasing at the same rate)

T Time in hours to reach 0 mass of silver

Q is flow at 30 mL/hr

The number of hours was divided by 24 to get the number of days and then converted to full sized filter flow multiplying the number of days by 4/10 and dividing that result by 12 to get the number of months of field use.

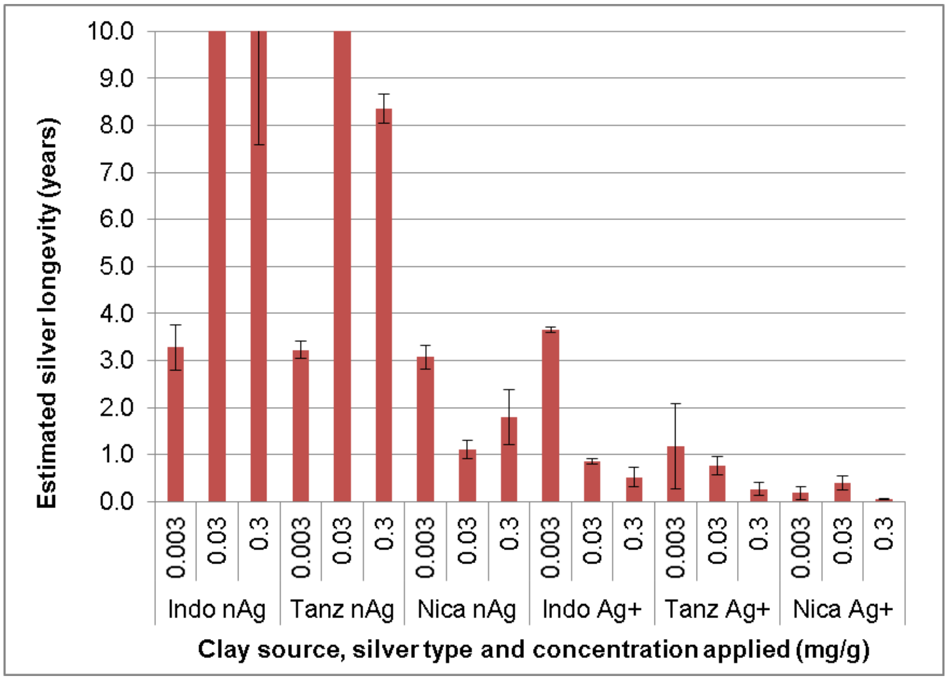

Figure 16: Estimated silver longevity, in years, Phase I

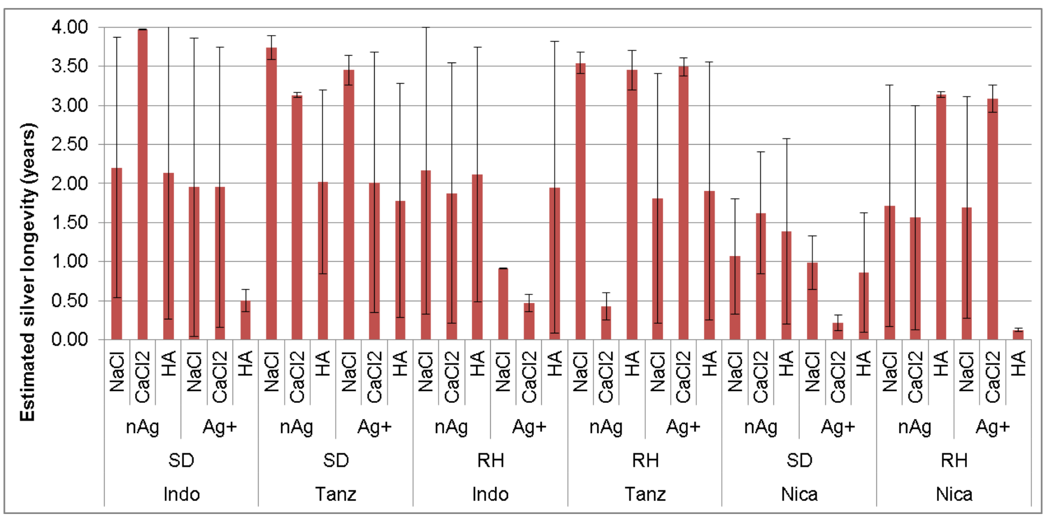

Figure 17: Estimated silver longevity, in years, Phase II

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3 The effects of input materials on ceramic water filter efficacy for household drinking water treatment

3.1 Abstract

Locally manufactured ceramic filters can improve drinking water quality and reduce diarrheal disease burden in developing countries; however, production methods and quality control protocols vary at the >50 factories. We manufactured filter disks with varied clay, burn-out material, burn-out material sieved with different mesh sizes and burn-out material to clay ratios, and calculated filter characteristics, including porosity, density, shrinkage and flow rate. Water was run through filters daily for four weeks, and flow rate and *E. coli* reduction, as measured by Log Reduction Value (LRV), were tested twice weekly. Our results suggest: 1) the first and last LRV test results do not correlate strongly (R^2=0.38, p<0.010); 2) there is not a strong association between flow rate and first, average, or last LRV results (R^2=0.17, p=0.090; R^2=0.30, p=0.020; R^2=0.24, p=0.040); and, 3) first and average LRV are associated with burn-out material (R^2=0.68, p<0.001; R^2=0.60, p<0.001) and last LRV is associated with burn-out material and mesh size (R^2=0.54, p<0.050). Recommendations for filter factories, are to: 1) verify filtration efficacy with repeated bacteria reduction tests when materials, processing, or filter characteristics vary; 2) carefully control production variables; and, 3) continue flow rate testing each filter to evaluate within and across batch production consistency.

3.2 Introduction

Worldwide, approximately 663 million people lack access to an improved water source and an estimated 1.2 billion more drink water at elevated risk of contamination at the source or during transport and storage (Onda, LoBuglio, and Bartram 2012, WHO/UNICEF 2015). Household water treatment (HWT) can be a cost effective means of improving drinking water quality (Clasen, Cairncross, et al. 2007) and reducing diarrheal disease in households that do not yet have access to water and sanitation infrastructure (Clasen 2015, Fewtrell et al. 2005, Clasen, Schmidt, et al. 2007). Locally manufactured ceramic "pot" water filters (CWFs) are one promising HWT technology. CWFs are comprised of an ~10L capacity, silver-treated ceramic filter element that suspends in a lidded receptacle. Water is poured into the filter, flows via gravity into a safe storage container and is dispensed through a tap.

In laboratory investigations, CWFs have demonstrated >2 log reduction value (LRV, 99%) of protozoa and protozoan-sized particles (Lantagne 2001b, Van Halem et al. 2007) and 1-7 LRV (90-99.99999%) of bacterial organisms from drinking water (Lantagne 2001b, Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al. 2007). Virus reduction remains a challenge, with results ranging from <1-3 LRV (63-99.9%) (Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al. 2007). In the field, water treated by CWFs is often improved to the World Health Organization's (WHO) low-risk classification (Roberts 2004, Brown, Sobsey, and Loomis 2008) of <10 CFU *E. coli* /100 mL (WHO 1997) and filter use has been associated with 49-80% reduction in diarrheal disease among users (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014).

Filters are typically manufactured by pressing a pre-determined ratio of locally-sourced clay and burn-out material, such as sawdust or rice husk, into the filter shape. After filters are pressed, dried and fired to a ceramic state (~800-900°C), they are flow rate tested for quality control. Flow rate is defined as the volume of water that flows through a water-saturated filter after one hour. Filters that meet factory established flow rate criteria are coated with silver, a known antimicrobial agent, and packaged for sale or distribution.

The filter mixture ratio is determined by manufacturing batches of filters with different clay to burn-out material ratios. The filters are tested for flow rate and filters from the batch that meet the factory-established flow rate range (typically 1-3 L/hr) are tested for bacteria reduction. The specific recipe of the batch that meets both flow rate and bacteria reduction criteria is then used in production. Since it is not practical to test every filter for bacteria reduction, flow rate is used as the ongoing indicator of production consistency (CMWG 2011). Minimum flow rate is an important to verify minimum rate of water treatment to meet a household's drinking water needs. Maximum flow rate is a topic of much research and debate (CMWG 2011).

Flow rate is affected by different input materials, such as the amount of burn-out material included in the filter mixture (Yakub et al. 2013, Oyanedel-Craver and Smith 2008, Lantagne et al. 2010, Bloem et al. 2009, Kallman, Oyanedel-Craver, and Smith 2011) and the type of burn-out material used (Lantagne et al. 2010). Flow rate is widely assumed to be an indicator of bacteria reduction efficiency. However, research on the relationship between flow rate and bacteria reduction has arrived at contradictory conclusions. Lantagne et al. found that total coliform reduction decreased to <2 LRV (<99%) when flow rates were >1.7L/hr. Filters in this study had flow rates ranging from 0.25-10.2 L/hr. and were manufactured with 40-60%, by volume, sawdust, coffee husk, or rice husk, processed through US #50 mesh sieves (0.30 mm openings) (Lantagne et al. 2010). Silver was not applied. In contrast, one study (Bloem et al. 2009) found no significant difference in *E. coli* LRV, independent of silver nitrate application, in filters with initial flow rates ranging from 1.7-7.6 L/hr. These filters were manufactured with 19-27% rice husk (mesh not specified), 5-17% laterite and 64-74% clay, by weight. van der Laan (2014) concluded that, in filters made with 24-31% rice husk processed through US #18 mesh sieves (1 mm openings), 2% laterite and 67-74% clay, by weight, with initial flow rates ranging from 2.2-19.1 L/hr, the majority of bacteria reduction does not occur during filtration, but rather, due to contact time with silver nitrate during storage. LRVs of samples with <5 minutes storage time; however, ranged from 0.6-3.1, suggesting variability in the filtration ability of the filter material.

Previous research has also investigated relationships between input materials and bacteria reduction, and found that filter material produced with a fine-grained clay with uniform particle size distribution resulted in higher bacteria reduction than material manufactured with clays containing larger, non-uniform particles (Oyanedel-Craver and Smith 2008). One study suggests that increased proportion of sawdust (4-17%, US #60 mesh, without silver) leads to lower bacteria reduction (Kallman, Oyanedel-Craver, and Smith 2011), yet a recent study found no correlation (R=-0.06) between LRV and rice husk proportion (24-31%, US #18 mesh, 2% laterite, 67-74% clay) (Soppe et al. 2015).

Lastly, silver nanoparticle application has been shown to improve bacteria reduction during filtration (Oyanedel-Craver and Smith 2008) and recent studies have found that the rate of silver elution varies depending upon the type of silver (silver nanoparticles or silver nitrate) and influent water quality characteristics (Rayner et al. 2013, Mittelman et al. 2015). Since we are unable to predict silver longevity in filters, the filtration ability of the filter material should be relied on as the principal means of bacteria reduction.

In summary, manufacturing recommendations are limited by these seemingly contradictory research results. A 2009 survey of filter manufacturers found that manufacturing and quality control protocols vary widely both between and within factories, including: 1) criteria for modifying filter mixture ratio; 2) flow rate criteria and test protocols; 3) amount and type of silver applied; and, 4) bacteria reduction test protocols (Rayner, Skinner, and Lantagne 2013). Since 2009, the number of factories has grown from 35 to 50 and continued growth is anticipated. Factory visits and water quality testing in households suggests manufacturing variability may have resulted in poor quality filters reaching the market (Rayner, Murray, et al. 2016).

The World Health Organization has recently launched an international scheme to evaluate HWT products to support member states in product selection; however, the possible variability both across and within factories poses a challenge in the selection of representative filters for testing. To address this, the Ceramics Manufacturing Working Group has committed to developing a certification process to support factories in developing and maintaining effective quality assurance and quality control processes. An improved understanding of the influence of input materials on filter characteristics and bacteria reduction is needed in order to further guide manufacturing recommendations, support factories in consistently manufacturing high quality filters and responsibly promote decentralized CWF production.

We carried out an exploratory investigation into the influence of input materials on filter characteristics, flow rate and LRV by: 1) manufacturing filter disks as surrogates for full-sized filters with varied input materials (clay source, burn-out type, burn-out mesh size, percent burn-out material); 2) calculating filter characteristics measurable at the factory level (porosity, density, shrinkage and flow rate); and, 3) testing disks for flow rate and LRV. Disks were tested without silver to evaluate filtration ability of the filter material. The main aims of this study were to evaluate: 1) the effects of input materials on filter characteristics; 2) the effects of input materials on LRV; and, 3) the relationship between filter characteristics, including flow rate and LRV.

3.3 Methods

Batches of six, 10-cm diameter disks were manufactured at Advanced Ceramics Manufacturing (ACM, Tucson, AZ, USA) with clay imported from filter factories in Indonesia (Pelita Indonesia), Tanzania (SafeWAterNow) and Nicaragua (Filtrón). Burn-out materials, sawdust and rice husks, were purchased locally in Tucson, AZ. Burn-out material was processed in a Nutrimill® grain mill (Hampton, NE, USA) and sieved with US #8/16, 16/30, or 30/60 mesh screens (2.38/1.19, 1.19/0.60 and 0.60/0.25mm openings, respectively). The material that passed through the larger mesh (smaller number) and was retained on the smaller mesh screen (larger number) was used in the filter mixture. Percent burn-out material for initial disk recipes was selected based on factory reported filter mixture ratios (Rayner, Skinner, and Lantagne 2013), then iteratively for subsequent recipes based on LRVs with the objective of meeting >2LRV guideline value (CMWG 2011, WHO 2011a).

Dry materials were measured by weight and mixed in a KitchenAid® mixer (Greenville, OH, USA) and, after adding water, further mixed until visually homogeneous. Filter material was hydraulically pressed into a disk shaped metal die with 4,500 lbs of force to simulate pressure reportedly applied to press full-sized filters (CMWG 2011). Disks were air-dried and fired in an electric furnace. Target fired disk thickness was 1.8 cm. Firing profiles followed *Best Practice Recommendations* (CMWG 2011) and peak firing temperatures and soak times were established for each clay source to achieve sufficient strength to mount the disks for testing. The absence of a black core, indicative of incomplete firing, was confirmed at the selected profiles.

The height, diameter and weight of each disk were measured after pressing and after firing. After firing, disks were saturated, by boiling in water for one hour, and weighed before and after saturation. Porosity was calculated by dividing the difference in weight by the geometric disk volume. Density was calculated by dividing the fired disk weight by the geometric disk volume. Shrinkage in diameter and height were calculated as the percent change between freshly pressed and fired disk diameters and heights, respectively.

Three disks from each of 25 batches were shipped to Lehigh University (Bethlehem, PA). Disks were tested for pH, flow rate and LRV eight times over four weeks. Disks were soaked in de-chlorinated tap water for 24-hours, attached to a PVC connector with plumber's putty, and then to a 3-inch diameter PVC column with a flexible coupling. Between test days, columns were filled with de-chlorinated tap water several times daily to maintain saturation and to flush out *E. coli* remaining from the previous test both to prevent clogging and to allow for more accurate performance evaluation. A sterile inoculating loop was dipped into filtered water on non-test days, placed in sterile LB broth and incubated for 24-hours at 38.5°C to check for presence of *E. coli* (detection level >15CFU/100 mL).

Influent and effluent pH were measured using an OAKTON® pH/CON 510 benchtop meter calibrated with 4, 7 and 10 standards. Flow rates were calculated by measuring the volume of water that filtered from a saturated disk with a 24cm falling head after 30-60 minutes and are presented in mL/hr. Testing was discontinued if flow rates were <10 mL/hr or >1,500 mL/hr.

To test LRV, *E. coli* was grown in LB broth to ~10^{11}CFU/100 mL, determined by spectrometer reading at a wavelength of 600nm, confirmed by plate counts, and diluted to

$1.1x10^7$CFU/100 mL with de-chlorinated tap water. Columns were filled to a 24 cm head (~2L) with *E. coli*-spiked water twice per week. Influent and effluent samples were collected 1-2 hrs after filling columns, diluted appropriately, tested by membrane filtration and incubated on m-FC broth media at 44.5°C±0.5°C for 22-26 hrs. Standard Methods were followed (APHA/AWWA/WEF 2012). LRV was calculated as the difference between the $\log_{10}$ of the influent and the $\log_{10}$ of the effluent *E. coli* CFU/100 mL.

Single and multivariable linear regression analyses were run using Stata 10.1 (College Station, TX, USA) to identify relationships between: 1) input materials (clay source, burn-out type, burn-out mesh size and percent burn-out material) and disk characteristics (porosity, density, shrinkage and flow rate); 2) input materials and LRV; and, 3) disk characteristics and LRV. As flow rates and LRV varied, the three-disk average of the first, average of the tests, and last (8^{th}) results were used. Variables were considered significant at $p<0.050$; insignificant variables were removed from models. The half-way point between larger and smaller mesh openings is linear, therefore mesh sizes were coded as 30/60=1, 16/30=2 and 8/16=3 for regression analysis.

3.4 Results

Filter disks were manufactured from filter material containing clay from Nicaragua, Tanzania, or Indonesia and 7.5%-25% of either sawdust or rice husk (by weight to clay) processed using 8/16, 16/30, or 30/60 mesh screens. Peak firing temperature varied per clay. The firing temperature and soak time selected for the Nicaraguan clay was 1085°C/60min; the Tanzanian clay, 950°C/60min; and the Indonesian clay, 800°C/180min. The high temperature required to sinter the Nicaraguan disks resulted in over-fired, non-representative filter material and therefore Nicaraguan clay disks were dropped from the study.

In total, twenty-five sets of disks manufactured with Tanzanian or Indonesian clay were sent to Lehigh University for testing. The porosity and density of Tanzanian clay disks were similar after firing to 800°C/180min or 950°C/60min, but after being fired to 950°C/60min, the flow rates tripled. Five sets of disks manufactured with Tanzanian clay were shipped for testing but only one set completed testing due to the excessive flow rates.

Of the 20 disk sets manufactured with Indonesian clay 18 completed testing, as two sets did not filter enough water for testing (Table 8). Nine sets were manufactured with sawdust and nine with rice husk. Burn-out material to clay ranged from 11%-24% sawdust and 7.5%-25% rice husk, by weight. Fired disk thickness averaged 1.87 cm (min-max: 1.78-2.0 cm).

Input materials, filter characteristics and LRVs are presented for the 25 disk sets shipped to Lehigh in Table 8. Both influent and effluent pH averaged 6.5 (ranging from 6.0-6.8 and 5.9-7.3, respectively). Please note only the 18 disk sets manufactured with Indonesian clay that completed flow rate and LRV testing were included in the regression analysis.

Table 8: Input Materials, Filter Characteristics and Log Reduction Value (LRV)

Clay source	Burn-out type	Mesh size	Percent burn-out	Density (g/cc) AVG (SE)	Porosity (%) AVG (SE)	Shrinkage (D) (%) AVG (SE)	Shrinkage (H) (%) AVG (SE)	Flow (mL/hr) AVG (SE)	LRV AVG (SE)
Indo	Saw dust	8/16	11.0%	1.18 (0.004)	55.5 (0.001)	11.7% (0.000)	15.4% (0.002)	87 (7.4)	1.79 (0.131)
			13.7%	1.13 (0.008)	56.3 (0.004)	11.3% (0.002)	15.6% (0.004)	70 (5.2)	1.87 (0.261)
		16/30	13.7%	1.16 (0.011)	53.2 (0.002)	11.8% (0.002)	17.3% (0.006)	27 (1.5)	4.43 (0.402)
			17.0%	1.04 (0.012)	56.2 (0.004)	10.8% (0.003)	15.1% (0.006)	100 (4.7)	2.37 (0.239)
			20.0%	1.00 (0.005)	60.1 (0.004)	10.5% (0.002)	15.6% (0.002)	126 (4.8)	2.83 (0.265)
		30/60	13.7%	1.17 (0.014)	50.4 (0.220)	11.7% (0.002)	18.7% (0.005)	17 (1.7)	2.06 (1.33)
			17.0%	1.11 (0.001)	52.7 (0.009)	10.9% (0.000)	18.4% (0.003)	17 (0.8)	4.00 (0.285)
			20.0%	1.05 (0.003)	57.0 (0.005)	11.3% (0.002)	19.4% (0.005)	27 (0.7)	3.41 (0.232)
			24.0%	0.95 (0.003)	64.6 (0.003)	10.8% (0.002)	17.4% (0.001)	172 (19.0)	2.78 (0.156)
	Rice husk	8/16	10.0%	1.30 (0.006)	48.0 (0.005)	9.3% (0.000)	12.1% (0.002)	387 (25.2)	0.98 (0.136)
			17.0%	1.12 (0.013)	53.8 (0.006)	8.4% (0.001)	13.7% (0.010)	671 (34.0)	0.86 (0.048)
			25.0%	0.91 (0.003)	60.1 (0.007)	7.7% (0.001)	12.9% (0.004)	1252 (127.8)	0.89 (0.075)
		16/30	7.5%	1.41 (0.007)	47.9 (0.000)	11.8% (0.002)	14.5% (0.001)	35 (4.5)	1.28 (0.105)
			12.0%	1.28 (0.004)	51.6 (0.003)	10.5% (0.003)	13.9% (0.002)	175 (14.4)	1.47 (0.118)
			17.0%	1.14 (0.005)	59.0 (0.046)	10.6% (0.001)	14.3% (0.002)	283 (14.5)	0.96 (0.079)
		30/60	*10.0%	1.43 (0.008)	39.5 (0.019)	11.9% (0.002)	15.5% (0.006)	3.4 (0.7)a	a
			*17.0%	1.36 (0.002)	46.9 (0.004)	11.8% (0.004)	15.2% (0.009)	7.5 (0.9)a	2.78 (0.229)a
			18.0%	1.18 (0.004)	56.2 (0.002)	10.0% (0.002)	14.7% (0.007)	171 (10.9)	1.93 (0.110)
			19.0%	1.16 (0.012)	56.5 (0.003)	10.8% (0.001)	14.6% (0.006)	180 (10.8)	1.26 (0.166)
			25.0%	1.02 (0.007)	58.7 (0.007)	9.9% (0.001)	13.5% (0.006)	374 (22.4)	1.26 (0.097)
Tanz	Saw dust	8/16	*13.7%	1.03(0.005)[b]	57.8 (0.007)[b]	5.0% (0.001)b	3.4% (0.002)b	3030 (n/a)b	a
		16/30	*13.7%	1.11(0.000)[b]	57.6 (0.004)[b]	7.0% (0.002 b	8.3% (0.002)b	3195 (285.0)b	a
				1.11 (0.000)	57.3 (0.002)	6.2% (0.001)	8.0% (0.003)	805.7 (81.7)	a
		30/60	*11.2%	1.36 (0.005)[b]	51.2 (0.003)[b]	7.7% (0.004)[b]	8.6% (0.001)b	525 (36.6)b	1.89 (0.159)b
			*20.0%	0.98 (0.003)	63.0 (0.001)[b]	7.6% (0.001)[b]	10.9% (0.005)[b]	1925 (152.3)b	a
				0.97 (n/a)	62.9 (n/a)	6.7% (0.001)	9.6% (0.005)	921.2 (n/a)	a
	Rice husk	30/60	*19.0%	1.16 (0.004)	55.1 (0.000)[b]	5.7% (0.01)b	5.5% (0.001)[b]	2060 (102.5)[b]	a

SE= Standard Error; *not included in regression analysis; a Disk set did not complete testing due to too low or excessive flow rates, or fragility;
b Measurements taken after 950°C/60min firing

Disk Characteristics

Density and porosity. The average density of disks manufactured with Indonesian clay (n=18) ranged from 0.91-1.41g/cc (mean 1.13g/cc) and average porosity ranged from 47.9-64.6% (mean 55.4%) (Table 8). Standard error within disk sets ranged from <0.001-0.014 for density and <0.001-0.046 for porosity. Density was greater in disks made with rice husks, with smaller burn-out mesh and lower percent burn-out material (R^2=0.99, $p<0.001$) (Table 9). Density and porosity had a strong inverse correlation (R^2=0.73, $p<0.001$).

Shrinkage. Shrinkage in diameter ranged from 7.7%-11.8% with standard error within disk sets ranging from <0.001-0.004 (Table 3). Shrinkage in height ranged from 12.1%-19.4% and standard error ranged from 0.001-0.010. Shrinkage in diameter and height were moderately correlated (R^2=0.42, p=0.004, n=18) (Table 9). This correlation was stronger for disks made with rice husks (R^2=0.43, p=0.05, n=9), than for disks manufactured with sawdust (R^2=0.01, p=0.53, n=9). Shrinkage in height was greater in disks made with sawdust, sieved with a smaller mesh (R^2=0.83, $p<0.001$).

Flow rate. The average flow rates of disk sets made with Indonesian clay (n=18) ranged from 17-1,252 mL/hr (Table 8). Flow rates fluctuated over the 4-weeks of testing (Figure 18), however there was a strong correlation between first and last flow rates (R^2=0.70, $p<0.001$). Flow rates were faster in disks made with rice husks (n=9), processed with a larger mesh and with greater percent burn-out material (R^2=0.69, $p<0.050$; R^2=0.84, $p<0.001$; R^2=0.88, $p<0.001$) (Table 9**)**. Flow rate declined with increased shrinkage in diameter (R^2=0.65, $p<0.001$; R^2=0.82, $p<0.001$; R^2=0.87, $p<0.001$).

E. coli Reduction. LRV fluctuated throughout the 4-weeks of testing (Figure 18) and the association between first LRV and last LRV was weak (R^2=0.38, $p<0.010$, n=18). LRVs on the first test ranged from 0.86-6.34 (mean 2.92), average LRVs ranged from 0.86-4.43 (mean 2.03) and the last LRVs ranged from 0.61-3.14 (mean 1.63).

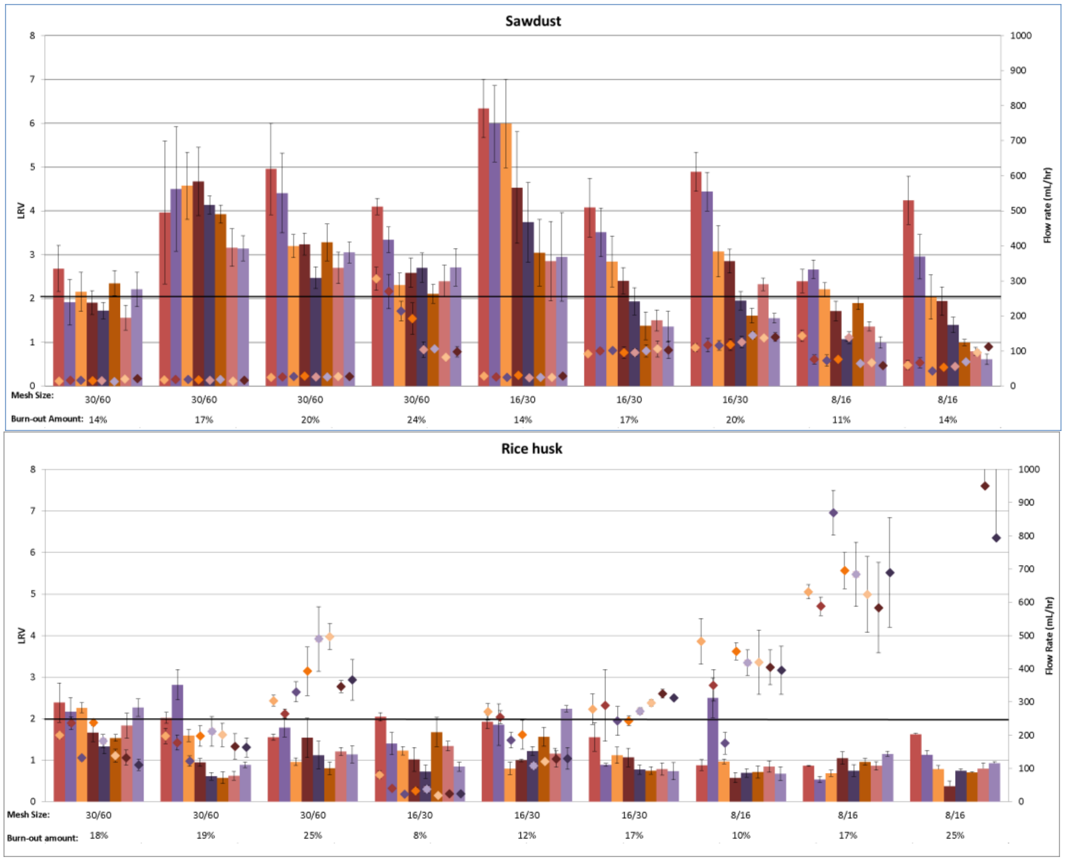

Figure 18: Flow rates (dots) and LRV (bars) with standard error bars of Indonesian clay disks with (a) sawdust and (b) rice husk. Bold horizontal line indicates 2LRV

For disks manufactured with sawdust (n=9), first LRVs ranged from 2.4-6.34 (mean 4.18), average LRVs ranged from 1.79-4.43 (mean 2.84) and last test results ranged from 0.61-3.14 (mean 2.06) (Table 8). For disks manufactured with rice husks (n=9), first LRVs ranged from 0.86-2.39 (mean 1.65), average LRVs ranged from 0.86-1.93 (mean 1.21) and last test results ranged from 0.67-2.26 (mean 1.21).

In the regression analysis, first and average LRVs were greater in disks made with sawdust (R^2=0.68, 0.60, $p<0.001$, respectively) and last LRVs were greater in disks made with sawdust using a smaller mesh (R^2=0.54, $p<0.010$). Shrinkage in height was associated with first, average and last LRVs (R^2=0.54, 0.65, 0.59, $p<0.001$, respectively).

Single variable linear regression results for flow rate and LRVs for the 18 disk sets manufactured with Indonesian clay were: 1) first flow rate with first LRV: R^2=0.17 (p=0.090); 2) average flow rate with average LRV: R^2=0.30 (p=0.020); and, 3) last flow rate with last LRV: R^2=0.24 (p=0.040).

Table 9: Linear regression model results

N	R^2	Outcome	Constant	Input materials and filter characteristics		
18	0.70	Porosity	43.332***	0.725***(ratio)		
18	0.99	Density	1.484***	-0.025***(ratio)	0.092***(burnout)	-0.042***(size)
18	0.79	Shrinkage (D)	0.161***	-0.001***(ratio)	-0.012***(burnout)	-0.007**(size)
18	0.83	Shrinkage (H)	0.219***	-0.029***(burnout)	-0.011***(size)	
18	0.69	First Flow Rate	-2071***	346.168*(burnout)	389.450**(size)	67.252**(ratio)
18	0.84	Average Flow Rate	-1300***	265.438***(burnout)	238.889***(size)	41.554***(ratio)
18	0.88	Last Flow Rate	-960.44***	221.610***(burnout)	185.463***(size)	28.592***(ratio)
N	R^2	Outcome	Constant	Input variables and LRV		
18	0.68	First LRV	6.717***	-2.534***(burnout)		
18	0.60	Average LRV	4.47***	-1.63***(burnout)		
18	0.54	Last LRV	3.852***	-0.725*(burnout)	-0.598**(size)	
N	R^2	Outcome	Constant	Filter characteristics, Flow Rate and LRV		
18	0.65	First Flow Rate	4148.38***	-36410.36***(Shrinkage[D])		
18	0.82	Average Flow Rate	2781.49***	-24165.08***(Shrinkage[D])		
18	0.87	Last Flow Rate	2159.90***	-18576.83***(Shrinkage[D])		
18	0.54	First LRV	-5.735*	56.218***(Shrinkage[H])		
18	0.65	Average LRV	-4.522**	42.546*** (Shrinkage[H])		
18	0.59	Last LRV	-3.516**	33.472***(Shrinkage[H])		

*p<0.050, **p<0.010, ***p<0.001

D=diameter, H=height; Burnout= burn-out type: Sawdust=1, Rice husk=2; Size=US mesh number: 8/16=3, 16/30=2, 30/60=1; Ratio=percent burn-out material to clay by weight.

3.5 Discussion

We manufactured 25 filter disk sets (without silver application) to evaluate relationships between input materials (clay source, burn-out type, mesh size and percent burn-out material) and filter characteristics measurable at the factory level (density, porosity, shrinkage and flow rate) against filter quality criteria of LRV over 4-weeks of testing (8 tests). Investigating these relationships offers potential to better understand relationships between input materials, filter characteristics and LRV, and is needed to guide manufacturing quality control recommendations.

Our primary findings include: 1) the first LRV test did not correlate strongly with the last test; 2) we did not find a strong association between flow rate and LRV for non-silver treated filter material; and, 3) we did find an association between burn-out type and mesh size with LRV. These are discussed below, along with the effects of input materials on filter characteristics.

All disks manufactured with sawdust and some rice husk disks achieved >2LRV on the first test; overall, 8th LRVs were lower than initial results. While it appears that the decline in LRV over time was greater in disks manufactured with sawdust, the lower initial LRV in disks manufactured with rice husk possibly limited the extent of decline in LRV, this also may have diluted some of the regression results. LRV in sawdust disks generally appeared to stabilize after about four tests; however, it is not clear whether performance would be maintained if testing had continued. This suggests a need for further long-term performance studies and factories should consider this when designing their quality control protocols.

There was only a weak association between flow rate and LRV. Flow rate is a primary quality control evaluation carried out at most factories to evaluate production consistency, minimum flow rate criteria and filter quality. Flow rate is affected by input materials including burn-out type, percent burn-out material and mesh size. While in disks manufactured with either sawdust or rice husks flow rate increased with increased percent burn-out material or mesh size, rice husk disks demonstrated a steeper change in flow rate, suggesting, in terms of flow rate, control of percent rice husk and mesh size is more sensitive than for sawdust. The high aspect ratio (oblong shape) of rice husk may allow long, thin particles to pass through the sieve, possibly resulting in a lower threshold for connected pores and a less tortuous filtration matrix than with more spherical sawdust particles.

Neither porosity nor density were associated with LRV and while flow rates were faster, disks manufactured with rice husk were less porous (and more dense). Materials were measured by weight and as rice husk is more dense than sawdust, the smaller volume of rice husk added to the filter mixture resulted in less porous material. Furthermore, while porosity and density remained similar, flow rates nearly tripled in the two Tanzanian disk sets that were re-fired at a hotter firing temperature. This supports findings by others (Soppe et al. 2015) who also measured a change in flow rates with firing temperature. This suggests that while changes in filter characteristics such as porosity and density may detect variability in input materials, they are unlikely to capture effects of wide variation in firing temperature, which may also impact LRV (Soppe et al. 2015). Shrinkage in diameter was associated with flow rate and shrinkage in height was associated with LRV; however, shrinkage direction in full-sized filters might vary according to the angle of pressure during pressing. We conclude that while flow rate is not a reliable indicator for LRV, it should still be used as an indicator for production consistency (and to confirm minimum rate of water treatment) as it can capture variation both in input materials and firing temperature.

While burn-out type, mesh size and percent burn-out material influence flow rate, input materials most associated with LRV were burn-out type and mesh size. Factory-produced filters manufactured with rice husks have demonstrated effective bacteria reduction (with and without silver) (Brown and Sobsey 2010); however, disks made with rice husk in this investigation did not meet >2LRV criteria throughout eight tests. Disks manufactured with sawdust achieved higher LRVs than disks manufactured with rice husks, and sawdust sieved with smaller mesh was associated with higher LRV. Theoretically, filter material of similar porosity but created by a greater number of smaller void spaces will have a greater surface area to trap bacteria than material with fewer large void spaces. While smaller mesh was associated with higher LRV in this study, there is likely a threshold for the proportion of sawdust that can be added before pores become interconnected and LRV decreases (Kallman, Oyanedel-Craver, and Smith 2011). If the higher aspect ratio (oblong shape) of rice husk impacts the pore structure, as discussed above, it could also impact LRV. LRV was associated with shrinkage in height, which was also associated with burn-out type and mesh size. Filter manufacturers have commented on a difference when working with hard versus soft woods, rice husk versus bran and rice husk versus sawdust, and it could be that burn-out material characteristics, such as absorbency, may affect shrinkage and/or the resulting pore structure.

Based on the results of this research, recommendations to manufacturers include: 1) verify filtration efficacy with repeated bacteria reduction tests when a new recipe is developed, or when there is variation in input materials, processing, or filter characteristics; 2) carefully control production variables, with special attention to sawdust particle size; and, 3) continue flow rate testing filters to evaluate both within and across batch production consistency (and verify minimum flow rate requirements), and if flow rates are not consistent, identify and correct the variation in production. We recommend quality assurance and quality control protocols address these recommendations to consistently produce high-quality filters.

Our results are limited by: 1) the use of disks as surrogates for full sized filters; and, 2) the small sample size available for statistical analysis. These are further discussed below.

The use of disks as surrogates for full-sized filters can improve research efficiency on CWFs; however, it would be useful to know if full-sized filters produced with the same input materials would meet minimum flow rate criterion of ≥1 L/hr. The flow rate model presented in van Halem (2006) was used to project full-sized filter flow rates, and filter recipes were iteratively selected based on flow rate predictions. At the conclusion of this research, an error in the reported filter dimensions was identified, calling into question the empirical model validation. The analysis was therefore carried out on non-converted disk flow rates. Additional models have since been proposed (Schweitzer, Cunningham, and Mihelcic 2013, Plappally et al. 2009) and are currently being evaluated empirically for use in predicting full-size filter flow rates.

The small sample size was primarily a result of the challenges of working with different clays, and remaining resources did not allow us to push input variables to reach thresholds. A post-study analysis of the sand-silt-clay distributions found the Indonesian clay had 50.5:18.5:31.0, the Tanzanian clay had 64:7.5:28.5 and the Nicaraguan clay had 82:17.5:0.5 (Duocastella and Morrill 2012). Variability in clay is a challenge faced by factories. When the Nicaraguan clay used in this research, which contained <1% clay-sized particles, reached production, the factory struggled to produce filters and suspended production until a new clay source was identified. Whenever a new clay source is introduced, factories need to establish a new recipe and test for bacteria reduction, which can be time consuming and costly.

Despite these limitations, we believe that our investigatory research results improve our knowledge of the relationships between input materials, filter characteristics and quality criteria. We identified key areas for manufacturing recommendations at the factory level and believe this is a promising model to further evaluate effects of input materials on filter characteristics and quality. Further research is recommended to empirically validate flow rate prediction models, as the use of disks to model full-size filters can reduce cost and time of research and may also be useful to improve efficiency in initial prototype development at factories. Evaluation of pore network morphology and variation in pore structure created by different clay characteristics, burn-out material characteristics, burn-out material processing, and firing profile and temperature on the effects on bacteria reduction is needed.

3.6 Conclusions

With the growing global interest in scaling up CWF production, ensuring quality-controlled production among decentralized filter factories is of increasing interest. We manufactured 25 sets of disks with different input materials (clay source, burn-out type, percent burn-out material and mesh size) and disk characteristics (porosity, density, shrinkage and flow rates) against LRV. We found that the first LRVs were not were not strongly correlated with the last (8^{th}) LRVs, flow rate did not correlate strongly with LRV in non-silver treated filter material and sawdust, and sawdust sieved with smaller mesh were associated with higher LRV compared with rice husk and larger mesh.

Recommendations to factories include: to verify bacteria reduction with repeated tests when a new recipe is developed or when there is variation in input materials, processing, or filter characteristics; carefully control production variables, with special attention to sawdust particle size; and, continue flow rate testing all filters to evaluate both within and across batch production consistency and minimum flow rate requirements.

3.7 Acknowledgements

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3.8 Citation

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4 Evaluation of household drinking water filter distributions in Haiti

4.1 Abstract

Household water treatment can reduce the diarrheal disease burden in populations without access to safe water. We evaluated five programs that distributed biosand, ceramic, or Sawyer filters in Haiti after the 2010 earthquake and cholera outbreak. We conducted household surveys and tested *E. coli* and turbidity in stored household untreated and treated water in ~50 randomly selected households from each program. Across programs, self-reported filter use ranged from 27-78%; confirmed use (participants with reported use who also showed the filter with water currently in it) ranged from 20-76%; and, effective use (participants who used the filter to improve water quality to international guideline values) ranged from 0-54%. Overall, programs that more successfully met evaluation metrics: 1) distributed an effective technology; 2) provided safe storage; 3) required cash investment; 4) provided initial training; 5) provided follow-up; 6) provided supply-chain access; 7) targeted households relying on contaminated water sources; and, 8) had experience working in the local context. These findings, similar to results of previous research on household water treatment, suggest that well implemented programs have the potential to result in sustained household filter use in Haiti.

4.2 Introduction

Household water treatment (HWT) can be a cost-effective means of improving drinking water quality (Clasen, Cairncross, et al. 2007) and reducing diarrheal disease in households where access to water and sanitation infrastructure is limited (Fewtrell et al. 2005, Clasen et al. 2006, Clasen 2015), and is therefore recommended as part of a comprehensive strategy to prevent diarrheal disease in low-income settings without access to safe drinking water (UNICEF/WHO 2011).

Worldwide, approximately 663 million people lack access to an improved water source and an estimated 1.2 billion more rely on contaminated water sources (Onda, LoBuglio, and Bartram 2012, WHO/UNICEF 2015). In Haiti, 48% of rural and 65% of urban households have access to an improved water source (WHO/UNICEF 2015). However, in a 2012 study, *Escherichia coli (E. coli)* was detected in half (50.9%) of the improved water sources tested in Artibonite, Haiti (Patrick et al. 2013).

Chlorination has been widely promoted to treat drinking water in Haiti. Nearly all (96%) of the 71% of Haitians who report treating their water report using chlorine-based products (Cayemittes et al. 2013). In a 2008 evaluation of a chlorine distribution program with training and follow-up, 56% of participants (versus 10% of controls) had free chlorine residual (FCR) in their drinking water and children <5 years old had 59% reduced odds of diarrhea (95% CI=0.21,0.79) (Harshfield et al. 2012). In 2010, after the earthquake, 72% and 90% of participants in this program had FCR in their drinking water two and ten months post-earthquake, respectively (Lantagne and Clasen 2013, Lantagne and Clasen 2012). In contrast, less than two years after chlorine tablets were distributed with just mass-marketing behavior change messages to rural households in Artibonite, Haiti, only 9.9% of households had stored water containing FCR (Patrick et al. 2013).

These results suggest that when sufficient training, follow-up, and supply chain are provided, chlorine can be used to improve drinking water quality and reduce diarrheal disease in Haiti.

Before the January 2010 earthquake, filtration-based technologies had not been widely promoted in Haiti; only ~1% of households that reported treating their drinking water reported using filtration-based systems (Cayemittes et al. 2013). In a 2005 biosand filter study in Artibonite, filters that had been used for an average 2.5 years reduced *E. coli* by 98.5% and turbidity by 85% (Duke et al. 2006). A follow-up study in 2011, on 55 households in this program, found that 53% of filters installed <1-12 years previously were still in use, and on average reduced *E. coli* by 92% (Sisson et al. 2013). These studies suggest potential for long-term use of biosand filters in Haiti.

Since 2010, distribution of filtration-based technologies has rapidly increased and little is known about whether filter implementation programs in Haiti are resulting in improved drinking water quality at the household level. We evaluated filter distribution programs by: 1) identifying and inviting distribution programs to participate in this evaluation; and, 2) visiting households, conducting a survey, and testing water quality to evaluate the effectiveness of filter implementation programs in the post-earthquake context in Haiti.

4.3 Methods

Program and household selection: Organizations operating filter distribution programs in Haiti between 2010-2014 were identified by asking those with HWT knowledge in Haiti, and invited to participate in the evaluation. Participating organizations provided household distribution lists. We selected a distribution region from each list based on the following criteria: 1) >50 recipient households in the region; 2) ability to locate households; and, 3) accessibility during the survey timeframe. After region selection, 253 households were randomly selected, 50-53 from each distribution list for survey and water sampling.

Household surveys: Household surveys were conducted in Haitian Creole by trained Haitian enumerators in August 2014. The survey consisted of a general section of 48 questions on demographics, water knowledge, attitudes, and practices. If the participant reported receiving a filter, 46-48 technology-specific questions were asked about filter use, maintenance, cleaning, and satisfaction. Personally identifying information was not collected. Informed consent was obtained before administering the ~40 minute survey. The Tufts University and Haitian Institutional Review Boards approved the protocol and survey tools.

Water sampling and testing: Enumerators requested a cup of drinking water; if respondents reported the water was filtered, enumerators also collected: 1) stored untreated water; and, 2) water directly from the filter outlet or tap (after wiping with a disposable alcohol pad). Samples were collected aseptically in Whirl-Pak™ bags with sodium thiosulfate (Nasco, Ft. Atkinson, WI), stored on ice, and processed within 12 hours of collection.

Samples were tested for *E. coli* and total coliform bacteria using membrane filtration. Samples were diluted appropriately with sterile buffered water, filtered aseptically through a 45-μm Millipore filter (Billerica, MA) on a portable Millipore filtration stand, placed in a plastic Petri-dish with a pad soaked in mColiBlue24® media, and incubated at 35-37°C for 24-hours. Sterile buffered water controls were tested every 20 plates, and 10% of samples were duplicated for quality control. Plates were considered countable at <200 colonies. Turbidity was measured in excess water from paired untreated/direct-from-filter samples with a calibrated Lamotte 2020 Turbidimeter (Chestertown, MD).

Analysis: Survey and water quality data were collected on paper, entered into Microsoft Excel (Redmond, WA), and all data were analyzed using STATA/IC 10.1 (College Station, TX).

Summary descriptive statistics were calculated. Primary program evaluation metrics were: reported use, confirmed use, and effective use. Reported use was calculated as the percentage of the surveyed population that provided a drinking water sample and self-reported that it had been filtered with the program filter. Confirmed use was the percentage that met reported use criteria plus showed the filter with water in it. Effective use was calculated as the percentage of the surveyed population that met reported use criteria and used the filter to improve drinking water from ≥1 *E. coli* coliform forming units (CFU)/100mL in untreated stored water to <1 *E. coli* CFU/100mL in treated drinking water (Lantagne and Clasen 2012). Effective use was also calculated using 10 *E. coli* CFU/100mL as a low-risk break-point (WHO 2011a).

Microbiological test results were reported using geometric mean, with values of <1 CFU/100 mL replaced with 0.5 CFU/100 mL. Additionally, where >40% of untreated water samples had ≥100 *E. coli* CFU/100mL, $\log_{10}$ reduction values (LRV) were calculated from paired untreated/direct-from-filter samples for *E. coli* as a risk reduction indicator. Where >40% of untreated water samples had ≤10 *E. coli* CFU/100mL and ≥100 total coliform bacteria CFU/100mL, LRV was calculated from paired untreated/direct-from-filter samples for total coliform bacteria as a filtration process indicator.

Cleaning was considered correct if respondents reported cleaning the tap/filter outlet and using treated (boiled, filtered, or chlorinated) water to clean their drinking water storage container, and: 1) for ceramic filters, cleaning the membrane with treated water and using a brush/cloth exclusively for cleaning the membrane; 2) for biosand filters, using the 'swirl and dump' method (CAWST 2012) to clean the sand layer; and, 3) for Sawyer filters, reporting back-flushing. Storage was considered safe if the drinking water container had a lid and tap.

4.4 Results

4.4.1 Program and household selection:

Organizations reported more than 140,000 biosand, ceramic, Sawyer, and Lifestraw® filters were distributed in Haiti between 2010-2014. Six filter distribution programs were identified and four organizations, representing five filter distribution programs, agreed to participate, including: 1) Pure Water for the World (PWW), which distributed plastic-casing HydrAid® biosand filters; 2) Clean Water for Haiti (CWH), which distributed locally-manufactured concrete-casing biosand and Atabey ceramic 'pot' filters manufactured in the Dominican Republic; 3) L'Association Saint-Luc d'Haiti (ASSLHA), which distributed locally-manufactured FilterPure ceramic 'pot' filters; and, 4) a Sawyer filter distributor who facilitated three Sawyer PointONE™ (hollow fiber membrane filters) filter distributions by different organizations.

4.4.2 Household surveys:

A total of 223 (88%) of 253 randomly selected households were visited: 44-46 households per each of the five programs (Table 10). Both PWW and CWH biosand programs have been working in Haiti since before the 2010 earthquake, distributed filters at a subsidized price, and provided on-going follow-up. The CWH ceramic program distributed filters at a subsidized price, but neither follow-up nor supply chain were provided. Both ASSLHA and Sawyer programs distributed free filters, but ASSLHA provided no follow-up or supply chain while follow-up and supply chain varied across the three Sawyer filter distributions. All programs provided initial training on filter use and maintenance.

Table 10: Program information

Program details	PWW Biosand	CWH Biosand	CWH Ceramic	ASSLHA Ceramic	Sawyer
Filter brand / source	HYDRAID® plastic casing	CWH concrete-casing	Atabey Dominican Republic	FilterPure Haiti	Sawyer PointONE™
Time working in Haiti	Pre 2010 earthquake	Pre 2010 earthquake	Post 2010 earthquake	Post 2010 earthquake	Post 2010 earthquake
Distribution timeframe	Mar.- Dec. 2013	Oct. 2012- Nov. 2013	Nov. 2011- Aug. 2013	Mar.- Apr. 2014	Mar. 2014
Context	Development	Development	Emergency	Development	Development
Geography	Rural / Semi-Rural Mountains	Artibonite Delta / Rural	Rural Mountains	Semi-Rural	Coastal / Semi-Rural Mountains
Training	Community meeting	During installation	Community meeting	Community meeting	Community meeting
Follow-up	Regular, paid technician	Regular, paid technician	None	None	Variable
Filter cost	Subsidized	Subsidized	Subsidized	Free	Free
Houses on list, n	92	406	70	106	98
Houses selected, n	50	50	53	50	50
Participants, n (%)	45 (90%)	44 (88%)	44 (83%)	44 (88%)	46 (92%)

n= number of households

The majority of respondents were female (68-86%) and the average respondent age was 39.4 years (Table 11). The average household size was 5.7 persons, and between 32-68% of households had ≥1 child less than five years old. Educational attainment of program participants was highest in ASSLHA ceramic, similar across PWW biosand, CWH biosand and Sawyer, and lowest in CWH ceramic programs. Top reported health concerns were fever (79%) and headache (63%). Respondents reported that during the prior week 9-27% of children <5 years of age had diarrhea (three or more loose or watery stools during 24 hours); this was highest in CWH biosand and ceramic programs, at 23% and 27% respectively.

In CWH biosand and CWH ceramic programs, 0-7% of households had access to improved water sources, respectively, in contrast with >71% in other programs (Table 11). Nearly all respondents (95%) believed water can make you sick and considered water safe to drink when 'treated' (95%) or has 'no bacteria' (54%). Households largely underreported filters, in comparison with chlorine-based disinfectants, when asked to name methods for 'treating' drinking water. Nearly all participants (98-100%) named an HWT method, with 81-100% mentioning Aquatabs, but just 37-71% mentioning the program filter; even fewer reported receiving a filter since the cholera outbreak. Access to latrines was lowest in CWH biosand and CWH ceramic programs (41% and 23%, respectively), whereas 67-79% of participants in other programs had access to a latrine.

Table 11: Survey respondent demographics, water practices and beliefs

	PWW Biosand	CWH Biosand	CWH Ceramic	ASSLHA Ceramic	Sawyer	Overall
Mean (SD) people per HH	4.7 (2.3)	6.1 (2.3)	6.5 (2.4)	5.5 (2.3)	6.0 (2.3)	5.7 (2.4)
HH has ≥ one child <5 years, % (n)	40% (45)	48% (44)	68% (44)	32% (44)	37% (46)	45% (223)
Female respondent, % (n)**	71% (45)	86% (44)	68% (44)	82% (44)	78% (46)	77% (223)
Mean (SD) respondent age in years*	42.4 (17.8)	38.4 (13.2)	36.7 (13.3)	37.7 (16.5)	41.6 (14.6)	39.4 (15.2)
Respondent attended school, % (n)	62% (45)	68% (44)	55% (44)	91% (44)	70% (46)	69% (223)
Mean highest grade (SD), n=	7.6 (3.4) n=28	7.2 (3.3) n=30	5.2 (2.8) n=24	10.3 (3.5) n=40	7.0 (3.7) n=32	7.7 (3.7) n=154
Female HOH can read, % (n)	61% (41)	59% (41)	44% (43)	76% (42)	55% (44)	59% (211)
Male HOH can read, % (n)	71% (41)	69% (39)	68% (41)	79% (38)	70% (40)	71% (199)
Has concrete floor, % (n)**	53% (45)	23% (44)	59% (44)	100% (44)	72% (46)	61% (223)
Has wired electricity, % (n)**	0% (44)	77% (44)	0% (44)	51% (43)	2% (46)	26% (221)
Had diarrhea in past week*, % (cases/ hh members)	6% (13/207)	8% (21/261)	17% (47/279)	2% (4/238)	2% (5/268)	7% (90/977)
Children <5 years old had diarrhea in past week, % (cases/ total children)	9% (2/23)	23% (5/22)	27% (15/56)	12% (2/17)	8% (2/24)	18% (26/142)
Primary water source improved, % (n)**	71% (45)	0% (44)	7% (44)	98% (44)	80% (46)	52% (223)
Primary water source surface water, %(n)**	0% (45)	80% (44)	2% (44)	0% (44)	11% (46)	18% (223)
Round-trip time (minutes) to collect water, median (lower, upper quartiles), n=	15 (5, 30) n=45	7 (4, 30) n=44	60 (30, 60) n=44	5 (1, 15) n=42	8 (3, 30) n=46	10 (5, 35) n=221
Average times per day water is collected (SD), n=	3 (1.5) n=43	4 (1.9) n=43	2 (0.9) n=44	4 (1.8) n=29	3 (1.6) n=38	3 (1.7) n=197
Believes water can make you sick, % (n)	100% (45)	86% (44)	89% (44)	98% (44)	100% (46)	95% (223)
Has received water treatment products since Cholera start, % (n), Product:	93% (45)	75% (44)	93% (44)	68% (44)	80% (46)	82% (223)
Biosand, % (n)	48% (42)	49% (33)	0% (41)	0% (30)	3% (37)	20% (183)
Ceramic, % (n)	0% (42)	0% (33)	32% (41)	20% (30)	3% (37)	11% (183)
Sawyer, % (n)	0% (42)	0% (33)	0% (41)	0% (30)	11% (37)	2% (183)
Aquatabs, % (n)	93% (42)	94% (33)	90% (41)	93% (30)	95% (37)	93% (183)
Has latrine, % (n)**	71% (45)	41% (44)	23% (44)	79% (43)	67% (46)	56% (222)
Has hand washing station, % (n)**	16% (45)	7% (44)	5% (44)	21% (44)	7% (46)	11% (223)
Has soap, % (n)**	7% (43)	2% (44)	0% (44)	14% (44)	2% (46)	5% (221)

n=sample size; SD=standard deviation; HOH=head of household; HH= household, All answers are self-reported by the respondent unless '**', which means result was observed or interpreted based on survey response.

The estimated time since distribution ranged from <1-5 years, averaging >1 year in CWH biosand and ceramic programs and <1 year in PWW biosand, ASSLHA and Sawyer programs (Table 12). Nearly all households in the PWW and CWH biosand programs reported paying for filters (96-98%), >50% in the CWH ceramic program, and few to none of ASSLHA and Sawyer participants. Of the total households surveyed, 82-100% of respondents reported receiving a filter (n=223), of which 94% reported they have used it to '*make the water clean'* (81%) or '*eliminate bacteria'* (47%), they like it (86-100%), and it meets their drinking water needs (80-100%). The majority of households (82-96%) in the PWW biosand, CWH biosand, and Sawyer programs reported use in the previous 24 hours; this was just 37% in the CWH ceramic program. Household members sometimes drink untreated water when '*outside the home*' (85%) or when there is '*no treated water*' (53%). Nearly half (19/39) of CWH ceramic filter participants no longer use the filter because the membrane (100%), tap (5%) or storage container (11%) had broken.

Most participants reported receiving training on filter use (96%) and cleaning (95%); this was slightly lower in CWH ceramic program (87% and 85%, respectively) (Table 12). Correct cleaning practices were reported by 32-65% of respondents. Nearly 40% of respondents reported cleaning filtered water storage containers with untreated water. Biosand programs recommend chlorinating filtered water to compliment filtration; however, less than half (48%) reported chlorinating filtered water and 7% showed a bottle containing chlorine to the enumerator. Supply chain knowledge was low across all programs (<25%), but 35-93% of participants reported knowing whom to contact with questions about their filter.

Table 12: Reported filter use and operation and maintenance knowledge

	PWW Biosand	CWH Biosand	CWH Ceramic	ASSLHA Ceramic	Sawyer	Overall
Received filter, % (n)	100% (45/45)	98% (43/44)	89% (39/44)	82% (36/44)	96% (44/46)	93% (207/223)
Time since distribution, mean (min-max, years), n=	11 months (<1-2), n=41	1.3 years (1-5), n=39	1.2 years (<1-3), n=36	<6 months (<1-1), n=32	8 months (<1-3), n=41	11 months (<1-5), n=189
Paid for filter, % (n)	96% (43)	98% (42)	64% (25)	<1% (2)	0% (0)	51% (112)
Has used the filter, % (n)	100% (45/45)	98% (42/43)	90% (35/39)	94% (34/36)	86% (38/44)	94% (194/207)
Used filter in last 24 hours, % (n)	96% (45)	93% (42)	37% (35)	82% (34)	84% (38)	80% (194)
Likes the filter	100% (44)	100% (41)	86% (35)	100% (34)	97% (38)	97% (192)
Filter meets water treatment needs	100% (45)	100% (42)	80% (35)	100% (34)	95% (38)	95% (194)
Uses filtered water for:, % (n):						
Drinking	100% (45)	100% (42)	83% (35)	100% (34)	97% (38)	96% (194)
Cooking	33% (45)	86% (42)	26% (35)	21% (34)	40% (38)	42% (194)
Bathing	16% (45)	31% (42)	6% (35)	21% (34)	21% (38)	19% (194)
Wash hands	13% (45)	10% (42)	6% (35)	15% (34)	8% (38)	10% (194)
Wash fruits/vegetables	9% (45)	0% (42)	0% (35)	9% (34)	0% (38)	4% (194)
Wash dishes	4% (45)	0% (42)	3% (35)	9% (34)	0% (38)	3% (194)
Reports, % (n):						
HH members sometimes drink untreated water	76% (45)	60% (42)	85% (39)	83% (36)	80% (44)	77% (206)
Received filter use training	100% (45)	100% (43)	87% (39)	97% (36)	96% (44)	96% (207)
Received filter cleaning training	100% (45)	100% (43)	85% (39)	97% (36)	91% (44)	95% (207)
Correct cleaning	40% (43)	55% (42)	33% (30)	65% (34)	32% (38)	45% (187)
Cleans storage container with untreated water, % (n)	41% (44)	24% (42)	43% (30)	24% (34)	53% (34)	37% (184)
Knows where to buy parts	24% (45)	2% (43)	3% (39)	14% (36)	0% (44)	9% (207)
Knows who to contact with questions	93% (45)	35% (43)	39% (39)	56% (36)	71% (44)	59% (207)

n=sample size, HH= household, all answers are self-reported.

The majority of respondents provided a drinking water sample (94%), but reported use varied as 78-80% of PWW and CWH biosand households surveyed, 50-57% of ASSLHA ceramic and Sawyer households surveyed, and 27% of CWH ceramic households surveyed both provided a water sample and reported it had been treated with the filter (Table 13). Respondents showed the filter to the enumerator in 48-100% of households, and of the observed filters, 57-100% had water in them (Table 13). Of the total households surveyed, 20-76% (n=223) both met reported use criteria and showed the filter with water in it to the enumerator. PWW and CWH biosand programs had the highest (70-76%) confirmed use, ASSLHA and Sawyer had intermediate (43-54%), and CWH ceramic had the lowest confirmed use (20%). Most households had a safe storage container (67-100%), with the exception of the CWH biosand program (7%).

Table 13: Reported, confirmed and effective use by total households surveyed

	PWW Biosand	**CWH Biosand**	**CWH Ceramic**	**ASSLHA Ceramic**	**Sawyer**	**Overall**
Reported received filter, % (n)	100% (45)	98% (44)	89% (44)	82% (44)	96%(46)	93% (223)
Provided drinking water sample, % (n)	93% (45)	95% (44)	91% (44)	93% (44)	96% (46)	94% (223)
Reported sample was treated, % (n)	89% (45)	89% (44)	52% (44)	66% (44)	72% (46)	73% (223)
Reported sample treated with filter, % (n)	78% (45)	80% (44)	27% (44)	50% (44)	57% (46)	58% (223)
Time (hours) since treating water, median (lower, upper quartiles), n=	24 (5, 24) n=35	6 (4, 24) n=34	24 (24, 72) n=12	24 (3, 24) n=22	5 (2, 24) n=26	24 (3, 24) n=129
Showed filter	100% (45)	98% (44)	48% (44)	82% (44)	85% (46)	82% (223)
Safe storage observed, % (n)	100% (44)	7% (43)	95% (21)	100% (36)	67% (39)	73% (183)
Water in filter, % (n)	100% (44)	91% (43)	57% (21)	75% (36)	85% (39)	82% (183)
Reported use, % (n)	78% (45)	80% (44)	27% (44)	50% (44)	57% (46)	58% (223)
Confirmed use, % (n)	76% (45)	70% (44)	20% (44)	43% (44)	54% (46)	53% (223)
Untreated sample ≥1 and treated <1 *E. coli* CFU/100mL, % (n)	44% (25)	25% (24)	0% (9)	57% (21)	48% (25)	39% (104)
Effective use, 1 *E. coli* CFU/100mL breakpoint, %	34%	20%	0%	29%	27%	23%
Untreated sample was >10 and treated ≤10 *E. coli* CFU/100mL, % (n)	48% (25)	67% (24)	33% (9)	43% (21)	40% (25)	48% (104)
Effective use, 10 *E. coli* CFU/100mL breakpoint, %	37%	54%	9%	22%	23%	28%

n=sample size

Median turbidity in source water (Table 14) was low in all programs (<5 NTU), with the exception of the CWH biosand program where households use surface water. CWH biosand filters reduced turbidity by 98%, from a median 25 NTU in untreated water to 0.49 NTU in direct-from-filter samples (n=6).

Geometric mean total coliform bacteria ranged from 383-5,233 CFU/100mL (n=104) in untreated water and 5-256 CFU/100mL in direct-from-filter samples (n=98) (Table 14). Geometric mean *E. coli* in untreated water ranged from 6.6-691.3 *E. coli* CFU/100mL (n=105) (Table 14, Figure 19). Geometric mean direct-from-filter samples had <2 *E. coli* CFU/100mL across all programs with the exception of CWH ceramic, which had geometric mean 21 *E. coli* CFU/100mL. Geometric mean *E. coli* concentrations in treated water ranged from 1.2–16.3 *E. coli* CFU/100mL (n=104). In all programs except CWH ceramic, these values were greater than direct-from-filter samples, suggesting post-filtration contamination.

More than 40% of untreated samples in the CWH biosand and ceramic programs had ≥100 *E. coli* CFU/100mL (Figure 19). The CWH biosand filters achieved a 2.9 LRV (99.87% reduction) in *E. coli* (n=22); in contrast, the CWH ceramic filters achieved an average 0.56 LRV (72.5% reduction) (n=3). More than 40% of untreated samples in the ASSLHA ceramic and Sawyer programs had ≤10 *E. coli* CFU/100mL (Figure 19). Ceramic filters in the ASSLHA program achieved a 2 LRV (99% reduction) in coliform bacteria (n=12) and Sawyer filters achieved a 1 LRV (90% reduction) in coliform bacteria (n=23).

The percentage of households whose water quality was improved from ≥1 *E. coli* CFU/100mL in untreated to <1 in treated water samples ranged from 0-57% (n=104). Effective use by the surveyed population (reported use and improved water quality with the filter), ranged from 0-34% (Table 14). The percentage of households whose water was improved water from >10 to ≤10 *E. coli* CFU/100mL was 33-67%; thus, using 10 *E. coli* as the breakpoint, effective use ranged from 9-54%.

Table 14: Water quality

	PWW Biosand	CWH Biosand	CWH Ceramic	ASSLHA Ceramic	Sawyer	Overall
Turbidity (NTU):						
Untreated stored, median (lower, upper quartiles), n=	0.58 (0.38, 1.04) n=10	25.44 (2.90, 50.1) n=6	2.43 (0.83, 4.06) n=6	0.89 (0.41, 3.78) n=12	0.12 (0.06, 0.47) n=13	0.64 (0.23, 2.33) n=47
Direct-from-filter, median (lower, upper quartiles), n=	0.13 (0.10, 0.67) n=10	0.49 (0.21, 0.73) n=6	6.8 (0.44, 8.92) n=6	0.70 (0.11, 1.88) n=12	0.28 (0.03, 0.91) n=13	0.39 (0.1, 1.37) n=47
Total coliform CFU/100mL:						
Untreated stored Geometric mean (min-max), n=	1963 (220-10485) n=25	5233 (800-14250) n=24	456 (134-1060) n=9	383 (<1-5184) n=22	1532 (40-8000) n=25	1451 (<1-14250) n=105
Direct-from-filter Geometric mean (min-max), n=	90 (<1-1800) n=25	13 (1-4140) n=24	256 (98-520) n=7	5 (<1-200) n=18	174 (3-4036) n=24	42 (<1-4140) n=98
Treated Geometric mean (min-max), n=	391 (2-4602) n=25	536 (6-8000) n=24	520 (179-4006) n=9	90 (<1-4032) n=21	608 (12-4150) n=25	356 (<1-8000) n=104
***E. coli* CFU/100mL:**						
Untreated stored Geometric mean (min-max), n=	29.3 (5-485) n=25	691.3 (46-4250) n=24	78.5 (10-755) n=9	6.6 (<1-250) n=22	12.6 (<1-4000) n=25	39.2 (<1-4250) n=105
Direct-from-filter Geometric mean (min-max), n=	1.5 (<1-40) n=25	1.1 (<1-140) n=24	21.5 (2-260) n=7	<1 (<1-<1) n=18	1.0 (<1-36) n=24	1.2 (<1-260) n=98
Treated Geometric mean (min-max), n=	2.3 (<1-110) n=25	6.1 (<1-4000) n=24	16.4 (2-980) n=9	1.2 (<1-400) n=21	2.2 (<1-400) n=25	3.0 (<1-4000) n=104

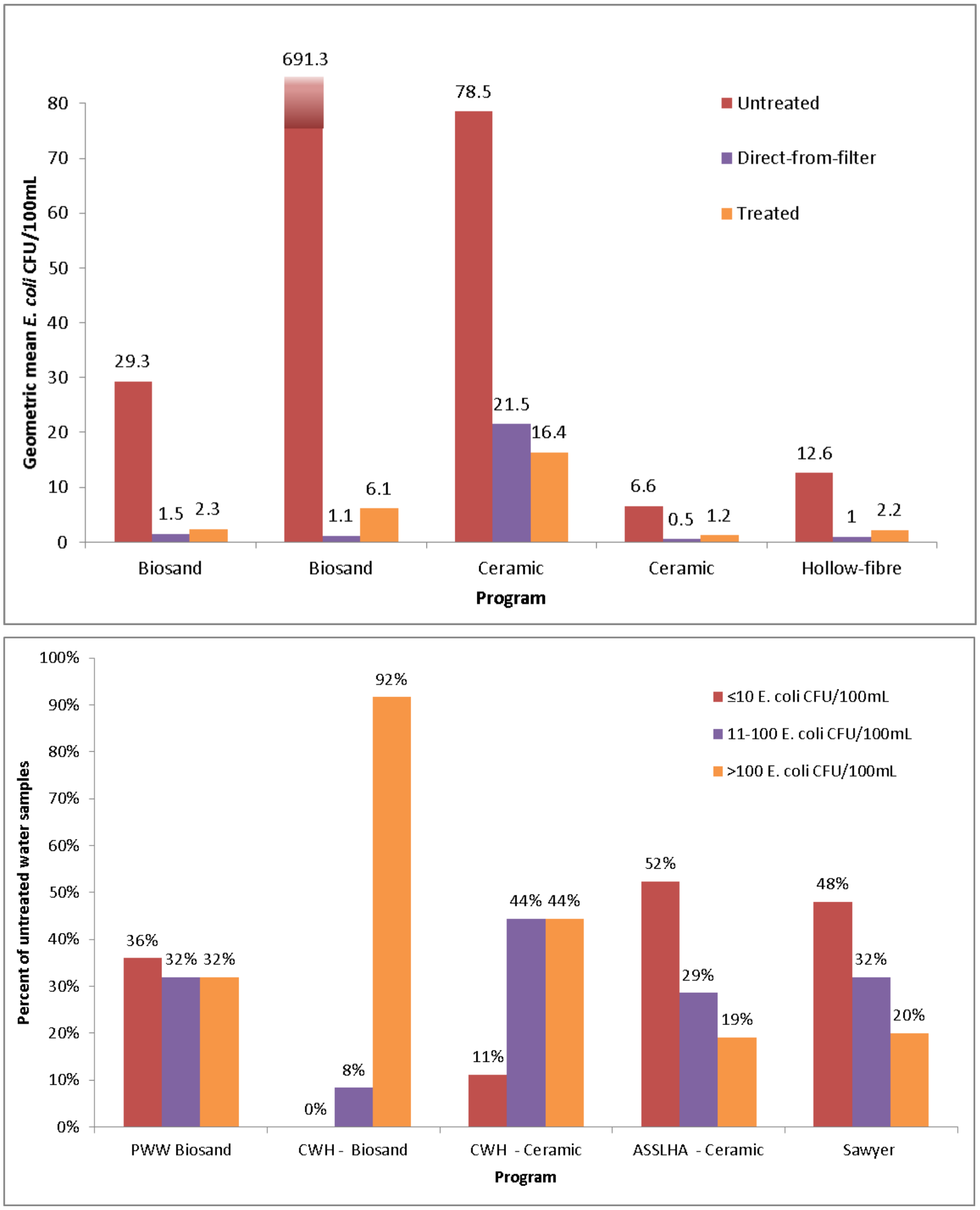

Figure 19: Geometric mean *E. coli* concentrations in household water per program (top); Percent of untreated water samples with ≤10, 11-100 and >100 *E. coli* CFU/100mL per program (bottom)

4.5 Discussion

We evaluated five programs that distributed biosand, ceramic, and Sawyer filters in Haiti since 2010. Our results indicate that, as measured by reported, confirmed, and effective use, program effectiveness is likely related to the extent to which programs: 1) distributed an effective technology; 2) provided safe storage; 3) required cash investment; 4) provided initial training; 5) provided follow-up; 6) provided supply-chain access; 7) targeted households relying on contaminated water sources; and, 8) had experience working in the local context (Table 15).

It is fundamental that HWT technologies are effective at removing bacteriological contamination from source water. On average direct-from-filter water quality was low risk (geometric mean <2 *E. coli*) in four of the five programs. The CWH ceramic filters; however, did not improve water quality to low-risk levels and only achieved 0.56 LRV. This contrasts both with results from the ASSLHA ceramic filters and previous research on ceramic filters (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014), and is hypothesized, based on factory visits, to be a result of poor quality control in manufacturing (Rayner, Murray, et al. 2016). The CWH biosand filters achieved an average 2.9 LRV in *E. coli*, suggesting these biosand filters are appropriate for the highly contaminated, turbid surface water in the Artibonite region where they were distributed. These results are consistent with, or better than, previous research results on biosand filters (Stauber et al. 2012, Stauber et al. 2006, Duke et al. 2006, Stauber et al. 2009, Sisson et al. 2013).

With the exception of households in the CWH biosand program, safe storage containers were observed in the majority of households. In comparison with other programs, *E. coli* concentrations in treated samples were relatively greater than direct-from-filter concentrations. This is reflected by the increase in effective use from 20-54% using 10 *E. coli* as the breakpoint. Although post-contamination could have occurred in the household cup, the lack of safe storage containers (7%) likely allowed for contamination during storage.

Controlling for time since distribution, cash investment has been associated with long-term filter use in previous ceramic filter research (Brown and Sobsey 2006), and likely represents both perceived need and interest in using the technology. In both the ASSLHA and Sawyer filter programs, where nearly all filters were free, reported use was just 50-57%. Additionally, households in these programs had access to improved water sources, possibly influencing perceived need to treat water. Although >50% of CWH ceramic participants paid for their filters, time since distribution, high breakage rates, and the absence of supply chain likely prohibited sustained use, as discussed below.

While all programs provided initial training, the percentage of respondents reporting correct cleaning was variable, with many reporting using untreated water to clean storage containers. Household cups used to provide water for sampling may also have been washed with untreated water. These likely contributed to post-contamination, which occurred across programs, and is widely documented (Wright, Gundry, and Conroy 2004). While biosand filter users are taught to chlorinate filtered water, which would protect water after filtration, reported compliance was low. Additionally, across all programs, respondents reported drinking untreated water when outside the home or when there is no filtered water, this could potentially limit health benefits, as high adherence is necessary to realize health gains (Brown and Clasen 2012, Hunter, Zmirou-Navier, and

Hartemann 2009). Programs are encouraged to emphasize these points in training and follow-up with households.

While CWH programs targeted high-risk populations that relied primarily on unimproved water sources, ASSHLA and Sawyer households relied primarily on improved water sources, where >40% of stored water samples had ≤10 *E. coli* CFU/100mL (Figure 19). This limits potential risk reduction and therefore, effective use results (Lantagne and Clasen 2013). Ceramic filters distributed by ASSLHA did however achieve a 2 LRV in total coliform and no *E. coli* were detected in any direct-from-filter samples. This suggests potential for effectiveness should water quality vary due to the use of alternate sources, an emergency, or seasonality (Kostyla et al. 2015). In contrast, Sawyer filters achieved a 1 LRV in total coliform bacteria and 33% of direct-from-filter samples had detectable *E. coli*. This relatively low LRV reduction is consistent with field data on Sawyer filters as summarized by Murray *et al.* (2015).

Access to a market-based supply chain was not available in any of the program communities; therefore, whether households would troubleshoot, identify and replace broken parts could not be assessed. Filter technicians fulfilled this role in the PWW and CWH biosand programs, contributing to long-term filter use. The absence of supply chain and/or follow-up prohibited potential for high use rates in the long-running CWH ceramic program where breakage was the primary reason for disuse. Time since distribution and breakage in the absence of supply chain have been associated with disuse of ceramic filters previously (Brown and Sobsey 2006, Clasen, Brown, and Collin 2006).

Programs in this evaluation with highest reported and confirmed use have been running HWT distribution projects in Haiti since before the 2010 earthquake; this is consistent with previous findings (Lantagne and Clasen 2012). These programs have developed and modified their distribution strategies over time and this experience likely contributed to sustained filter use.

The limitations of this work include the small sample size limiting statistical analysis, cross-sectional study design, voluntary nature of program participation, time restrictions during field research in community selection, and that stored water quality is not necessarily representative of actual filter influent water. Despite these limitations, we do not expect our conclusions would vary much as they are consistent with HWT research in Haiti and elsewhere.

Table 15: Program strategies and characteristics

	PWW Biosand	**CWH Biosand**	**CWH Ceramic**	**ASSLHA Ceramic**	**Sawyer**
Average time since distribution	11 months	1.3 years	1.2 years	<6 months	8 months
Technology effective	+	+	−	+	≈
Safe storage container	+	−	+	+	≈
Cash investment by household	+	+	≈	−	−
Received initial training	+	+	≈	+	+
Follow-up provided	+	+	−	−	≈
Supply chain present or respondent knows who to contact	+	−	−	≈	≈
Primary water source is unimproved	≈	+	+	−	−
Program experienced in local context	+	+	≈	−	−

Extent to which program addressed: + high; − low; ≈ average

4.6 Conclusions

The themes identified in this research are consistent with previous studies. Program effectiveness is likely related to the extent to which programs: 1) distributed an effective technology; 2) provided safe storage; 3) required cash investment; 4) provided initial training; 5) provided follow-up; 6) provided supply-chain access; 7) targeted households relying on contaminated water sources; and, 8) had experience working in the local context. Our results suggest potential for long-term effective use of filters in Haiti. The extent to which program strategies address these themes will likely contribute to program success in achieving health gains and reducing the burden of diarrheal disease.

4.7 Acknowledgements

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4.8 Citation

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5 Developing a Framework to Evaluate Quality Control Protocols of Ceramic Filter Factories

5.1 Abstract

Ceramic water filters are produced in >50 factories worldwide. Manufacturing and quality control protocols vary widely both within and across factories leading to concerns about production quality and consistency within and across decentralized production facilities. The aim of this project was to develop a framework to evaluate quality control protocols in ceramic water filter manufacturing. Protocol assessment tools were developed, four factories were visited, production protocols were observed and documented, and filters from each factory were tested for flow rate and *E. coli* $\log_{10}$ reduction value (LRV). Filters from two factories met ≥2 LRV criteria; however, none of the factories applied criteria to monitor production consistency. Two of four factories documented production and promoted safe working environments. We propose this framework be incorporated into a Quality Control Protocol Evaluation Process, whereby protocols are evaluated against two primary criteria: 1) filters are tested and achieve ≥2 *E. coli* LRV, and 2) production consistency criteria are applied. Additionally, production should be documented and a safe working environment promoted. Recommended future work includes further developing this protocol evaluation process, including an on-site method to test filter efficacy for *E. coli* and the development of a strength testing protocol.

5.2 Introduction

Household water treatment (HWT) can be a cost effective way of improving drinking water quality (Clasen, Cairncross, et al. 2007) and reducing diarrheal disease (Fewtrell et al. 2005, Clasen et al. 2006, Clasen 2015), and thus, is recommended as part of a comprehensive strategy to prevent diarrheal disease where access to safe drinking water and sanitation infrastructure is limited (UNICEF/WHO 2011).

Ceramic ‘pot’ water filters (CWF) are an effective HWT technology (Sobsey et al. 2008). They are comprised of a ~10L capacity, silver-treated, ceramic filter element, suspended in a lidded receptacle. After water is poured into the filter, it flows via gravity into the safe storage container and is dispensed through a tap. CWFs are manufactured by pressing a predetermined ratio of processed raw clay and sieved burn-out material into the filter shape. Once dry, they are fired to a ceramic state (~800-900°C). During firing, the burn-out material fires out, creating a porous structure. The primary quality control evaluation at factories is a filter’s flow rate, the volume of water that filters from a full, water-saturated filter in one hour (L/hr). Silver is added to filters as a bactericide, either by surface application to fired filters or by directly including silver in the filter mixture.

In households, water treated by CWFs is often improved to the World Health Organization’s (WHO) low-risk classification of <10 CFU *E. coli* /100 mL (WHO 1997, Roberts 2004, Brown, Sobsey, and Loomis 2008). Laboratory studies have documented ≥2 Log Reduction Value (LRV) of protozoa and protozoan-sized particles (Lantagne 2001b, Van Halem et al. 2007, Bielefeldt et al. 2010), >2-7 LRV of bacterial organisms (Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al. 2007) and variable virus reduction (<1-3 LRV) (Brown and Sobsey 2010, Matthies et al. 2015, Van Halem et al.

2007). Epidemiological data has also shown that filter use is associated with a 49-80% diarrheal disease reduction (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014). Thus, CWFs are expected to meet the World Health Organization (WHO) HWT health-based performance classification of "one-star", as meeting reduction criteria for two classes of pathogens (>2 LRV of protozoa and bacteria, but not >3 LRV of viruses) and having evidence of health impact (WHO 2011a).

Currently, CWFs are manufactured in >50 independently run factories worldwide. While research on filters has widely documented that filters can be effective in the laboratory and in situ, and decentralized manufacturing provides a local supply chain and small business opportunities, there is concern that variability in quality control protocols results in variable filter quality. A survey of filter manufacturers found that manufacturing and quality control protocols vary within and across factories in: 1) criteria for modifying filter mixture ratio; 2) flow rate criteria and test protocols; 3) the amount and type of silver applied; and, 4) bacteria reduction test protocols (Rayner, Skinner, and Lantagne 2013). This leads to concerns about production consistency and quality control both within and across decentralized production facilities. Furthermore, recent evaluations have reported of filters of variable quality reaching households (Lemons et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Rayner, Murray, et al. 2016).

With recognition that factories have access to different materials and resources and the aim of providing guidance to assist "factories in producing the most effective ceramic filters possible at the lowest cost", the Ceramics Manufacturing Working Group (CMWG), comprised of individuals from governments, academia, non-governmental organizations and filter manufacturers, compiled a set of guidelines, *Best Practice*

Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment (CMWG 2011). *Best Practice* recommendations for quality control in filter manufacturing, briefly, are to develop a recipe that produces filters that meet both factory flow rate criteria and ≥2 LRV of bacteria pre-silver application (if silver is not fired-in), then produce subsequent filters the same way. It is recommended that production be documented and consistency monitored through regular flow rate testing, to demonstrate that subsequently produced filters are representative of those tested for microbiological removal.

While originally, a 1-2 L/hr flow rate guideline was established reportedly as theoretically this would provide the required contact time between the water and silver for disinfection during filtration (Lantagne 2001b), research has demonstrated that silver longevity in filters can depend on type and concentration of silver applied (Rayner et al. 2013) and influent water characteristics (Mittelman et al. 2015). Thus, the current recommendation is that filters be tested and achieve ≥2 LRV of bacteria in advance of silver application (CMWG 2011).

The aim of this project was to develop a framework for evaluating quality control protocols in decentralized ceramic water filter factories by: 1) developing tools that can be used to document manufacturing protocols in advance of and during a factory visit; 2) visiting four factories to evaluate and refine the tools and document manufacturing protocols; and, 3) testing the filters manufactured at the factories for flow rate and bacteria removal. Results from factory visits and filter tests were evaluated to provide recommendations for modification of the quality control protocol evaluation framework and lessons learned are presented.

5.3 Methods

Quality control evaluation tools development. A *Manufacturing Protocol Questionnaire* was developed from the recommendations included in the *Best Practice* guidelines (CMWG 2011). The intention was for a factory representative to complete this questionnaire in advance of a factory visit. A *Factory Evaluation Checklist,* was developed for an external assessor to complete during a factory visit.

Factory visits. Four factories were visited. During approximately 1-week long visits to each factory, the following activities were conducted: 1) discussing the proposed quality control evaluation process; 2) discussing and documenting current reported production methods and quality control protocols; and, 3) observing and documenting current filter production.

Laboratory testing: Six filters from each factory, three with and three without silver application, as available, were transported to the Environmental Sustainability Laboratory at Tufts University, Medford, MA, USA for flow rate, *E. coli* removal testing. Upon arrival in the laboratory, to reduce possible contamination, filters were heated gradually to 100°C, temperature was held for 15 minutes, then allowed to cool.

Before flow rate testing, filters were filled with deionized water to saturate overnight. Pore volume was calculated as saturated weight minus dry weight. Flow rate was calculated as the volume (in liters) of water passing through a full (falling-head), water-saturated filter, per hour (L/hr).

E. coli (ATCC® 25922) was grown in LB broth (Difco™ Lennox). *E. coli* concentration was estimated by spectrophotometer reading (GeneQuant 100, GE Healthcare, Pittsburgh, PA). Challenge water was prepared by adding enough broth to deionized water to achieve a concentration of 1 x 10^7 *E. coli* CFU/100 mL and stirred for 1 minute with a sterile stirring stick. Three water-saturated (deionized) filters were filled with *E. coli*-spiked water (6-10 L, depending on the filter capacity). After ~3 pore volumes of water had accumulated in the receptacle (to displace the volume of non-spiked water remaining within the filter pores), samples were collected directly from a control of spiked-water (to evaluate for bacteria die-off), from inside the filter and from each filter using a sterilized funnel to direct the filtered water sample into a sterilized container. Samples were refrigerated at 4ºC and processed within six hours.

Samples were processed using the IDEXX Quanti-Tray® /2000 method and Colilert® media for quantifying the most probable number (MPN) of *E. coli*/100 mL. Samples expected to have greater concentrations than the test detection limit of <2,419 MPN/100mL were diluted appropriately with phosphate buffer solution (0.05 m). Trays were incubated at 35ºC for 24-48 hours. *E. coli* MPN/100mL results were interpreted according to manufacturer instructions by counting the number of large and small wells that fluoresced. The Quanti-Tray/2000™ Most Probable Number table was used to calculate the *E. coli* concentration in MPN/100mL. Log_{10} reduction value was calculated by subtracting the Log_{10} filtered concentration from the Log_{10} influent concentration.

Each filter was tested twice for flow rate and *E. coli* removal. Between tests, filters were emptied, dried, heated gradually to 100°C and held at that temperature for 15 minutes. After flow rate testing and before adding *E. coli*-spiked water to the filters, a sample was collected from the filtered saturation water to check for *E. coli* presence in the filtered water.

5.4 Results

5.4.1 Quality control evaluation tools

The *Manufacturing Protocol Questionnaire* was developed in Microsoft Excel (Redmond, WA, USA) to obtain information regarding filter manufacturing before a site visit assessment was conducted. The form had 10 sections, including: background information, raw materials and processing, filter production, firing, quality control evaluations, filtered water testing, silver, packaging, documentation, and health and safety. Unfortunately, it was not possible to administer the survey in advance due to project timing. Thus, the questionnaire was completed during the site visit in an interview with a factory representative.

A *Factory Evaluation Checklist* was developed in Microsoft Word to guide the site visit. This form followed the same framework as the pre-visit questionnaire, but contained additional sections on observed practices and recommendations. This form was completed by the assessor while observing production. When it was not possible to observe all stages of production, this was noted on the form, and the form was completed based on verbal information provided by the production manager.

5.4.2 Factory visits

Four factories were visited during 2013–2014. Production was observed at three of four factories, as one factory was not producing filters during multiple scheduled visits. Mechanized filter production at the four factories was established between 2004 and 2010. Monthly production capacity ranged from 150–4,800 filters and the number of employees ranged from 6–59. Three of four factories produce filters regularly; the remaining manufactures filters when they receive an order. Filter units are sold for between 28–71 USD; one factory includes delivery and education in the price. Two factories also offer wholesale pricing. Filters are advertised to last from 1–5 years.

Equipment: Three of the four factories have reliable access to electricity from the grid. All factories have at least one hammer mill and a mixer. Mixer capacities ranged from 6–31 filters per mixture batch. Two factories have manual presses and two factories have automatic presses with between 1–3 molds per press. Factories have 1–2 kilns for filter production with capacities ranging from 70–250 filters per kiln load and are fueled by wood, agricultural by-products and two factories fire with propane.

Raw materials and processing: Two factories have on-site private wells, one factory collects rainwater (supplemented by tanker truck water) and the fourth factory relies exclusively on tanker truck water (Table 16). One factory has reserved a single–seam of clay, and the other three acquire clay from a single mine. Factories receive enough clay to manufacture 400-14,400 filters per shipment. None of the factories reported testing clay for shrinkage or porosity. While one factory did not describe their clay evaluation protocol, the other three factories described: 1) carrying out visual and tactile evaluations on the clay for uniformity of color, plasticity and sand content; 2) carrying out visual evaluations and removing non-uniform clumps of clay; and 3) by manufacturing and testing filters for flow rate with every new shipment of clay.

Three factories process the clay dry; the fourth processes it wet or dry (Table 16). All four factories mill the clay and two sieve it through 20 or 32 mesh screens (Tyler equivalent). All four factories use sawdust for burn-out material; two of the four exclusively acquire pine sawdust from a contracted mill, and the other two acquire multiple types of sawdust from multiple sources. One factory mills the sawdust, and all four sieve the sawdust. Mesh size ranges from 10 mesh to 32 mesh. Three factories purchase silver nanoparticles from a regular supplier and the fourth purchases a colloidal silver solution of varying concentrations from multiple sources.

Table 16: Materials & processing

	Factory 1	Factory 2	Factory 3	Factory 4
Water source	Rain / Tanker	Tanker	Private well	Private well
Clay source	Single seam	Single source	Single source	Single source
Clay testing	Visual, tactile	N.I.*	Test filters	Visual
Number of filters per clay shipment	800	400-500	14,400	6000
Clay processing	Dry	Wet or Dry	Dry	Dry
Clay milled	Yes	Sometimes	Yes	Yes
Clay mill screen	5mm	N.I.	5mm	5mm
Clay sieve mesh	32	N/A	N/A	20-25
Burn-out source	Contracted mill	Variable	Contracted mill	Variable
Sawdust type	Pine	Variable	Pine	Variable
Burn-out milled	Yes	No	No	Equipment broken
Burn-out sieve mesh	32	~12	10	20 - 24
Silver supplier	Regular	Regular	Multiple	Regular
Silver type	nAg	nAg	Colloidal	nAg
Silver form	Solution	Powder	Solution	Solution

*N.I. no information provided
nAg: silver nanoparticles

Filter manufacturing: Factories modify the filter mixture ratio when flow rates fall out of target (2 factories) or with each new shipment of clay (2 factories) (Table 17). The procedure to establish or change the filter mixture ratio varies. One factory manufactures 2-3 filters with three different ratios and selects the ratio that produces filters that fall within the target flow rate range; another factory carries out this same process, but using 10 filters and 10 ratios. One factory manufactures 30 filters and tests them for flow rate, and the other manufactures 50 filters and requires that 90% of the filters fall within the flow rate to use the new mixture ratio. At one factory, one filter of the proposed ratio is tested at a laboratory for microbiological removal.

Filter mixture ratios are measured by weight at three factories, with one factory commenting that the same weight of burn-out material varies widely by volume (Table 17). The remaining factory measures sawdust by volume and clay by weight. Two factories include reprocessed filter material in the filter mixture. One factory includes grog (ground and sieved fired ceramic from rejected, fired filters) regularly in the filter mixture and one factory includes up to 3% reprocessed filter mixture from rejected, unfired filters in new filter mixture.

Filter material is mixed from ~2-10 minutes dry, or until visually homogeneous at one factory and from 6-35 minutes wet, or until visually homogeneous at one factory (Table 17). Between 6 and 31 filters can be pressed from each mixture batch. Mold mis-alignment was both reported and observed as an issue at two factories; at these two factories mold alignment is either checked before pressing each new mixture batch, or when uneven thickness is extreme enough to cause cracking. After filters are pressed, all factories report stamping filters with a serial number and three factories stamp filters with a logo; however, filters from one of the factories were unmarked.

Firing: The peak firing temperatures range from 760-1100°C across factories (Table 17). None of the factories use pyrometric cones to measure the 'heatwork', the effect of time and temperature on the ceramic wares (Table 17). However, all factories use a pyrometer with 1-6 thermocouples to measure the temperature in the kiln. Two factories report 4-4.5 hours of firing time, the other two report that reaching peak temperature can take 1.5 to2 days, or from 5 to 12 hours or more.

Silver application: All four factories apply silver to filters (Table 17). Two factories apply silver to the filter mixture, one dips fired filters in silver solution and one brushes silver solution onto the fired filter. Two factories carefully measure out silver for application, while the other two factories do not prepare silver consistently. One factory uses the same dilution process (the same volume of concentrated silver solution is added to the same volume of water to prepare silver application solution) regardless of the initial silver concentration received and the other demonstrated preparing silver solution by visually estimating the amount of silver to add to an unmeasured volume of water.

Table 17: Filter manufacturing

	Factory 1	Factory 2	Factory 3	Factory 4
Filters made per new ratio	2-3	10	50	30
Criteria to accept new ratio	Flow rate	Flow rate	Flow & lab	Flow rate
Reason to adjust	Flow rate	New clay	New clay	QC concern
Filter mixture ratio (clay:burnout:grog)	80:20:0	N.I.	86:14:0	65:23:12
Ratio by	Weight	Weight/Volume	Weight	Weight
Reprocessed in mix	≤3% Raw	Yes	No	Grog
Filters per batch	25	N.I.	6	29-31
Mix time dry (min)	10	Visual	2	10
Mix time wet (min)	35	Visual	6	30-35
Mold alignment check	Each batch	N.I	Not needed	If cracking
Filter I.D.	Serial	Serial	Serial	Serial
Logo	Yes	No	Yes	Yes
Peak temperature	860°C	1100°C	760°C	830°C
Soak time, min	30	0	0	0
Pyrometer	Yes (2)	Yes	Yes	Yes
Thermocouples	2	1	6	1
Firing time	4.5 hrs	1.5-2.0 days	5-12+ hrs	4 hrs
Silver concentration applied	Consistent	Variable	Variable	Consistent

N.I. = no information

Quality control: Factories had variable quality control practices and rejection criteria (Table 18). The only consistently applied quality control check carried out at all factories and on all filters were visual inspections to look for cracks, irregular rim shape, or inconsistencies after firing. Three of four factories carry out auditory testing – by knocking the filter to listen for a ringing sound suggesting the filter has been fired to temperature and does not have cracks – on all of their filters, and the fourth carries out this test occasionally. Pressure tests are carried out at one factory but only on selected filters: those that fail auditory testing and pass the rim pull test, or those that are to be flow rate tested; however, there is no rejection criteria for this pressure test, all filters pass. A quality control test not described in *Best Practices* is rim pull testing. This test was introduced to address high breakage rates and consists of pulling the filter rim in various locations. Filters with weak spots or small fissures will break. This test was carried out at two factories, but one factory discontinued this test. At the factory that carries out rim pull tests, only filters that failed auditory testing are rim tested.

Target flow rate ranges from a minimum 0.4-1.5 to maximum 2.0-2.3 L/hr (Table 18). Only one factory flow rate tests 100% of filters; however, filters that have flow rates falling within the acceptable range pass regardless of the within batch consistency. The other three factories test from 4 -10% of filters, and accept filters that have flow rates outside of their target range. Filters are selected either per mixture batch or per kiln load.

All factories test filters for microbiological removal (Table 18). Laboratory testing of filters is carried out at three of the four factories on 0.1-0.4% of filters. Filters are tested at the factory at two of the four factories on 4-6% of filters. Laboratory test protocols were not available and the lower test detection limit for the on-site test method used at two factories is 20 MPN/100mL. At one of the factories, only the filtered water is tested, so verification of contamination of influent water is not carried out.

Overall, factories report 2-5% rejection rate before firing and 2-11% rejection rate after firing (based on cracking, distortion and/or auditory tests) (Table 18). Rejection rates from flow rate testing were not applicable for two factories, no information was provided at one factory and variable at the other factory – with up to 70% of filters rejected per firing based on flow rate. All factories, regardless of the consistency within the batch, accept filters that fall within the target flow rate range. Two factories document production extensively, one discontinued documenting production and one factory did not provide information on production documentation.

Table 18: Quality control and documentation

	Factory 1	Factory 2	Factory 3	Factory 4
Quality and consistency evaluations				
Visual inspections	100%, 4 stages	100%, 2 stages	100%, 2 stages	100%, 4 stages
Auditory test	100%	100%	Occasional	100%
Pressure test	0%	0%	0%	Selected filters
Rim pull test	0%	0%	0%	Selected filters
Flow rate test	12%	4-100%*	100%	6%
Flow rate (L/hr)	0.4-2.3	1.5-2.0	1.0-2.0	0.7-2.2
Microbiological testing				
In house	4%	0%	0%	6%
Water tested	Source/filtered	N/A	N/A	Filtered
Laboratory	0.1%	0.4%	~0.1%	0%
Water tested	Source/filtered	Unknown	Source/filtered	N/A
Tested pre-silver	No (N/A)	No		No (N/A)
Rejection rates				
Before firing	8-12%	N.I.**	3-4%	2-5%
After firing	2-10%	6-8%	3%	10-11%
Flow rate	N/A	N.I.	30- 70%	N/A
Total	10-22%	N.I.	~30%, variable	15-20%
Documentation	Extensive	N.I.	Extensive	None

*4% are tested per batch, if any fail, the rest of the batch is tested
**N.I. No information provided

Packaging: All four factories sell filters with plastic 5-gallon/20-Liter buckets for distribution in rural areas and two have terra cotta or glazed ceramic receptacles for urban sales (Table 19). Each filter comes with cleaning instructions. The advertised filter lifespan varies from 1-5 years.

Table 19: Packaging

	Factory 1	Factory 2	Factory 3	Factory 4
Receptacle	Food-grade plastic 20-L bucket (rural) Ceramic (urban)	Food-grade 20-L plastic buckets	20-L buckets (rural) Terra cotta/glazed (urban)	Food-grade 20-L bucket
Cleaning instructions	Once a week brush inside and outside. Every 3 months submerge in boiling or chlorinated water for 5 minutes.	When flow rate slows, wash with brush inside and outside	Every 3 months clean with a new sponge and filtered water	Once a week brush inside and outside, dip in chlorinated water for 5 minutes.
Lifespan	5 years	1.5+ years	1 year	2 years

Health and safety: Production was only observed at 3 of the 4 factories, thus health and safety precautions observations were limited to three factories (Table 20). Two of the three factories had sanitation facilities and all had hand-washing facilities and filtered water available. Employees at all three factories where production was observed had access to personal protective equipment (PPE), such as N95 facemasks, a uniform or plastic to cover clothing and eye protection. While there was access to PPE, not all employees were observed using it at critical times. Only one factory cleaned the floor with water, which is important to reduce the suspension clay dust in the air. Dust suspension was noted as a particular concern at one factory while sieving clay. Smoke emissions from the kiln are also a health concern at one factory. At one factory, some processes were carried out at night to reduce exposure to all employees. One factory actively promoted a healthy working environment, including providing employees with freshly prepared meals.

Table 20: Health & Safety observations

	Factory 1	Factory 2	Factory 3	Factory 4
Sanitation	Toilet on-site, hand washing and filtered drinking water available	Not observed	Toilets on-site, hand washing and filtered drinking water available	No on-site sanitation, hand washing and filtered drinking water available
Dust control	Equipment location separate from production floor; dry sweeping of floor		Equipment model and location reduces exposure; floors cleaned with water	Sieving method promotes dust suspension; dry sweeping of floor
Smoke control	Fine		Fine	Flames & smoke exit kiln chamber
PPE available	N95 facemask, eye protection, work gloves, plastic sheets as aprons		N95 face masks, eye protection, gloves (silver application), uniforms	N95 facemasks, eye protection, no heat gloves, plastic sheets as aprons

5.4.3 Laboratory testing

Three filters, each with and without silver application, as available, from each factory (21 filters) were transported to Tufts University for laboratory testing (Table 21). Eleven (11) filters broke during transport, thus 10 filters were tested for flow rate and LRV. At least one filter from each factory was tested. One filter without silver was tested from three of the four factories and three filters with silver from each of two factories were tested, one filter with silver was tested from one factory and no filters with silver were tested from the remaining factory.

Table 21: Summary of filters tested

	Factory 1	Factory 2	Factory 3	Factory 4
Without silver	1	1	1	0
With silver	3	0	1	3

Flow rates ranged from 0.6-3.5 L/hr on the first test to 0.7-5.3 L/hr on the second test (Figure 20). The only filter that did not meet the minimum flow rate on both tests was a filter produced without silver fired-in and thus was not from a standard factory production batch.

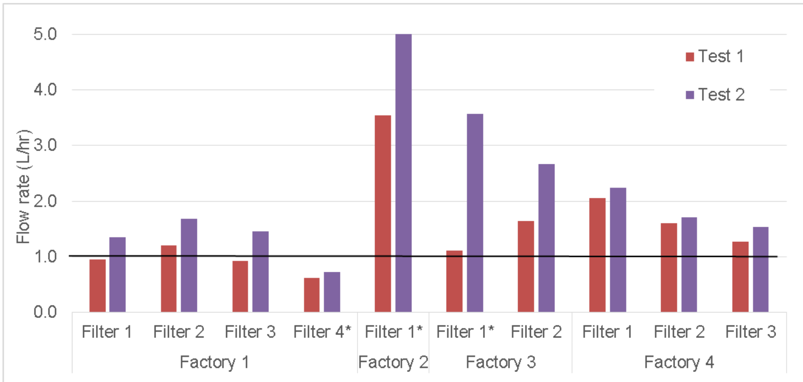

Figure 20: Flow rates of filters
* indicates filters without silver

Three filters from three factories were tested without silver application; seven filters from three factories were tested with silver application (Figure 21). Influent *E. coli* concentrations ranged from 1 x 10^6 to 1 x 10^8 MPN/100 mL. Only one filter met the *Best Practice* guideline of ≥2 LRV without silver application and it achieved this on two consecutive tests. For filters with silver, maximum LRV was achieved by five of six filters from two factories on the first test (1 *E. coli* MPN/100mL was detected in the filtered water of the sixth) and between 3-4.3 LRV on the second test. Filters from the other two factories did not achieve 2LRV on both tests with or without silver application.

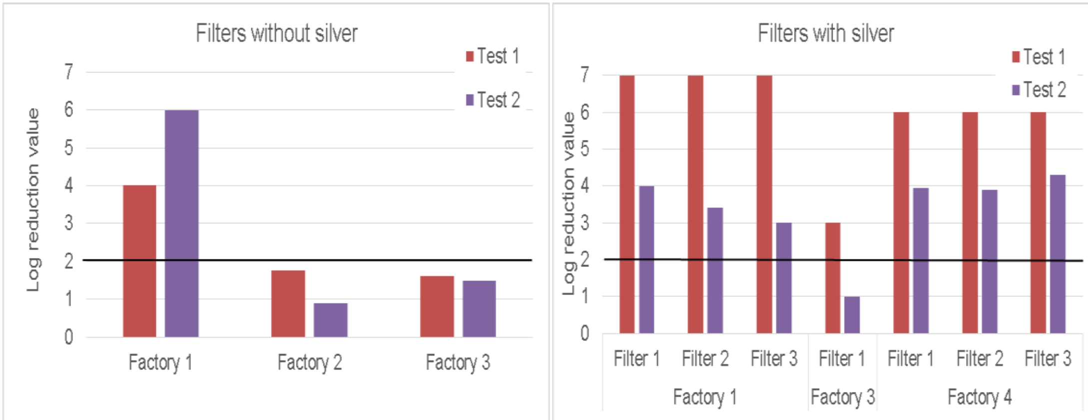

Figure 21: Log reduction values of filters without and with silver application

5.5 Discussion

We developed a framework to evaluate quality control protocols at ceramic filter factories based on *Best Practice* guidelines. Protocol assessment tools were developed, four factories were visited, production protocols were documented and observed, and filters were tested for flow rate and *E. coli* LRV. We recommend that filters achieve ≥2 *E. coli* LRV (pre-silver application, if possible), the quality control protocol in place applies production consistency criteria, production is documented and a safe working environment is promoted. Filters from two factories met the ≥2 *E. coli* LRV guideline; however, across the four factories, quality control protocols either did not evaluate consistency or did not apply consistency criteria; only two factories documented production, and health and safety was a concern at one factory (Table 22).

Table 22: Overall quality control assessment

	Factory 1	Factory 2	Factory 3	Factory 4
Met ≥2 LRV criteria	Yes	No	No	Yes
Applies consistency criteria	No	No	No	No
Documents production	Yes	Production not observed	Yes	No
Promotes safe working environment	Yes		Yes	No

While filters produced at two factories (Factories 1 and 4) met quality criteria for LRV, the quality control protocols did not monitor production consistency. Therefore, it was not possible to evaluate whether the filters tested were representative of other filters produced at the factories. The reported filter rejection rates of 10-22% and 15-20% fall within the expected range set forth in *Best Practices* (10-20%); however, only a selection of filters are flow rate tested, the primary recommended production consistency evaluation. For some quality control tests there was no rejection criteria.

At Factory 3 where flow rate testing is carried out on 100% of filters, the current manufacturing process does not result in consistent filters being produced. Up to 70% of filters in a batch can fail flow rate testing but filters that fall within the 1-2 L/hr flow rate can still be sold or distributed. Thus, flow rate is used as rejection criteria, but production consistency is not required.

While all of the factories meet *Best Practice* recommendations for frequency of either laboratory or in-house testing, the following possible limitations to the effectiveness of water quality testing were noted: 1) laboratory testing methods were not available, and the verbal description provided by one laboratory was not technologically viable; 2) on one occasion, factory representatives incorrectly interpreted laboratory test results; and,

3) when testing at the factory, paired analysis of influent and effluent bacteria concentrations was not conducted.

Over half of the filters brought for testing broke in transit (11 of 21). The high breakage rate could be a result of poor filter strength or packaging. While broken filters could not be tested, internal cracks, though not visually identified, in filters that did undergo laboratory testing may have affected test results. This implies that filters that meet specifications in the factory and subsequently transported in-country, may not effectively treat drinking water in homes. While filter strength is an important aspect of filter quality (along with LRV and flow rate) as breakage has been cited as a primary reason for discontinued filter use (Brown, Proum, and Sobsey 2009), currently no protocol or criteria exist for evaluating filter strength. Thus, it is recommended that a protocol for CWF strength testing be developed.

While factories have access to different materials and resources, and therefore production and quality control processes may vary, filter quality and production consistency should be carefully monitored. We propose this framework be incorporated into a Quality Control Protocol Evaluation Process. Recommendations for modification of the quality control protocol evaluation framework include:

1) The factory quality control protocol evaluation should include two site visits. Since none of the factories met the proposed criteria, it is expected that follow-up visits will be needed. The level of detail documented during on-site visits allows for specific recommendations to help factories in troubleshooting problems. The second visit does not need to be conducted if all criteria are met.

2) Filters should be tested locally. Very few filters were tested due to breakage during transport, and concern has been raised that some filters may have had internal cracks that formed during transport. It is therefore recommended that filters be evaluated for microbiological removal during the on-site assessment rather than transporting filters for testing. This is both to ensure a minimum of three filters are tested (pre-silver application) and to reduce the chances of testing cracked filters.

3) Strength evaluation should be carried out. Manufacturing protocols should optimize three performance criteria: LRV, flow rate and strength. Currently there is no protocol for testing or criteria for filter strength. This framework does not, but should, include strength evaluations. It is recommended that a protocol be developed and incorporated into the quality control evaluation process.

A possible limitation of the framework is that a ranking system of importance across individual production variables was not developed. Due to variability in materials characteristics and methods, it may not be possible to develop a transferrable ranking system and thresholds for variability.

Lastly, it is recommended that a Quality Control Protocol Evaluation Process include: 1) information about expectations for quality controlled filter manufacturing, the theory behind quality control processes and tests, consistency and the purpose of rejection criteria; 2) information on microbiological testing and lab protocols, options and methods for on-site testing, and sample laboratory methods protocols and laboratory results interpretation; 3) tools for factories for analyzing production documentation; and, 4) information about health and safety risks and suggestions for exposure prevention or reduction, in particular surrounding silica dust exposure.

5.6 Conclusions

The Ceramic Manufacturing Working Group has been working on quality control in filter manufacturing since 2008. The results help to understand challenges factories face and how to promote quality controlled filter production. We propose this framework be incorporated into a Quality Control Protocol Evaluation Process, with recommendations that filters achieve ≥2 *E. coli* LRV (pre-silver application, if possible) guideline, criteria to monitor production consistency is applied, production is documented and a safe working environment is promoted.

Some recommended modifications are that two factory visits be expected, that filters be tested locally and that a strength testing protocol be developed and incorporated into this process. Based on the results of these evaluations and the criteria developed for evaluating quality control protocols, we expect that the development of a Quality Control Protocol Evaluation Process will support factories in developing and maintaining quality control systems to consistently produce high quality filters.

5.7 Acknowledgements

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6 A Systematic Review of Ceramic 'Pot' Filter Effectiveness for Drinking Water Treatment

6.1 Abstract

Ceramic water filters (CWF) are manufactured at >50 decentralized factories worldwide; thus, materials and methods vary. Much research has been carried out to investigate the effectiveness, efficacy and impact of CWFs; however, the breadth of research on CWF effectiveness has not been compiled, contextualized and evaluated. The aim of this review is to systematically evaluate and synthesize published research on CWF performance, with a specific focus on manufacturing materials and methods, in order to further guide manufacturing recommendations and to identify research needs. A protocol was developed, which consisted of inclusion criteria, search strategy, selection and processing strategies, quality assessment and an analysis plan. Data was extracted from 57 full-text manuscripts. With the exception of investigations specifically designed to evaluate manufacturing variables, little information on manufacturing materials and methods and their effects on CWF performance criteria of flow rate, bacteria removal, and filter strength, was reported in the published literature. Results from these studies suggest that: 1) an increased proportion of burn-out material or firing temperature can increase flow rate and may not substantially compromise bacteria removal performance; 2) particle size of burn-out material is important to control for consistent bacteria removal; 3) an increase in firing temperature can increase filter strength while increased proportions or size or rice husk reduces strength; and 4) silver nitrate application to fired filters may not result in sustained improved performance; nAg appears to be retained better in the filter, thus may provide sustained improved performance. Thus, it is recommended to test filters for LRV prior to silver application to evaluate the efficacy of the filter material at bacteria removal and to control the particle size of burn-out material during manufacture. These findings and recommendations are limited by the parameters

evaluated in the literature. Further research is recommended into the effects of manufacturing variables on performance criteria.

6.2 Introduction

Household water treatment (HWT) can improve drinking water quality (Clasen, Cairncross, et al. 2007) and reduce diarrheal disease (Fewtrell et al. 2005, Clasen et al. 2006, Clasen 2015) where access to safe drinking water is limited (UNICEF/WHO 2011). Locally manufactured ceramic ‘pot’ water filters (CWF) are considered an effective HWT technology (Sobsey et al. 2008). The technology was developed in Guatemala in 1981 and designed to be manufactured by artisans using locally available materials. In 1999 the manufacturing process was mechanized, standardized and promoted internationally. Currently, CWFs are manufactured at >50 independently operated factories worldwide. CWFs are comprised of an ~10L capacity, silver-treated ceramic filter element that suspends in a lidded safe-storage container. Water is poured into the filter, is gravity fed into the safe-storage container (receptacle) and is dispensed through a tap.

CWFs are manufactured by pressing a predetermined ratio of processed raw clay and burn-out material into the filter shape. Once dry, they are fired to a ceramic state (~800-900°C). During firing, the burn-out material combusts, creating a network of pores. The primary quality control check is a falling-head flow rate test where the volume of water that filters from a full, water-saturated filter in the first hour is measured and expressed as liters per hour (L/hr). Filters that meet flow rate criteria are coated with silver, a bactericide, before packaging and distribution. Originally, a 1-2 L/hr flow rate guideline was established, as theoretically this would provide the required contact time between the water and silver for disinfection during filtration (Lantagne 2001b).

Research has documented that CWFs can: 1) improve microbiological quality of water in the laboratory (Lantagne 2001b, Van Halem et al. 2007, Bielefeldt et al. 2010, Brown and Sobsey 2010, Matthies et al. 2015); 2) improve microbiological water quality during use (Roberts 2004, Brown, Sobsey, and Loomis 2008); and, 3) reduce diarrhea by 49-80% (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014). However, concerns about the production consistency of filters produced for distribution have been noted in household evaluations (Rayner, Murray, et al. 2016, Lemons et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011).

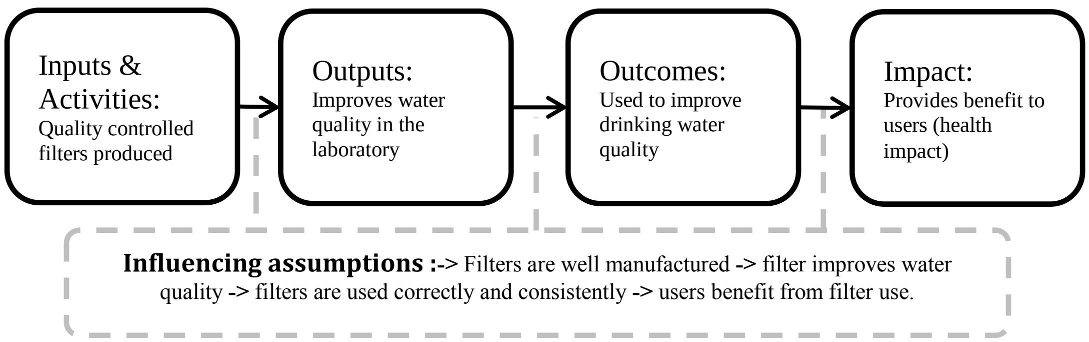
A survey of filter manufacturers documented variation in manufacturing processes and quality control protocols, both within and across factories, particularly with regards to filter mixture preparation, flow rate criteria, amount and type of silver application and quality control protocols (Rayner, Skinner, and Lantagne 2013). These results raise questions about the consistency of CWF quality.

While CWFs are designed to accommodate variability in materials and production processes, tolerance thresholds are not currently well defined or understood. In conducting this review, we attempted to gain insight into some research findings that do not appear consistent in the CWF literature. These include: 1) the relationship between flow rate and microbiological effectiveness (Lantagne et al. 2010, Rayner, Luo, et al. 2016); 2) the role of silver in filter performance (Brown and Sobsey 2010, van der Laan et al. 2014, Oyanedel-Craver and Smith 2008); 3) the effects of influent water characteristics on silver release (Mittelman et al. 2015, Rayner et al. 2013, Ren and Smith

2013); and, 4) differences in microbiological performance depending on materials specifications (Soppe et al. 2015, Rayner, Luo, et al. 2016). It is possible that discrepancies are due to differences in methods and materials, either during manufacture or research.

Theoretically, a well-manufactured CWF (input) that improves water quality in the laboratory (output) and is used to improve drinking water quality (outcome) should result in health benefits for the users (impact) (Figure 22).

Figure 22: Theoretical framework



To date, the breadth of research on CWF effectiveness has not been compiled, contextualized and evaluated. The aim of this review was to systematically evaluate research carried out on CWFs, with a specific focus on manufacturing materials and methods, to synthesize research findings, provide manufacturing recommendations and identify future research needs.

6.3 Methods

A protocol for the systematic review was developed that included: inclusion criteria, search strategy, selection and processing strategy, quality assessment and an analysis plan. Included in the review were peer-reviewed, published, primary research in any language that investigated CWFs used for drinking water treatment, and that measured: 1) outputs, 2) outcomes and/or 3) impacts.

Five electronic databases were searched: Engineering Village, Medline, Scientific Electronic Library Online (SciELO), Scopus and Web of Science, using key word strings including: “ceramic, filter, drinking water”. Identified records were entered into EndNote™ X7.7.1 (Thomson Reuters, New York, USA) and duplicates removed. All titles and abstracts of passing titles were screened for inclusion. Peer-reviewed manuscripts that measured outputs, outcomes, or impacts of CWF use were included in the review. For included full text documents, data (including manufacturing specifications, research methods, results and conclusions) were extracted into an Excel® 2013 (Microsoft Corporation, Redmond, WA) spreadsheet. First authors’ Google Scholar profile pages and references of all included manuscripts were reviewed to identify additional relevant publications and unpublished seminal papers (>20 citations in the literature).

Manuscript quality was assessed for risk of bias at research design, data collection and data analysis levels. For studies evaluating outputs, studies were assessed for risk of methodological bias, sampling variation and sample homogeneity. Outcome studies were assessed for risk of methodological bias, test method quality, detection bias, selection bias, attrition bias and response bias. Health impact evaluations were assessed for potential randomization bias, confounding, population variability, response bias and attrition. Each study was assigned a score of ‘low risk’=1, ‘medium/unclear risk’=2 and ‘high risk’=3 for each category. These scores were averaged for each study and studies were classified as having a low, medium or high risk of bias.

Manuscripts were grouped according to evaluation of outputs (laboratory efficacy), outcomes (filtered water quality during use) and impacts (health impact). Output studies were sub-grouped into studies that evaluated: 1) filter efficacy of factory-manufactured filters; 2) manufacturing variables; and 3) silver. Outcome studies were divided into: 1) observational studies; and 2) interventional studies. Impact studies were not further grouped. Manuscripts could be included in more than one group. Across all groups, results were stratified by manufacturing specifications (inputs), where possible, including: burn-out material type, processing, filter mixture ratio, firing temperature, and silver type, application methods and silver concentration (dose). For all study types, where results were only presented graphically, values were approximated by the author.

For output evaluations, filter efficacy was evaluated against Log_{10} Reduction Value (LRV) of pathogens or a surrogate as a performance indicator. Results were classified according to guidelines for filter performance in *Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment* for bacteria removal, which is ≥2LRV pre-silver application (CMWG 2011), and the WHO HWTS Certification Scheme 2-star performance criteria for distribution-ready products (i.e. with silver), which are ≥ 2 LRV for bacteria and protozoa and ≥3 LRV for viruses (WHO 2016). Where LRVs were not presented, if sufficient data were available, LRVs were calculated by the author as: Log_{10} influent–Log_{10} effluent. Test organism concentrations presented as concentration per mL were converted to concentration per 100mL. Please note that where influent water microbial concentrations were presented in units per mL, and maximum removal was achieved (filtered water samples were non-detect), LRV was also converted to maximum removal per 100mL.

For outcome evaluations, because log reduction calculations can be influenced by variability in indicator bacteria concentrations in source water, filtered water quality was classified by the WHO risk classification where <1 *E. coli* CFU/100mL meets drinking water quality guidelines, 1-10 represents 'low risk', 11-100 'medium risk', 101-1000 represents 'high risk' and >1,000 represents 'very high' risk (WHO 2011c).

6.4 Results

The systematic database search conducted in May 2017 returned 857 titles (Figure 23). After removing duplicates, 198 titles and 130 abstracts were excluded. An additional 15 titles were identified through reference tracing and Google Scholar profile searching of included manuscripts. Data were extracted from 47 manuscripts: 35 measured outputs, 14 measured outcomes and three evaluated health impact. Manuscripts spanned from 2001-2017, with two seminal reports produced in 2001 and two publications annually from 2007-2009, 4-7 publications annually from 2010-2016 and two manuscripts through April 2017. A list of all included studies are listed by group and sub-group in Table 23 (Section 6.7). Studies classified as high risk of bias were not included in the synthesis; these are noted in the relevant sections.

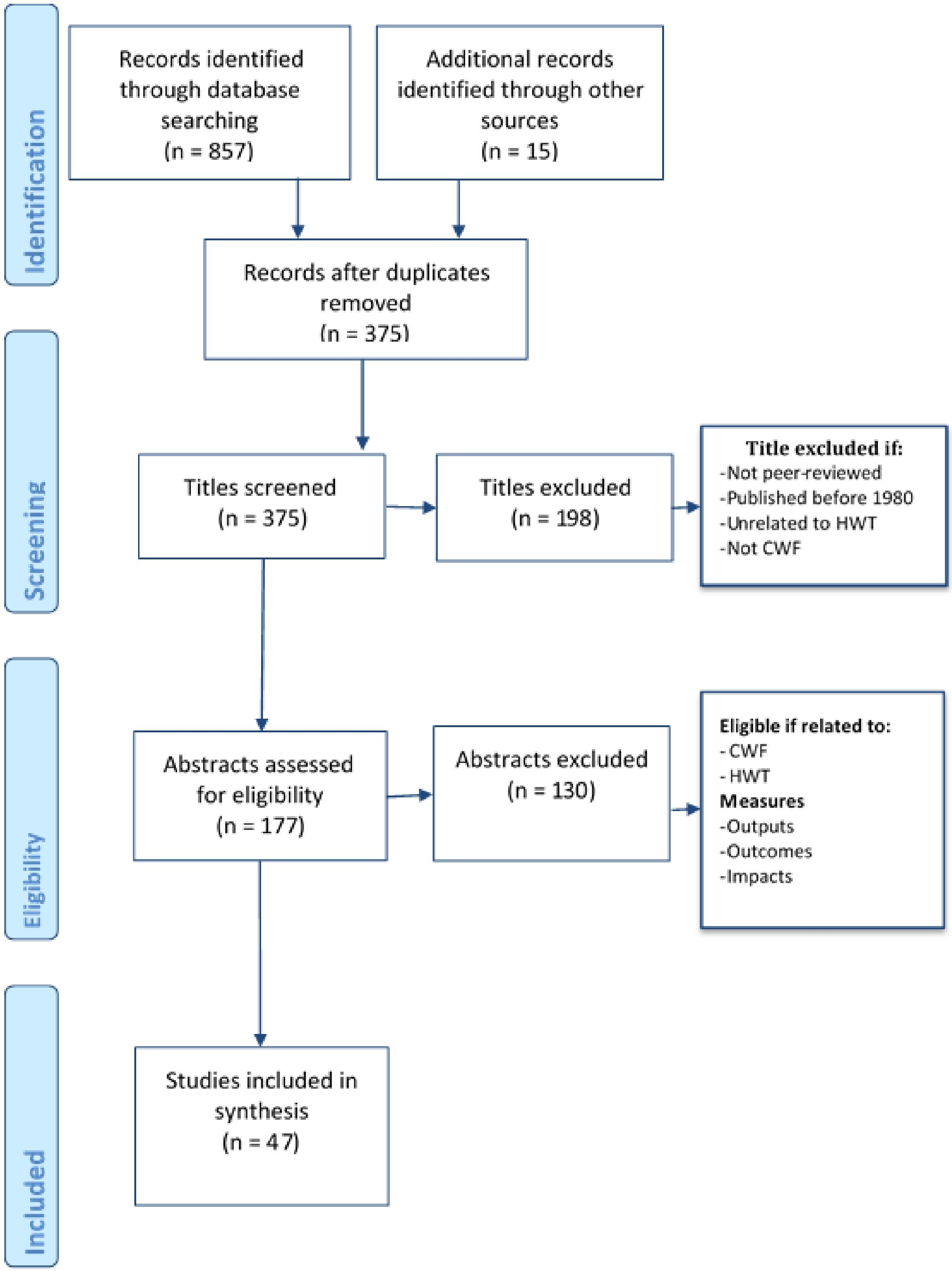


Figure 23: Record identification

6.4.1 Output evaluations

Results from the literature that measured outputs are sub-grouped into laboratory studies that measured factory-produced filter efficacy, that evaluated the effects of manufacturing variables filter characteristics and/or filter performance and that evaluated the role of silver on filter performance, are presented in the following sections.

6.4.1.1 Filter efficacy

Of 22 studies that evaluated filter efficacy in the laboratory, ten studies were not included in the synthesis: five evaluations tested factory-manufactured filters, but without controlled addition of surrogates (Baumgartner, Murcott, and Ezzati 2007, Clark and Elmore 2011, Murphy et al. 2009, Mikelonis, Lawler, and Passalacqua 2016, Salvinelli and Elmore 2015) and five evaluations were of non-factory manufactured filters (Adeyemo, Kamika, and Momba 2015, Mwabi et al. 2011, Mwabi, Mamba, and Momba 2012, 2013, Abebe, Chen, and Sobsey 2016). Several studies evaluated filters from multiple factories, or with varying use history, where this occurred and results were stratified, these are referred to as 'filter types'.

The remaining 12 studies evaluated 61 factory-manufactured filters and completed from 1-84 tests for pathogen surrogate removal with laboratory prepared challenge water (Matthies et al. 2015, Bielefeldt et al. 2010, Brown and Sobsey 2010, Farrow, McBean, and Salsali 2014, Lantagne et al. 2010, Pérez-Vidal, Diaz-Gómez, et al. 2016, Pérez-Vidal, Díaz-Gómez, et al. 2016, Van Halem et al. 2007, Salsali, McBean, and Brunsting 2011, Bielefeldt, Kowalski, and Summers 2009, Lantagne 2001b, Plappally et al. 2011). Filters were manufactured at nine factories in seven countries.

In three of the studies (14 filter types), filters had been used for previous research or in households, in five studies (12 filter types) filters were new and the remainder of the studies (n=4, 7 filter types) did not report whether the filters were new or had been previously used.

Included in the 12 studies were 33 filter types manufactured with local clay and sawdust (4 studies, 10 filter types), rice husk (3 studies, 10 filter types) or the burn-out material type was not specified (5 studies, 13 filter types). One study reported the clay had been sieved, one study reported on clay characteristics and five studies (17 filter types) reported the burn-out material had been sieved through screens up to 1.2 mm openings. Filter mixture ratios (ranging from 40:60 to 60:40 clay to sawdust by volume) were reported for 10 filter types (4 studies). Goethite, an iron based mineral thought to increase virus removal, was included in the filter mixture in two studies (3 filter types) (Farrow, McBean, and Salsali 2014, Salsali, McBean, and Brunsting 2011). Two studies reported burn-out type, ratio and mesh size (Lantagne et al. 2010, Bielefeldt, Kowalski, and Summers 2009). Peak firing temperatures ranged from 830-900°C (7 studies, 19 filter types). "Colloidal" silver was applied to 22 of the filter types (7 studies), silver nitrate had been applied to two filter types (2 studies), no silver was applied to six filter types (4 studies) and in three studies, it was not specified whether or not silver had been applied (3 filter types). The lack of reported manufacturing data prevents the comparison of filter performance against filter manufacturing specifications. Thus, LRVs of pathogen surrogates achieved by factory-manufactured filters for the three pathogen classes – bacteria, virus and protozoa – are summarized in the following sub-sections without stratification.

Bacteria. Nine studies measured bacteria removal in the laboratory from factory-produced filters (Matthies et al. 2015, Bielefeldt, Kowalski, and Summers 2009, Brown and Sobsey 2010, Lantagne et al. 2010, Pérez-Vidal, Diaz-Gómez, et al. 2016, Pérez-Vidal, Díaz-Gómez, et al. 2016, Van Halem et al. 2007, Plappally et al. 2011, Bielefeldt et al. 2010). Influent *E. coli* concentrations ranged from 1 x 10^5-10^9 CFU/100mL (18 filter types, 8 studies). Other bacteria surrogates tested included *Enterococcus faecium* (*E. faecium*) at 3.4 x 10^6 and 2.0 x 10^8 CFU/100mL and *Pseudomonas aeruginosa* (*P. aeruginosa)* at 8.7 x 10^7 and 1.8 x 10^9 CFU/100mL (Matthies et al. 2015) (1 filter type) and bacteria-sized microspheres (0.5μm, 1.0μm and 2.0μm) at 1.4 x 10^8 #/100mL, 8.6 x 10^6 #/100mL and 8.1 x 10^5 #/100mL influent concentrations, respectively (Bielefeldt et al. 2010).

All studies reported ≥ 2LRV (2-8 LRV) for bacteria surrogates by factory-produced filters regardless of silver application, with the exception of one study (Bielefeldt, Kowalski, and Summers 2009). In this study, three successive batches containing 1 x 10^8 *E. coli* CFU/100mL were filtered; however, following this, high concentrations of *E. coli* (1 x 10^7 *E. coli* CFU/100mL) where detected in filtered water from non-spiked influent; thus $\log_{10}$ reduction calculations were likely affected.

In other studies that tested filters over time (6 to 49 tests over six weeks to six months, with influent ranging from 1 x 10^5-10^7 *E. coli* CFU/100mL) the minimum reported LRVs for *E. coli* ranged from 2.8 to >5 LRV (Van Halem et al. 2007, Pérez-Vidal, Diaz-Gómez, et al. 2016, Pérez-Vidal, Díaz-Gómez, et al. 2016, Lantagne et al. 2010). One study that filtered >660 L (simulating ~3 months of use) of water from two different sources through filters with and without silver application reported that LRVs in the first

100 L of throughput, were significantly different from the LRVs achieved throughout the remainder of testing (minimum LRV was not presented) (Brown and Sobsey 2010).

Six filters challenged with bacteria-sized microspheres (0.5μm, 1.0μm and 2.0μm), tested 12 times per microsphere size, achieved mean 2 LRV, ≥2.5 and ≥2.7, respectively (Bielefeldt et al. 2010). For both the 1.0μm and 2.0μm particle sizes, filters achieved maximum removal in over half the tests (due to detection limits, maximum LRV for 1.0μm and 2.0μm microspheres ranged from 2.3-2.7 LRV and 2.9-3.5, respectively).

Protozoa. Three studies tested 31 filters for protozoa and protozoa surrogate removal (Bielefeldt et al. 2010, Van Halem et al. 2007, Lantagne 2001b). Protozoa and surrogates and influent concentrations were: *Giardia lamblia* (340,000 cysts/7L), *Cryptosporidium parvum* (260,000 oocysts/7L), sulphite reducing *Clostridium* spores (10^3-10^5 n/100mL) and protozoa-sized microspheres of 4.5μm (1.3 x 10^6 #/100mL) and 10μm (4.0 x 10^5 #/100mL).

Mean LRV results of protozoa and surrogates for the three studies ranged from 3-5 LRV and the minimum exceeded 2 LRV across all studies. One filter, tested once, achieved 4.3 and 4.6 LRV of *Giardia lamblia* and *Cryptosporidium parvum*, respectively. Six filters each from Cambodia, Ghana and Nicaragua with silver, and six filters from Nicaragua without silver, achieved mean 3.3 (range 2.1-3.6), 3.5 (range: 2.2-5.3), 4.2 (range 3.5-5.3) and 4.0 LRV (range: 2.5-5.3) in *Clostridium* spores. In another study, pooled results from six filters manufactured in Nicaragua with varying previous use history achieved mean 3 LRV (SD=0.20) and ≥3.25 LRV (SD=0.25) in 4.5μm and 10μm sized microspheres, respectively. Please note that the maximum LRV for 4.5μm spheres was 3.3-3.8 LRV and for the 10μm spheres 2.9-3.3LRV.

Viruses. Seven studies tested 48 filters for virus surrogate removal (Matthies et al. 2015, Brown and Sobsey 2010, Farrow, McBean, and Salsali 2014, Van Halem et al. 2007, Salsali, McBean, and Brunsting 2011, Lantagne 2001b, Bielefeldt et al. 2010). Six studies evaluated MS2 bacteriophage removal with influent values ranging from 1 x 10^5-10^{10} PFU/100mL (Matthies et al. 2015, Brown and Sobsey 2010, Farrow, McBean, and Salsali 2014, Van Halem et al. 2007, Salsali, McBean, and Brunsting 2011, Lantagne 2001b), one study (1 filter type) evaluated phi X 174 bacteriophage (φX174) removal with 9.0 x 10^4 and 2.4 x 10^4 PFU/100mL (Matthies et al. 2015) and one study evaluated 0.02μm and 0.10μm (1.3 x 10^{12} and 1.2 x 10^{10} #/100mL, respectively) sized microsphere removal (Bielefeldt et al. 2010).

None of the studies reported ≥3 LRV for virus removal for any of the surrogates. The highest LRVs achieved were by filters, with and without silver nitrate application, tested 34 times with each with rain or surface water. Filters with silver nitrate (n=4) achieved 1.3 LRV (95% CI: 0.83-1.8) and 1.5 LRV (95% CI: 1.1-1.9) of MS2 spiked in rain and surface water respectively, and filters without silver (n=4) achieved a mean 1.6 LRV (95% CI: 1.2-2.0) and 1.7 LRV (95% CI: 1.3-2.0), respectively (Brown and Sobsey 2010). MS2 LRVs of 24 filters manufactured in three factories in three countries, with and without silver, ranged from 0.65-1.25 LRV and 1.0-2.1 LRV at the two test time points of the study (weeks 5 and 13) (Van Halem et al. 2007).

MS2 virus removal for the remainder of the studies, that tested 1-6 filters up to seven times each, reported <1 LRV (0.21-0.6 LRV) (Matthies et al. 2015, Lantagne 2001b, Farrow, McBean, and Salsali 2014, Salsali, McBean, and Brunsting 2011). Similarly, <1 LRV was measured in phi X 174 bacteriophage (φX174) (0.5 and 0.6 LRV) (Matthies et al. 2015). Mean LRVs of virus-sized microspheres (0.02μm and 0.10μm) were 1.5 (SD=0.40) and 1.4 (SD=0.8), respectively, for six filters tested 12 times each per microsphere size (Bielefeldt et al. 2010).

Filter efficacy summary: Results suggest that filters should meet WHO HWT ‘two-star’ performance target for bacteria and protozoa removal as studies measured ≥2 LRV in bacteria and protozoa removal. Virus removal results are consistently below the 3 LRV WHO HWT ‘two-star’ performance target. Virus removal results are inconsistent, ranging from ~0.2-2.1 LRV. Some studies documented inconsistent bacteria removal performance across multiple tests; however, it is unclear whether this apparent variability is due to test methods or variability in filter performance over time.

6.4.1.2 Manufacturing variables

Thirteen studies evaluated manufacturing variables. Three studies were not included in the synthesis due to high risk of bias scores (Goodwin et al. 2017, Abiriga and Kinyera 2014, Varkey and Dlamini 2012) and bacteria removal results for one study were not included in the synthesis because influent water was not controlled (Lantagne et al. 2010).

Of the ten remaining studies, three evaluated researcher manufactured flat-bottomed filters (Soppe et al. 2015, Plappally et al. 2011, Yakub et al. 2013), one evaluated round-bottomed filters (Lantagne et al. 2010) and one did not specify filter shape, but only that filter dimensions were scaled (Guerrero-Latorre et al. 2015). Five studies manufactured and evaluated ceramic disks as surrogates for full-sized filters ranging from 3.8-10 cm in diameter and from 1.5-1.8 cm in thickness (Abebe et al. 2015, Rayner et al. 2013, Rayner, Luo, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Oyanedel-Craver and Smith 2008).

Studies evaluated the influence of filter manufacturing variables, including clay (n=4), burn-out material type (n=3), burn-out material to clay ratio (n=7), burn-out material processing (mesh size) (n=4), and firing conditions (n=2) on flow rate, LRV and/or strength. Flow rates were tested using a falling (Rayner, Luo, et al. 2016, Lantagne et al. 2010, Yakub et al. 2013, Plappally et al. 2011) or constant head (Soppe et al. 2015), by a variety of methods. In four studies that evaluated disk filters, flow rates were not tested as the influent flow rate was controlled at 0.5-0.6 mL/min (Rayner et al. 2013, Kallman, Oyanedel-Craver, and Smith 2011, Oyanedel-Craver and Smith 2008, Abebe et al. 2015).

LRVs were measured for each of the pathogen classes. Eight studies evaluated filters for *E. coli* removal with influent concentrations ranging from $1 \times 10^5 – 1 \times 10^9$ CFU/100mL (Guerrero-Latorre et al. 2015, Soppe et al. 2015, Yakub et al. 2013, Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Kallman, Oyanedel-Craver, and Smith 2011, Plappally et al. 2011, Rayner, Luo, et al. 2016), one study evaluated protozoa removal (0.6 ml pulse of 1×10^7 *C. parvum*) (Abebe et al. 2015) and one study evaluated virus removal (1×10^7 IU/100mL) (Guerrero-Latorre et al. 2015).

Strength was evaluated by measuring Modulus of Rupture (MoR) in one study (Soppe et al. 2015).

Results from these studies are presented below by manufacturing variable: clay, burn-out material type, ratio, mesh size and firing conditions. Results are presented in relation to the three performance criteria: 1) flow rate; 2) LRV; and 3) strength, and where reported, filter characteristics are noted.

6.4.1.2.1 Clay

Four studies evaluated filters manufactured with clay from different sources (Guerrero-Latorre et al. 2015, Rayner, Luo, et al. 2016, Rayner et al. 2013, Oyanedel-Craver and Smith 2008). One study characterized three clays for sand (>20μm)-silt (2-20μm)-clay (<2μm) distribution, surface area (m^2/g) and predominant clay mineral (Oyanedel-Craver and Smith 2008). Filter disks were manufactured, fired to 900°C and porosity, pore size distribution, hydraulic conductivity and *E. coli* reduction were measured. In disks with similar porosity values, median pore size was smaller and hydraulic conductivity and *E. coli* LRV increased with increasing clay content (Oyanedel-Craver and Smith 2008). Similarly, in a study that manufactured filter disks with clays from three different factories, higher *E. coli* LRVs were measured in disks manufactured with clay with higher clay content (Duocastella and Morrill 2012, Rayner et al. 2013, Rayner, Luo, et al. 2016). Each of the three clays; however, required different firing temperatures to achieve sufficient strength for testing. Another study compared calcareous (high calcium carbonate [lime content]) and two non-calcareous clay sources and found differences in chemical and mineralogical compositions between the clays, but filters (fired in a reduced atmosphere) did not demonstrate significant differences in LRVs of HAdV, MS2 or *E. coli* (α=0.05) across filters made with the different clays (Guerrero-Latorre et al. 2015).

Clay summary: Little research has been carried out to evaluate the influence of clay content and mineralogy on LRV and filter characteristics. It is hypothesized that higher clay content contributes to improved LRV. Additional research into clay characteristics (content and mineralogy) is needed to further evaluate possible influences on CWF performance.

6.4.1.2.2 Burn-out material

Three studies investigated the effect of burn-out material type on flow rate (Rayner, Luo, et al. 2016, Lantagne et al. 2010) and/or *E. coli* LRV (Rayner, Luo, et al. 2016, Rayner et al. 2013) on filters or filter disks. No studies were identified that evaluated burn-out material type on strength. Filters manufactured with the same volume ratio of sawdust, rice husks, or coffee husks to clay had flow rates of 2, 3.7 and 10 L/hr, respectively (Lantagne et al. 2010). Similarly, disks manufactured with rice husks had faster first-hour flow rates (24-cm falling-head) than disks manufactured with sawdust and the increase in flow rate with increased burn-out material or sieve size was steeper for rice husk disks (Rayner, Luo, et al. 2016). In this study, burn-out material type was a significant predictor of flow rate in multivariable regression analysis (α=0.05). It was also noted that disks manufactured with rice husk shrank less in height than disks manufactured with sawdust (Rayner, Luo, et al. 2016).

In disks manufactured with rice husk or sawdust, burn-out material type was a significant predictor of *E. coli* LRV in regression analysis (α=0.05); however, overall disks with rice husk did not achieve 2 LRV in *E. coli,* thus the study did not produce suitable reference filters with rice husks at the selected recipes (Rayner, Luo, et al. 2016). In contrast, disks manufactured with the same materials by the same manufacturer, but using only one recipe for both sawdust and rice husk disks, achieved similar *E. coli* LRVs (>2 LRV throughout 10 days of testing) whether manufactured with sawdust or rice husk (Rayner et al. 2013). A low concentration of silver (0.003 mg/g) had been applied to the disks and while no difference was observed between controls with and without silver, the control disks were manufactured with sawdust. Another difference between the studies is that in the first study (Rayner, Luo, et al. 2016), a 24-cm falling-head method was used for influent water; whereas in the other study, inflow rate was controlled at 0.5 mL/min (Rayner et al. 2013).

Burn-out material summary: Results are consistent across two studies that different burn-out materials behave differently: flow rates were faster in filters and filter disks manufactured with rice husks than in those manufactured with sawdust. The increase in flow rate was steeper for rice husk filters with increased proportion of burn-out material. In two studies, filter disks were manufactured by the same manufacturer using the same materials; in one study (using falling-head method) filters manufactured with rice husk did not perform as well as filters manufactured with sawdust; however, in the other study (using controlled inflow rate) LRV performance was similar and >2LRV was achieved throughout the test period by disks manufactured with either sawdust or rice husk. This difference raises a question about a possible influence of the different test methods, and the transferability of results to full-sized filters.

6.4.1.2.3 Ratio

Seven studies evaluated the effect of burn-out material to clay ratio on filter characteristics (morphology and/or flow rate) and/or LRV (Plappally et al. 2011, Soppe et al. 2015, Lantagne et al. 2010, Yakub et al. 2013, Rayner, Luo, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Abebe et al. 2015), and one study also evaluated the effect of burn-out material ratio on strength (Soppe et al. 2015). Researchers manufactured filters (Plappally et al. 2011, Soppe et al. 2015, Lantagne et al. 2010, Yakub et al. 2013) or filter disks (Rayner, Luo, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Abebe et al. 2015) with varying burn-out material content. Studies evaluated: 3-5 mass ratios of rice husk to clay ranging from 7.5-25% (Rayner, Luo, et al. 2016) and 24-31% (Soppe et al. 2015); 3-6 volume ratios of sawdust to clay ranging from 25-50% (Yakub et al. 2013), 35-55% (Plappally et al. 2011) and 40-60% (Lantagne et al. 2010); and 3-5 mass ratios of sawdust to clay ranging from 7-17% (Kallman, Oyanedel-Craver, and Smith 2011), 9-11% (Abebe et al. 2015) and 11-24% (Rayner, Luo, et al. 2016). Two studies did not specify the number of replicates manufactured (Abebe et al. 2015, Plappally et al. 2011) and the remaining studies manufactured between one (Yakub et al. 2013) and six (Soppe et al. 2015) filters per recipe for testing. Predominantly, filters were tested without silver application (Abebe et al. 2015, Rayner, Luo, et al. 2016, Yakub et al. 2013, Soppe et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011), although one study did not specify whether or not silver had been applied (Plappally et al. 2011). Filters were tested for *C. parvum* (Abebe et al. 2015) or *E. coli* LRV (Rayner, Luo, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Soppe et al. 2015, Plappally et al. 2011, Yakub et al. 2013). Filters were tested two (Abebe et al. 2015, Plappally et al. 2011, Yakub et al. 2013), eight (Rayner, Luo, et al. 2016) or 12 times (Kallman, Oyanedel-Craver, and Smith 2011); one study did not specify how many times filters were tested (Soppe et al. 2015).

Studies that evaluated filter characteristics with varied burn-out material to clay ratios measured an increase in porosity (Yakub et al. 2013, Rayner, Luo, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Abebe et al. 2015), median pore size and hydraulic conductivity (Kallman, Oyanedel-Craver, and Smith 2011) with an increase in burn-out material. One study measured a greater percentage of smaller pores with less sawdust (50%, 37%, 26% of pores <1µm diameter, respectively) (Kallman, Oyanedel-Craver, and Smith 2011) and one study found that permeability decreased, and tortuosity increased, with decreasing sawdust content (Yakub et al. 2013). Flow rate increased with increased burn-out material content (Soppe et al. 2015, Lantagne et al. 2010, Yakub et al. 2013, Rayner, Luo, et al. 2016) and burn-out material type, mesh size and ratio were significant predictors of flow rate in multivariable linear regression (α=0.05) (Rayner, Luo, et al. 2016).

In disks manufactured with rice husks, a change in average LRV with different ratios was not observed; however, overall, LRVs by rice husk disks were low. A small decrease in average LRV with increased ratio was observed in some disk sets manufactured with sawdust (Rayner, Luo, et al. 2016). Controlling for burn-out material type and mesh size, ratio was not a significant predictor of LRV in multivariable linear regression results (α=0.05). In another study, no apparent trend in LRV with varying rice husk ratios (24-31%) was identified (~1-5 LRV) and no correlation between flow rate and LRV in filters manufactured with varying rice husk content was found (R=-0.06) (Soppe et al. 2015). In contrast, one study measured an ~1-log decrease in *E. coli* LRV (4.5, 3.5, 2.5 LRV) with increasing sawdust content (7, 9, 17% mass ratio) in disk filters tested using a controlled inflow rate (Kallman, Oyanedel-Craver, and Smith 2011). Three other study results suggested no trend in LRV across two-three ratios (sawdust) (Yakub et al. 2013, Plappally et al. 2011, Abebe et al. 2015). In these three studies; however, filters were only tested twice and either only one filter was manufactured per ratio or the number of replicates per ratio was not specified.

Modulus of Rupture (MoR) test results suggest that strength decreases with increasing rice husk content, from a median ~2.25 (MPa) with 24% rice husk to a median ~1.4 (MPa) with 31% rice husk (R=-0.96) (Soppe et al. 2015).

Ratio summary: Study results are consistent in that an increase in the proportion of burn-out material results in increased porosity and flow rates. Conclusions differ regarding the influence of burn-out material ratio on LRV, which is possibly attributable to differences the ratios selected, burn-out materials and/or test methods. Within a tested range of ratios LRV may not be affected, but after a threshold is reached, a reduction in LRV likely occurs. It is not expected that a threshold for burn-out material ratio in terms of LRV can be determined independently of other materials characteristics and manufacturing conditions. Filter strength decreased with an increase in rice husk content.

6.4.1.2.4 Mesh

Four studies evaluated filters or filter disks manufactured with burn-out material processed through different sized mesh. Two studies evaluated filters manufactured with sawdust sieved through two different mesh: one measured flow rate, but influent was not spiked and thus LRV could not be calculated (Lantagne et al. 2010) and the other tested disks for LRV but not flow rate as inflow rate was controlled (Abebe et al. 2015). Two studies evaluated filters or filter disks against flow rate and LRV (Soppe et al. 2015, Rayner, Luo, et al. 2016) and one against strength (Soppe et al. 2015). The results of these studies in terms of the influence of burn-out material mesh size and filter characteristics (morphology and/or flow rate), LRV and strength are presented below.

Flow rate was not different across filters made with sawdust sieved with two different mesh (Lantagne 2010) and neither percent porosity nor LRV in *C. parvum* by filter disks manufactured with sawdust sieved with 10, 16 and 20 mesh (opening size/standard not provided) corresponded with mesh size (Abebe et al. 2015). In contrast, results from two studies suggest that particle size or mesh size used to process burn-out material is associated with flow rate and LRV (Rayner, Luo, et al. 2016, Soppe et al. 2015). In the first study, filter disks manufactured with either sawdust or rice husk with different clay to burn-out material ratios processed through different sized mesh (openings: 2.38/1.19mm, 1.19/0.60mm and 0.60/0.25mm) were tested for flow rate and *E. coli* removal (Rayner, Luo, et al. 2016). In multivariable linear regression burn-out material type, mesh size and ratio were significant predictors of flow rate (α=0.05). Mesh size, along with burn-out type, was a significant predictor of the mean LRV on the last test day (eighth test) (α=0.05).

In the second study, three sets of six filters were manufactured with the same clay to rice husk to laterite ratio (74:24:2) but the rice husk particle size varied depending on whether the rice husk was: 1) acquired in the dry season and sieved with 1mm mesh; 2) acquired in the wet season and sieved with 1 mm mesh, or 3) acquired in the dry season, sieved using 1.0/0.5 mm mesh (thus excluding fines) (Soppe et al. 2015). During the wet season, the rice husk contained an overall wider variation in measured particle sizes <1mm, with more >0.8mm and more <0.25mm particles (Soppe et al. 2015). Mean pore size, flow rate, LRV and strength were evaluated. The mean pore size was greater in the filters manufactured with the fines excluded (32.3μm) than with the filters containing all particles <1 mm (28.9μm). Flow rates also increased with increasing mesh and/or particle size, from a mean 3.0 L/hr (dry season, <1 mm) to 6.7 L/hr (wet season, <1 mm), to 10.1

L/hr (dry season, 1.0/0.5 mm). The median LRV decreased with increased overall rice husk particle size. Filters achieved median 2.8 LRV (dry season, <1 mm), 1.7 LRV (wet season, <1 mm) and 0.7 LRV (dry season, 1.0/0.5 mm).

The increase in rice husk particle size and pore size correlated with a reduction in strength; the median MoR reduced from 2.4 to 1.3 MPa when the fines were excluded, suggesting that larger particle sizes of rice husk resulted in weaker filters (Soppe et al. 2015).

Mesh summary: While one study did not identify a relationship between mesh size used to process burn-out material and flow rate, and another did not identify a relationship with mesh size and LRV, two studies that evaluated both flow rate and LRV found mesh or overall particles size to be important. An increase in mesh size or particle size increased flow rate; however, LRV decreased. These studies suggest particle size of burn-out material is important to control for LRV. Additionally, a decrease in strength was measured with an increase in particle size of rice husk.

6.4.1.2.5 Firing conditions

In two studies the influence of firing conditions (Guerrero-Latorre et al. 2015) or firing temperature (Soppe et al. 2015) on filter characteristics (morphology and/or flow rate), LRV and/or strength.

Guerrero-Latorre et al. (2015) evaluated MS2, Human Adenovirus 2 (HAdV2) and *E. coli* removal from model filters fired in either oxidation or reduction (reduced oxygen) atmospheres and filters with 1-3 L/hr flow rates were selected for testing. Filters fired in reduction had similar pore size distributions but a greater specific surface area (mean:

6.65 m^2/g) in comparison with filters fired in oxidation (mean: 2.41 m^2/g); differences in zeta potential were also noted. Filters fired in reduction achieved mean 2.3-2.4 LRV *E. coli*, 1.27-2.98 LRV MS2 and 2.86-3.54 LRV HAdV. While LRV was significantly higher in comparison with the reference filters fired in oxidation, the reference filters did not meet *E. coli* LRV criteria (mean 0.68 LRV, n=12).

One study evaluated firing temperature on mean pore size, flow rate, LRV and strength (Soppe et al. 2015). Four batches of six filter pots were manufactured and fired to peak target temperatures of 685°C, 800°C, 885°C and 950°C (actual peak temperature appeared to range from ~650-1050°C). Mean pore diameters increased with temperature, from 27.8μm to 28.9μm to 30.6μm, for filters pots fired to 800°C, 885°C and 950°C, respectively. A small reduction in *E. coli* LRV with increased temperature was measured: 2.3, 2.1 and 1.9 LRV for pots fired to 800°C, 885°C and 950°C, respectively. Flow rates increased from an average 3.8 to 8.0 L/hr with an increase in firing temperature from 800°C to 950°C. Although not specifically evaluated, another study noted that flow rates nearly tripled when disks were re-fired from 800°C/180min to 950°C/60min to improve strength (Rayner, Luo, et al. 2016). Mean MoR increased with firing temperature: from ~1.1 to 1.9 to 2.2 to 3.9 MPa in filters fired to 665°C, 800°C, 900°C and 950°C, respectively.

Firing conditions summary: Only two studies were identified that evaluated firing conditions. One study that evaluated firing atmosphere documented a nearly 3 LRV in virus removal by filters fired in a reduced oxygen atmosphere. One study evaluated the effects of temperature on flow rate, LRV and strength and findings suggest flow rate and strength can be increased with higher firing temperatures. With the clay and at the temperatures evaluated, LRV only slightly reduced with hotter temperatures; however, these findings may not be transferrable across clays.

6.4.1.3 Silver

Twelve studies published between 2001 and 2016 evaluated the influence of silver on bacteria removal (Bielefeldt et al. 2010, Brown and Sobsey 2010, Van Halem et al. 2007, van der Laan et al. 2014, Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Bielefeldt, Kowalski, and Summers 2009, Zhang and Oyanedel-Craver 2013, Lantagne 2001b, Mikelonis, Lawler, and Passalacqua 2016, Kallman, Oyanedel-Craver, and Smith 2011, Lantagne et al. 2010), two evaluated removal of protozoa or protozoan surrogates (Bielefeldt et al. 2010, Van Halem et al. 2007) and four evaluated removal of virus surrogates (Bielefeldt et al. 2010, Van Halem et al. 2007, Brown and Sobsey 2010, van der Laan et al. 2014).

Four studies evaluated laboratory manufactured disk shaped filters as surrogates for full-sized filters (Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Zhang and Oyanedel-Craver 2013, Kallman, Oyanedel-Craver, and Smith 2011), seven studies evaluated factory-manufactured filters (Lantagne 2001b, Bielefeldt et al. 2010, Bielefeldt, Kowalski, and Summers 2009, Van Halem et al. 2007, Brown and Sobsey 2010, Lantagne et al. 2010, Mikelonis, Lawler, and Passalacqua 2016) and one study evaluated researcher-manufactured filters (van der Laan et al. 2014).

Silver and LRV. Eleven studies evaluated removal efficacy of filters with and without silver application (Bielefeldt et al. 2010, Brown and Sobsey 2010, Van Halem et al. 2007, van der Laan et al. 2014, Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Bielefeldt, Kowalski, and Summers 2009, Zhang and Oyanedel-Craver 2013, Lantagne 2001b, Mikelonis, Lawler, and Passalacqua 2016, Kallman, Oyanedel-Craver, and Smith 2011). Four of the studies applied nAg (Zhang and Oyanedel-Craver 2013, Rayner et al. 2013, Mikelonis, Lawler, and Passalacqua 2016, Kallman, Oyanedel-Craver, and Smith 2011), six applied silver nitrate (Bielefeldt et al. 2010, Brown and Sobsey 2010, van der Laan et al. 2014, Rayner et al. 2013, Bielefeldt, Kowalski, and Summers 2009, Lantagne 2001b) and two reported "colloidal" silver application (Van Halem et al. 2007, Oyanedel-Craver and Smith 2008). Please note that one study tested filters with either nAg or silver nitrate application. One study is not included in the bacteria removal sections of the synthesis because influent water was not spiked (Mikelonis, Lawler, and Passalacqua 2016).

Of the ten included studies, seven found that in initial test results, the application of silver – colloidal, nitrate or nAg – improved bacteria reduction over filters without silver (Bielefeldt, Kowalski, and Summers 2009, Van Halem et al. 2007, Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Zhang and Oyanedel-Craver 2013, Kallman, Oyanedel-Craver, and Smith 2011, Lantagne 2001b). Two studies measured similar LRVs in bacteria or bacteria sized microsphere removal in filters with and without silver nitrate application (Brown and Sobsey 2010, Bielefeldt et al. 2010). Another study also found no difference in LRV filters with or without silver, but filters were researcher manufactured with varying proportions of rice husks. Reference filters without silver had flow rates that ranged from 5.3-21 L/hr and *E. coli* LRVs that ranged from 0.6-2.5 LRV (median ~0.7 LRV). The study concluded that that bacteria deactivation by silver occurs during storage rather than during filtration (van der Laan et al. 2014).

Results from two studies (Rayner et al. 2013, Kallman, Oyanedel-Craver, and Smith 2011) suggest that silver application improves the performance of some filters more than others. In disks manufactured with varying percentages of sawdust, LRV was relatively similar before and after nAg application for disks with higher initial *E. coli* LRV (3-4 LRV, 4-9% sawdust). For the filter disks with more sawdust (17%), LRV increased from 2.6 LRV to nearly 5 LRV after nAg application (Kallman, Oyanedel-Craver, and Smith 2011). Likewise, in disks manufactured with different clays tested over 10 days with and without silver (nAg or nitrate, 0.03 mg/g), disks manufactured with either clay achieved similar LRVs at the start of testing without silver and at the end of the 10 day test period with silver (~3.5 LRV); however, control disks with one of the clays, without silver application, achieved ~1 LRV less than the disks with silver (Rayner et al. 2013). In both of these studies, inflow was controlled at 0.5–0.6 mL/min.

Three studies found that silver application is not necessary for protozoa and protozoa-sized particle removal (Lantagne 2001b, Van Halem et al. 2007, Bielefeldt et al. 2010). Conclusions vary as to whether silver application may improve (Bielefeldt et al. 2010), reduce (Van Halem et al. 2007) or have no effect (van der Laan et al. 2014, Brown and Sobsey 2010) on virus surrogates and virus-sized particle removal. Overall, regardless of silver application virus reduction across the studies was consistently below 3 LRV.

Silver application methods. Widely used silver application methods include brushing on or submerging fired filters in silver solution; however, a few factories include a proprietary amount of silver in the filter mixture, thus firing silver into the ceramic pot (Rayner, Skinner, and Lantagne 2013). Four studies evaluated silver application methods (van der Laan et al. 2014, Oyanedel-Craver and Smith 2008, Lantagne 2001b, Lantagne et al. 2010). Studies evaluating application methods against microbiological performance have concluded: 1) when brushing silver onto fired filters, silver solution should be applied to both the inside and the outside of the filter (Lantagne 2001b); 2) brushing and dipping showed similar bacteria reductions when controlling for silver dose (Oyanedel-Craver and Smith 2008); and 3) filters with silver fired-in and brushed on silver were both effective (3.1-6.1 LRV in *E. coli*) though silver type, dose and manufacturer varied (Lantagne et al. 2010). One study found no difference in *E. coli* removal regardless of application method (both sides or outside only); however, it was concluded silver nitrate application did not improve *E. coli* removal during filtration (van der Laan et al. 2014).

Silver dose. The current recommended silver application amount (dose) for ceramic filter production is 0.03 mg/g as silver (CMWG 2011). Three studies have evaluated the effects of different application concentrations on bacteria removal (Rayner et al. 2013, Oyanedel-Craver and Smith 2008, Lantagne 2001b) and found that bacteriological efficacy is dose-dependent. One study found that silver dose is more important than the application method in comparing dipping vs brushing silver onto fired filters (Oyanedel-Craver and Smith 2008). Two studies found that the application of an order of magnitude less silver than the recommended dose does not consistently result in improved bacteriological performance over control filters without silver (Lantagne 2001b, Rayner et al. 2013), and an increase in silver dose by an order of magnitude (from 0.03 mg/g to 0.3 mg/g) resulted in an ~1-1.5 increase in LRV (Rayner et al. 2013). Please note that with silver nitrate application higher concentrations of silver in filtered water was measured. Furthermore, with increased nAg dose (from 0.03 mg/g to 0.3 mg/g) fewer viable bacteria remained on the surface and inside the filter disks after testing (Rayner et al. 2013).

Silver type. One study compared the performance of nAg with silver nitrate and found that in disks manufactured with different clays with either 0.003 mg/g or 0.03 mg/g of silver added, LRV performance between nAg and silver nitrate were similar over 10 days of testing (Rayner et al. 2013). LRV was higher with silver nitrate application at 0.3 mg/g; however, this may have been due to high concentrations of silver in the treated water as previously mentioned. Fewer viable bacteria were retained on the surface and within the disks with 0.3mg/g nAg disks than disks with 0.3mg/g of silver nitrate applied (Rayner et al. 2013).

Silver elution. Some silver elutes into filtered water and while silver in filtered water may provide residual protection (to prevent recontamination and improve water quality through increased contact time with the silver), this will also result in silver depletion over time. The WHO guideline value for silver in drinking water is 0.1 mg/L (WHO 2011b). The current recommendation is for filter users to discard the first three batches (~30 liters) of filtered water from a new filter, in part due to initial high concentrations of silver (CMWG 2011).

In ten studies, silver concentration in filtered water from filters or filter disks was at or below drinking water quality guideline values either initially or after ~30 liters or equivalent of water throughput. (van der Laan et al. 2014, Bielefeldt, Kowalski, and Summers 2009, Mikelonis, Lawler, and Passalacqua 2016, Rayner et al. 2013, Bielefeldt et al. 2010, Oyanedel-Craver and Smith 2008, Zhang and Oyanedel-Craver 2013, Lantagne et al. 2010, Matthies et al. 2015, Van Halem et al. 2007). In one study, silver concentration in filtered water never exceeded 0.5 mg/L, but it was not reported whether silver concentrations were below the guideline value of 0.1 mg/L (Brown and Sobsey

2010). However, in one study, after 305 L of throughput (23.5 g silver nitrate fired into the filter), silver concentration in filtered water from ground, surface and deionized influent water were above guideline values (0.23-0.77 mg/L) (Adeyemo, Kamika, and Momba 2015). Please note that these results are also presented in (Mwabi, Mamba, and Momba 2012, 2013).

One study found that silver concentration in filtered water and elution can be affected by dose and silver type (nAg vs silver nitrate) (Rayner et al. 2013). Silver concentration in effluent increased with dose and was greater in filtered water from silver nitrate coated disks than nAg coated disks (Rayner et al. 2013). Disks coated with nAg retained more silver than disks coated with silver nitrate; with nAg desorption ranging from 5-10% in comparison with 10-40% from silver nitrate coated disks (Rayner et al. 2013).

Influent water characteristics may also affect silver elution. One study did not measure a difference in silver concentration in filtered surface or ground water after 305 L of throughput (0.26 and 0.23 mg/L, respectively); however, silver concentration in filtered deionized water was 0.77 mg/L, as noted above (Adeyemo, Kamika, and Momba 2015). Please note that these results are also presented in (Mwabi, Mamba, and Momba 2012, 2013). Another study, did not measure a difference in silver retention and release after applying different influent water characteristics (150 mg/L Na^{+}−NaCl, 150 mg/L Ca^{2+}−NaCl and 5 mg/L humic acid as total organic carbon) (Rayner et al. 2013). However, this may have been due to the low silver dose applied (0.003 mg/g nAg or silver nitrate which is an order of magnitude less than the current recommended amount). However, one study measured a significantly ($p<0.05$) greater initial increase and sustained loss of silver (0.018 mg/g nAg) when surface ('dugout') water (pH 6.8, total dissolved solids: 19mg/L, <1 – 1.25 mg/L chloride [n=5]) was filtered than when rainwater (pH 7.5, TDS 60 mg/L, chloride 1.31-2.36 mg/L [n=5]) was filtered (Mikelonis, Lawler, and Passalacqua 2016).

One study evaluated the effects of stabilizing agents- citrate, PVP (polyvinylpyrrolidone), BPEI (branched polyethylenimine) and casein - on nAg release. No significant effect on either initial or sustained loss of silver was found (α=0.05) (Mikelonis, Lawler, and Passalacqua 2016).

Silver summary: Silver initially improves bacteria LRV, but this may not be sustained over time. Silver application does not seem to affect protozoa removal and it is unclear whether it influences virus removal. When applied to fired filters, both inside and outside surfaces should be coated (whether dipped or brushed) but dose is more important than application method. Bacteria LRV by silver is dose dependent. Initial high concentrations of silver in filtered water have been measured, but silver concentration typically falls to below the guideline value after initial throughput. Silver elution and concentration in filtered water can be influenced by dose, silver type and influent water characteristics. Controlling for dose, lower silver concentrations have been measured in filtered water with nAg application than with silver nitrate and nAg appears to be better retained in the filter. Influent water characteristics appear to influence silver release, but specific characteristics were not identified in this body of literature. Further research is needed to evaluate long-term performance with nAg application and the extent to which treatment by silver occurs during or after filtration. Effluent silver concentration and sample storage time after filtration may have influenced some of the findings in the literature.

6.4.2 Outcome evaluations

Fourteen manuscripts that measured outcomes were identified. Eleven manuscripts with low and medium bias scores were included in the synthesis (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014, Mellor et al. 2015, Mohamed et al. 2016, Salvinelli et al. 2017, Rayner, Murray, et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Lemons et al. 2016, Casanova et al. 2012b, Murphy et al. 2010, Lantagne 2001a). Three manuscripts classified as high risk of bias were not included in the synthesis (Murphy, McBean, and Farahbakhsh 2010, Casanova et al. 2012a, Murphy et al. 2009).

The 11 included studies were sub-grouped into observational (n=4), where filters had been previously distributed (Lantagne 2001a, Casanova et al. 2012b, Rayner, Murray, et al. 2016, Murphy et al. 2010), and interventional (n=7), where filters were distributed at the start of the study (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014, Lemons et al. 2016, Mellor et al. 2015, Mohamed et al. 2016, Salvinelli et al. 2017, Kallman, Oyanedel-Craver, and Smith 2011).

6.4.2.1 Observational

Observational studies were published between 2001-2016 (Rayner, Murray, et al. 2016, Murphy et al. 2010, Casanova et al. 2012b, Lantagne 2001a). Filters were factory-manufactured in five countries (Cambodia, Dominican Republic, Haiti, Sri Lanka and Nicaragua) and distributed in four countries (Cambodia, Haiti, Sri Lanka and Nicaragua). Two studies reported burn-out material type and that filters contained silver (Lantagne 2001a, Murphy et al. 2010). Additionally one study reported filter mixture ratio and firing temperature (Lantagne 2001a). Filters had been in use for <6 months to ~2 years. Filters were distributed for free (Lantagne 2001a, Casanova et al. 2012b, Rayner, Murray, et al. 2016) or were purchased (Murphy et al. 2010, Rayner, Murray, et al. 2016).

Household selection varied by evaluation, including: 1) random selection from filter distribution lists for each of two programs (n=53 and n=50) (Rayner, Murray, et al. 2016); 2) visiting households known to have received filters (n=33) (Lantagne 2001a); 3) visiting households reported to have purchased a filter and enrolling current filter users (n=57) (Murphy et al. 2010); and, 4) randomly selecting communities where filters had been distributed and enrolling respondents that had previously received filters during door-to-door visits (n=450) (Casanova et al. 2012b).

Flow rate. Flow rates were measured in two of the four studies (Lantagne 2001a, Casanova et al. 2012b). Though flow rate test methods varied, one study concluded that 58% of filters would not meet a minimum guideline of 11.4 L/day for drinking water if filled just once a day (Lantagne 2001a) and the other reported that 60% of filters had flow rates of <1 L/hr (Casanova et al. 2012b); of note is that just 14% of respondents in this evaluation reported that flow rates were too slow.

Water quality. Influent and filtered water was quantitatively tested for *E. coli* in three evaluations (Casanova et al. 2012b, Rayner, Murray, et al. 2016, Murphy et al. 2010). In Haiti, in households that had filters from one factory, the geometric mean *E. coli* was 78.5 *E. coli* CFU/100mL (ranging from 10-755, n=9) in untreated water and 21.5 *E. coli* CFU/100mL (ranging from 2-260, n=7) from the filter tap (Rayner, Murray, et al. 2016) (Figure 24). In households that received filters from a different factory, the geometric mean *E. coli* was 6.6 *E. coli* CFU/100mL in untreated water (ranging from <1-250, n=22) and *E. coli* was not detected (<1 *E. coli*/100mL) in any filtered water samples (n=18) (Rayner, Murray, et al. 2016).

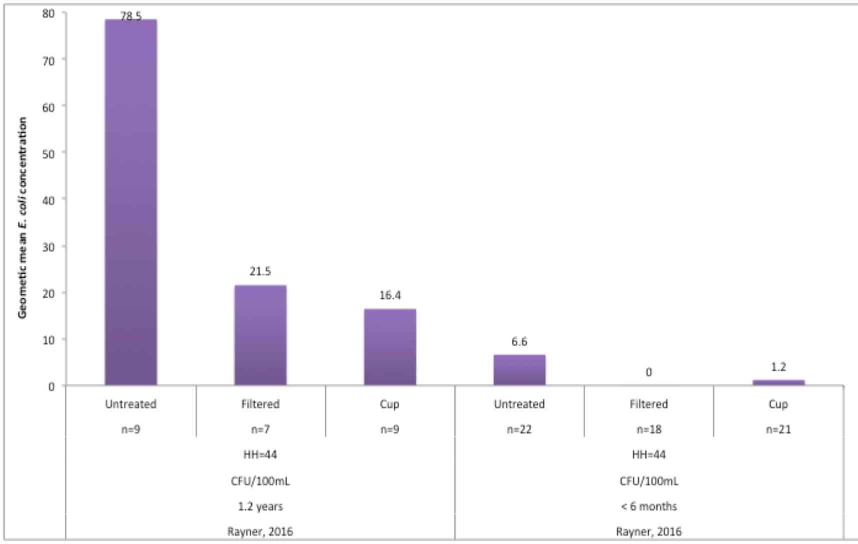


Figure 24: Geometric mean E. coli concentrations in untreated and filtered water samples

In Sri Lanka, water quality was grouped by source. Mean $\log_{10}$ *E. coli* concentration in tap water was 0.27 MPN/100 mL while $\log_{10}$ *E. coli* concentration well water was 1.15 MPN/100 mL (n=not reported) (Casanova et al. 2012b). In this study, <1 *E. coli* MPN/100mL were detected in 80-90% of filtered water samples and <10 *E. coli* MPN/100mL were detected in ~90-95% of filtered water samples (n=not reported) (Casanova et al. 2012b). Of note is ~33% of respondents reported boiling drinking water but it was not reported whether households combined treatment methods and if so, the sequence.

In Cambodia, untreated water quality results were grouped by water source and median source *E. coli* ranged from ~40 to ~5,000 CFU/100mL (Murphy et al. 2010). Less than 10 *E. coli* CFU/100mL were detected in 88% of filtered water samples, 11-100 *E. coli*

CFU/100mL were detected in 11% of samples and 101-1,000 *E. coli* CFU/100mL were detected in 2% of samples (n=56) (Murphy et al. 2010).

All four studies documented turbidity reduction with the exception of one filter group in one study (Rayner, Murray, et al. 2016, Lantagne 2001a, Casanova et al. 2012b, Murphy et al. 2010). Median turbidity was 2.4 NTU in influent and 6.8 in filtered samples (n=6) (Rayner, Murray, et al. 2016). In the other study group (filters from a different factory), median turbidity was <1NTU in both the source and filtered water samples (n=12) (Rayner, Murray, et al. 2016). In the other studies, turbidity ranged from: <1-30 NTU in source water and from <1-3 in filtered water (n=56) (Murphy et al. 2010), 0-62 NTU in source and 0-23 NTU in filtered water (n=12) (Lantagne 2001a) and while one study reported significant turbidity reduction, influent mean turbidity was <2 NTU across water sources (n=not reported) (Casanova et al. 2012b).

Breakage. Breakage was reported as a primary reason for disuse in two studies (Rayner, Murray, et al. 2016, Lantagne 2001a). Nearly half (19 of 39) of the respondents in one study (average 1.2 years since filters were acquired) and 27% (9 of 33) in the other study (time since filters were acquired not specified) reported they were no longer using the filter because it had broken.

6.4.2.2 Interventional

Seven studies evaluated filter performance over time; three studies were randomized controlled trials (RCT) (Abebe et al. 2015, Brown, Sobsey, and Loomis 2008, Mellor et al. 2015), one was a cross-over trial (Mohamed et al. 2016) and three longitudinal studies that evaluated source and filtered water quality over time (Lemons et al. 2016, Salvinelli et al. 2017, Kallman, Oyanedel-Craver, and Smith 2011). Filters were factory-manufactured in six of the studies and distributed in Cambodia (Brown, Sobsey, and Loomis 2008), Tanzania (Lemons et al. 2016, Mohamed et al. 2016) and Guatemala (Salvinelli et al. 2017, Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011); one study distributed filters in South Africa that had been manufactured in the USA (Abebe et al. 2014). Filters had been manufactured with rice husk (Brown, Sobsey, and Loomis 2008) or sawdust (Mellor et al. 2015, Salvinelli et al. 2017, Kallman, Oyanedel-Craver, and Smith 2011), but in two manuscripts the burn-out material type was not specified (Abebe et al. 2014, Lemons et al. 2016, Mohamed et al. 2016). Materials ratio was reported in one manuscript (Kallman, Oyanedel-Craver, and Smith 2011) and firing temperature and the amount of silver applied were reported in two manuscripts (Brown, Sobsey, and Loomis 2008, Kallman, Oyanedel-Craver, and Smith 2011). Silver nitrate (Brown, Sobsey, and Loomis 2008), colloidal silver (Salvinelli et al. 2017) or nAg (Abebe et al. 2014, Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011) had been applied to filters. Two studies did not report whether or not silver had been applied (Mohamed et al. 2016, Lemons et al. 2016). Study duration ranged from six weeks to two years and study size ranged from 20-603 households. Three studies measured flow rates, two before distribution (Abebe et al. 2014, Lemons et al. 2016) and one after (Salvinelli et al. 2017). All seven studies included water quality testing for bacteria, five studies tested for turbidity removal (Brown, Sobsey, and Loomis 2008, Abebe et al. 2014, Lemons et al. 2016, Salvinelli et al. 2017, Kallman, Oyanedel-Craver, and Smith 2011) and three tested filtered water for silver concentration (Abebe et al. 2014, Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011).

Flow rate. Flow rate were measured before filter distribution in two of the evaluations (Abebe et al. 2014, Lemons et al. 2016) and during one study flow rates were measured households (Salvinelli et al. 2017). Before distribution, average flow rates were relatively high, and in one study with a high standard deviation suggesting a lack of consistency in production. Flow rates averaged 3.9 L/hr (SD=1.1, n=80, methods not described) (Abebe et al. 2014) and 3.8 L/hr (min=0.3, max=10.8, SD=2.4), tested by measuring the volume of water filtered after 30 minutes from a saturated filter, then converting the results to L/h (Lemons et al. 2016). In this study flow rates for 4% of filters were <1 L/hr (2 filters), 46% were 1–3 L/hr (23 filters), 50% were 3.1–11.0 L/hr (25 filters); a correlation was not found between flow rates (grouped: <1 L/hr, n=2, 1-3 L/hr, n=23 and >3 L/hr, n=25) and *E. coli* concentrations of <10 *E. coli* CFU/100mL (93% of the filtered samples).

Flow rate was evaluated in one study every 2 months by trained personnel who measured the volume filtered after 1 hour, using a falling-head method (CMWG 2011). For the first 8 months of use, filters maintained a 1-3 L/hr flow rate; at ~10-12 months, flow rates decreased to <1 L/hr (n=27) (Salvinelli et al. 2017). Participants reported filling filters 2.1 times per day (range 1-4). Eight households recorded the filtered water volume daily for two months; on average these households treated 10-12 L/day.

Water quality: Studies tested for different indicators of fecal contamination or process efficacy including *E. coli* (Brown, Sobsey, and Loomis 2008) (Lemons et al. 2016), *E. coli* and Total Coliform (TC) (Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011), TC (Abebe et al. 2014) and Thermotolerant Coliform (TTC) (Mohamed et al. 2016). Reporting of water quality data was by arithmetic mean (Brown, Sobsey, and Loomis 2008, Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011), geometric mean (Brown, Sobsey, and Loomis 2008, Lemons et al. 2016), Log_{10} mean (Mohamed et al. 2016) and median (Abebe et al. 2014). Untreated and filtered samples were evaluated against percent reduction (Kallman, Oyanedel-Craver, and Smith 2011, Mohamed et al. 2016, Brown, Sobsey, and Loomis 2008, Lemons et al. 2016) and/or samples were grouped by risk classification (Abebe et al. 2014, Brown, Sobsey, and Loomis 2008, Lemons et al. 2016, Mohamed et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011, Mellor et al. 2015). Water quality data from one study is not presented in this synthesis due to the test method detection limit (Salvinelli et al. 2017).

Results from the two studies that reported geometric mean *E. coli* concentrations were 22.4 *E. coli* CFU/100 mL (Lemons et al. 2016) and 420 and 520 *E. coli* CFU/100mL in untreated samples (Brown, Sobsey, and Loomis 2008) and geometric mean 2.8 *E. coli* CFU/100 mL (Lemons et al. 2016) and 15 and 17 *E. coli* CFU/100mL (Brown, Sobsey, and Loomis 2008) in filtered samples (Figure 25).

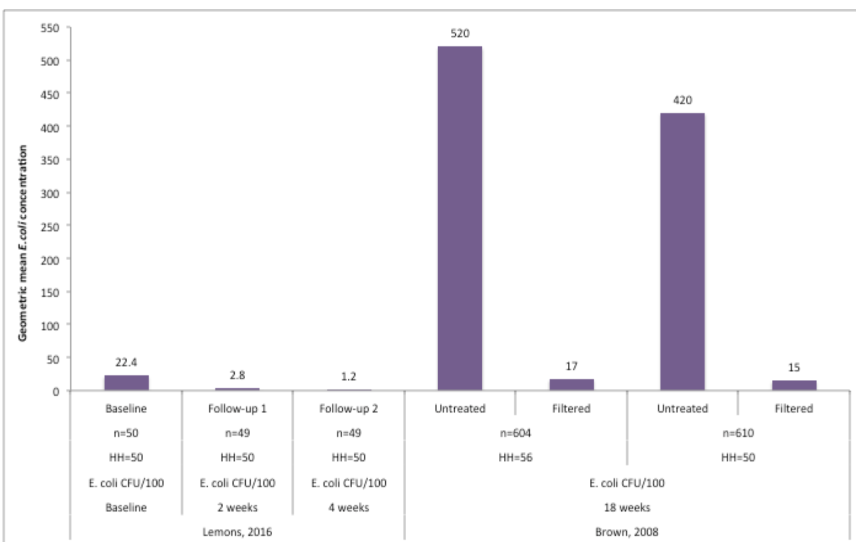


Figure 25: Geometric mean *E. coli* concentrations in untreated and treated water samples

One study reported Log_{10} mean 2.9 TTC CFU/100mL in untreated water and Log10 mean 0.6 TTC CFU/100mL in filtered water (Mohamed et al. 2016).

An 88-96% reduction in *E. coli* was reported in two studies (Brown, Sobsey, and Loomis 2008, Lemons et al. 2016, Kallman, Oyanedel-Craver, and Smith 2011) and a ≥99.5% reduction in TTC was reported in one study (Mohamed et al. 2016).

The percentage of untreated and filtered water samples that contained fecal contamination indicators (*E. coli* or TTC) grouped by WHO risk classification are presented in Figure 26. Across four studies, less than 2% of untreated water samples conformed to guidelines whereas 37-80% of filtered samples contained <1 CFU/100mL. The percentage of untreated water samples that contained >100 CFU/100mL ranged from 72-97% whereas 0-21% of filtered samples contained >100 CFU/100mL (Mellor et al. 2015, Mohamed et al. 2016, Brown, Sobsey, and Loomis 2008, Kallman, Oyanedel-Craver, and Smith 2011). Filtered water samples were overall low risk with <10 CFU/100mL measured in 59-100% of samples, in comparison with 3-28% of untreated water samples falling within this classifcation.

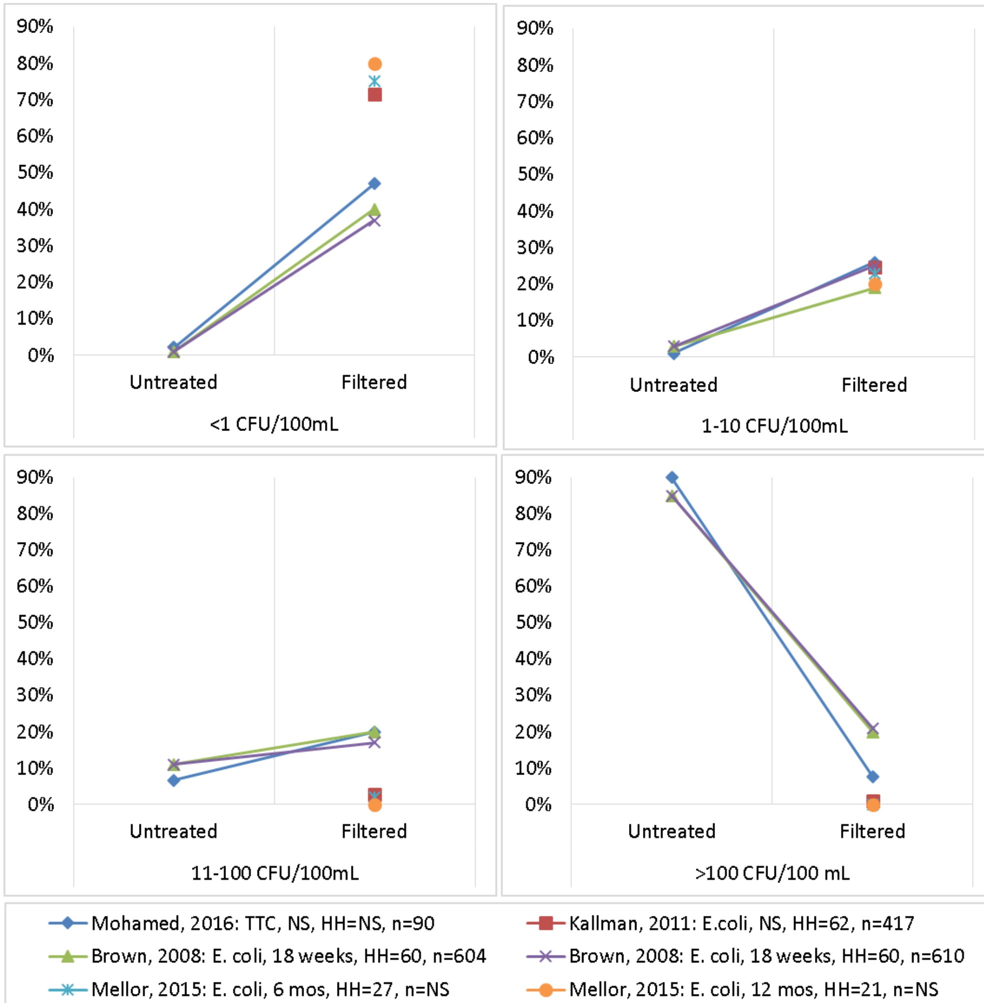


Figure 26: Percentage of unfiltered and filtered water samples with indicators of fecal contamination by WHO risk classification

Four studies presented both source and filtered water quality results grouped by the WHO risk classification categories (Mohamed et al. 2016, Lemons et al. 2016, Brown, Sobsey, and Loomis 2008, Abebe et al. 2014). These results, which are for TTC, *E. coli* and TC (the latter is not an indicator of fecal contamination), are presented in Figure 27.

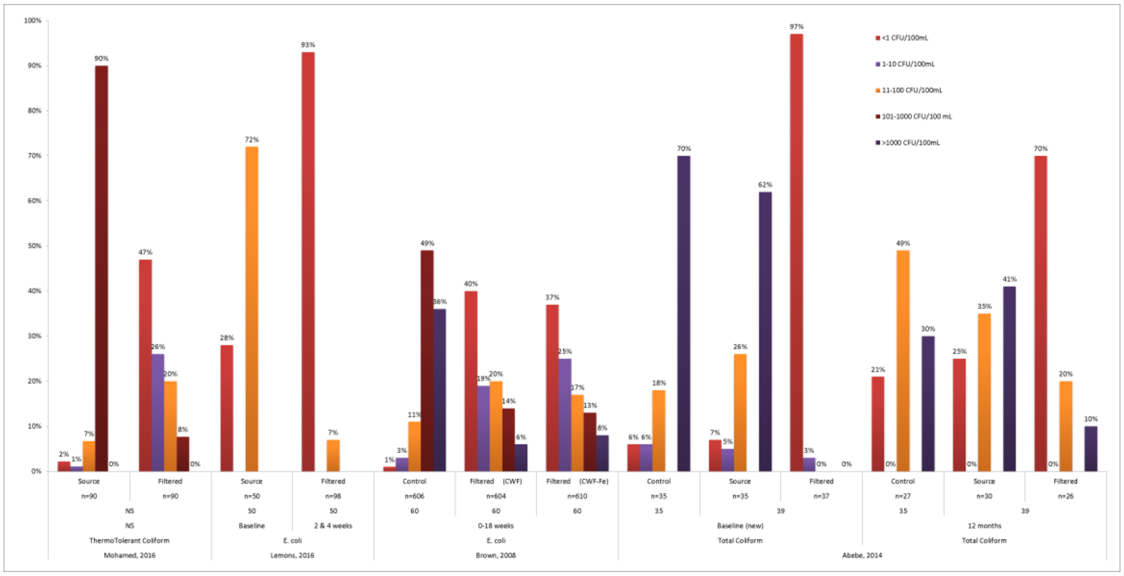


Figure 27: Percentage of paired untreated and filtered samples with *E. coli*, thermotolerant or total coliform bacteria by WHO risk classification

Across the five studies that measured turbidity, mean or median turbidity was lower in the filtered samples than in the source samples (Abebe et al. 2014, Brown, Sobsey, and Loomis 2008, Lemons et al. 2016, Salvinelli et al. 2017, Kallman, Oyanedel-Craver, and Smith 2011). Median (Abebe et al. 2014), mean (Kallman, Oyanedel-Craver, and Smith 2011) and maximum (Lemons et al. 2016, Salvinelli et al. 2017) turbidity in influent samples were all <5 NTU. Only one study had mean influent turbidity values >5 NTU (Brown, Sobsey, and Loomis 2008). Arithmetic mean turbidity dropped from 7.5 NTU (7.1-8.0) and 8.7 (8.3-9.2) to 3.1 (2.7-3.5) and 3.1 (2.3-3.8) NTU in the two filter intervention groups (Brown, Sobsey, and Loomis 2008).

Silver: Three studies measured silver concentrations in filtered water (Mellor et al. 2015, Kallman, Oyanedel-Craver, and Smith 2011, Abebe et al. 2014), with no sample exceeding the guideline value of 0.1 mg/L (WHO 2011b). The highest concentration of silver reported was 0.09 mg/L, recorded after 12 hours of filter use (Kallman, Oyanedel-

Craver, and Smith 2011); from 24 h – 10 months, mean ion silver concentration was 0.02 mg/L (Kallman, Oyanedel-Craver, and Smith 2011). In two other studies, median total silver in filtered samples was 0.012 mg/L at baseline and 0.002 mg/L after one year (n=NS), but the maximum value was not reported (Abebe et al. 2014), and in the other study, mean silver concentration in filtered water did not exceed 0.04 mg/L at any of the three sampling periods (Mellor et al. 2015).

Breakage. Breakage was reported in one study, 18% of filters broke over the course of six weeks (~10% breakage rate per month) (Lemons et al. 2016).

Outcome evaluations summary: Manufacturing specifications were not widely or consistently reported in outcome studies. Two evaluations noted a lack of manufacturing consistency and variable filter quality. Methods and results reporting varied, complicating comparison. Low flow rates measured in households were raised as a possible concern by the authors in three studies. Source water quality varied widely, limiting comparison of filter performance, along with study characteristics such as time in use; however, overall, 37-90% of filtered water samples conformed to the guideline value of <1 *E. coli* CFU/100mL and 59-100% of samples were low risk with <10 *E. coli* CFU/100mL. This is in comparison with <2% and 3-28% of untreated water samples falling within these classifcations, respectively. Breakage rates could not be compared due to differences in study duration, but two studies noted breakage as the primary reason for filter disuse.

6.4.3 Impact evaluations

Two randomized controlled trials that performed health impact evaluations in Cambodia and South Africa were included in the review (low and medium risk of bias scores)

(Brown, Sobsey, and Loomis 2008, Abebe et al. 2014). In Cambodia, a 22-week trial included 180 households divided into three groups: a control group that did not receive filters and two intervention groups, which received CWF (CWF) without and with iron amendment (CWF-Fe). Sixty households in each group were followed for 18-weeks after receiving filters and visited 11 times for water sample collection and testing. In South Africa, a 12-month trial was conducted that included 74 participants divided into a control group that did not receive filters and an intervention group that received filters manufactured in the USA (n=39). Water quality testing for TC was carried out at baseline and at one year. Both studies measured self-reported diarrhea, defined as three or more soft/watery stools in a 24-hour period with 7-day recall (Abebe et al. 2014, Brown, Sobsey, and Loomis 2008); one study also evaluated *Cryptosporidium sp*. presence in stool samples (Abebe et al. 2014). A third study was identified but not included as it received a high risk of bias score (Plappally et al. 2011).

Both studies documented an improvement in water quality from untreated to filtered water. One study documented a mean 1.4 LRV in *E. coli* during the 18-week trial (~600 samples per each of two intervention groups). The other study reported a 100% median reduction in TC between untreated and treated samples at both baseline and the 1-year follow-up (74 and 56 samples, respectively).

Both studies documented statistically significant diarrheal disease reduction in the CWF-receiving intervention groups. In Cambodia, the adjusted longitudinal prevalence ratio effect estimate for the CWF groups for all ages corresponded to a mean diarrheal disease reduction of 49%, after controlling for clustering within households and individuals over time and 42% for the CWF-Fe group. Mean reduction in children <5 years of age was 35-42% in the CWF and CWF-Fe groups, respectively.

In South Africa, the mean diarrhea rate was 0.015 days/week in the intervention group and 0.064 days/week in the control group. Using a Poisson regression model, this effect was estimated at an 80% reduction in diarrhea. In South Africa, a statistically significant difference in *Cryptosporidium* sp. prevalence was not found between the control and intervention groups (22% and 7% prevalence, respectively, p=0.11). While a statistically significant decrease in *Cryptosporidium* sp. prevalence in stool samples at 12-months compared to baseline in the intervention group (p =0.020) was reported, the difference seen in the intervention group may be attributable to other factors or the sample size may not have been large enough to detect statistical significance.

6.5 Discussion

A systematic database search was carried out to identify manuscripts that evaluated outputs, outcomes and/or impacts of CWFs. Of the 47 studies that met inclusion criteria: 35 measured outputs, sub-grouped into filter efficacy, manufacturing variables and silver; 14 measured outcomes, sub-grouped into observational and interventional studies; and three measured impact evaluations. Please note that some studies were included in multiple categories.

6.5.1 Outputs

Reported laboratory test results of factory-manufactured filters suggest that filters should meet the WHO ‘two-star’ performance target for bacteria (range: 2-8 LRV, 9 studies) and protozoa removal (mean 3-5 LRV, minimum 2.1 LRV, 3 studies), but not for virus removal (0.21-1.5 LRV, 7 studies); however, results could not be related back to manufacturing specifications due to inconsistent reporting of manufacturing methods.

Research into manufacturing variables investigated: clay, burn-out material type, ratio, burn-out material processing, firing conditions and silver. The development of a filter mixture ratio requires the optimization of materials and methods to achieve the quality criteria of flow rate, microbiological removal and strength. However, an optimal burn-out material particle size and ratio identified when working with one clay body or one burn-out material type might not be transferrable to other materials. Therefore, results of investigations into the effects of the different manufacturing variables on quality criteria will not result in prescriptive recommendations. The identification of relative influences of different parameters; however, are expected to aid in more targeted optimization, quality control and troubleshooting during filter manufacture.

Study methods varied, including filter shape (full-sized, scaled or disk) and test methods varied (controlled inflow, falling-head, constant head). Sample sizes were generally small limiting the depth of statistical analysis and variability across researcher-manufactured filter material was not consistently characterized. Results are limited by the methods, materials and parameters tested in each of the studies. A synthesis of the findings presented in the literature with regards to the relative influences of manufacturing variables on flow rate, LRV and strength, and the role of silver, is presented below.

Flow rate. In terms of balancing flow rate and LRV criteria, findings suggest increasing the proportion of burn-out material and/or firing temperature to increase flow rate. Study results are consistent in that an increase in the proportion of burn-out material results in increased porosity and flow rates. Two studies did not identify a trend between LRV and the proportion of burn-out material, though one study reported a decrease in LRV with an increased proportion of burn-out material (sawdust). While methods varied across studies, theoretically, as the proportion of burn-out material is increased additional pores will become interconnected, thus it is likely that a threshold will be reached when LRV begins to decrease, which will need to be balanced with flow rate requirements.

One study evaluated the effects of firing temperature on filter characteristics and found that with increased peak firing temperature, from 800°C to 885°C to 950°C, flow rates nearly doubled but there was not a large decrease in LRV (from 2.3 to 2.1 to 1.9 LRV). This study only evaluated one clay body; thus, results may not be transferrable to other clay bodies. While further research is needed, and filters should be tested for microbiological removal to confirm specific production parameters, peak firing temperature selection and control may aid in achieving flow rate criteria without substantially compromising LRV.

LRV. Clay content and mesh used to process burn-out material may be important variables to control to achieve LRV criteria. Three studies reported an association between higher clay content (<2μm) and higher *E. coli* LRV. While other characteristics may be responsible for the observed differences, theoretically higher clay content (more plastic clays) will result in a tighter pore structure. Manufacturers are limited by the characteristics of the locally available clays, but are recommended to, and typically do, select more plastic clays (CMWG 2011, Rayner, Skinner, and Lantagne 2013).

Results from two studies suggest that control of particle size of burn-out material is important for LRV. While flow rate can be increased with increased burn-out material particle size, theoretically, filter material of similar porosity but created by a greater number of smaller void spaces will have a greater surface area to trap bacteria than material with fewer larger void spaces. Burn-out material processed through a smaller mesh was associated with higher LRVs. Processing burn-out material through a relatively large mesh (1 mm openings) may not adequately control burn-out material particle size and may result in variable LRV.

Strength. Burn-out material content (both ratio and particle size) and temperature may be associated with filter strength. One study was identified that evaluated manufacturing variables in relation to filter strength and found that an increase in the proportion of rice husk or rice husk particle size resulted in decreased strength and an increase in firing temperature (800°C, 885°C, 950°C) resulted in increased filter strength. Only one clay body and one burn-out material (rice husk) were tested in this study.

Silver. Silver application improves initial bacteria removal performance, does not appear to influence protozoa removal and findings on virus removal are inconclusive. Increased silver dose results in increased bacteria LRV. Silver concentration in filtered water is influenced by silver dose and silver type. Controlling for dose, lower silver concentrations have been measured in filtered water with nAg application than with silver nitrate. It appears nAg is retained better in the filter than silver nitrate, and thus would last longer. Furthermore, nAg dose could potentially be increased (from 0.03mg/g to 0.3 mg/g) without exceeding guideline values in filtered water. Influent water characteristics may affect the rate of silver release, and thus the persistence of silver in the filter and the potential for sustained improved performance. Results from included manuscripts did not identify specific water characteristics that influence silver release; however, research has found that silver elution can be affected by influent water characteristics such as pH, ionic strength and cation species (Mittelman et al. 2015). It is therefore recommended that silver not be relied upon as the principal treatment mechanism.

6.5.2 Outcomes

Results from household evaluations could not be related back to manufacturing specifications as manufacturing specifications were not consistently reported. In one study filters from multiple factories had been distributed, but results were not stratified by manufacturer (Casanova et al. 2012b). In another study a second group of filters was distributed during the same study after manufacturing consistency was improved, but improvements to manufacturing were not detailed (Kallman, Oyanedel-Craver, and Smith 2011). Two studies reported distributing filters with wide ranging flow rates (Lemons et al. 2016, Abebe et al. 2014), suggesting variability in manufacturing consistency.

Flow rate. Little information on flow rate was reported. In the three studies that measured flow rate, ~60% of filters <1 L/hr flow rates were measured (Lantagne 2001a, Casanova et al. 2012b) and filtration rates dropped from 1-3 L/hr to <1 L/hr after ~8 months of use (Salvinelli et al. 2017). While researchers expressed concern about low flow rates, just 14% of participants in one study reported flow rates were too slow and 76% in another study reported that filters treated enough water for drinking.

Water quality. Technology evaluation during use can be limited by source water quality and comparison is limited by study methods and reporting. The level of bacterial contamination in untreated water varied across the studies, filters had been in households for varying amounts of time and test methods and reporting varied; however, overall, 37-90% of filtered water samples conformed to the guideline value of <1 *E. coli*

CFU/100mL and 59-100% of filtered samples were low risk with <10 *E. coli* CFU/100mL. This is in comparison with <2% and 3-28% of untreated water samples falling within these classifcations, respectively.

Strength. Breakage was reported as a primary reason for participant disuse in two studies (Lantagne 2001a, Rayner, Murray, et al. 2016). In one study, 18% of filters broke during the six week study, ~10% per month. This is higher than reported in other studies (Casanova et al. 2012b, Brown, Sobsey, and Loomis 2008), thus the authors attributed it to poor quality control in manufacturing. While one advantage of CWFs is that local manufacture provides supply chain access, in some cases local markets are not sufficiently established to facilitate filter replacement.

6.5.3 Impact

An estimated 49% diarrheal disease reduction was reported in one study. This study measured both self-reported diarrhea and tested unfiltered and filtered water samples for indicators of fecal contamination (Brown, Sobsey, and Loomis 2008). In the other study a statistical difference in prevalence of *C. parvum* was not measured between the control and intervention groups and only median total coliform reduction results were presented. Thus the 80% reduction in diarrheal disease conclusion was determined by self-reported illness.

6.5.4 Manufacturing recommendations:

Filter manufacturing specifications are optimized at each factory to achieve performance criteria of flow rate, LRV and strength according to local materials and characteristics. When a filter mixture recipe is developed, changed or materials or filter characteristics vary, it is recommended that filters be tested for bacteria removal performance. It is recommended that filters be tested and achieve ≥2LRV in bacteria before silver application to evaluate the quality of the filter material. During production it is recommended that input materials and manufacturing processes are carefully controlled and manufacturing consistency monitored and evaluated. Recommendations by manufacturing variable are discussed below.

Clay. High clay content (high plasticity) has been associated with higher bacteria removal. Thus it is recommended that manufacturers seek clays with high plasticity, monitor clay consistency, and when clay characteristics vary additional bacteria removal testing is recommended.

Burn-out material type. It is recommended that manufacturers work with a single burn-out material type; however, where local resource availability requires working with different burn-out materials, additional monitoring for consistency and quality (bacteria removal testing) is recommended.

Burn-out material processing. Burn-out material may not be adequately controlled with a relatively large mesh depending on the characteristics of the burn-out material received (1 mm opening). Additionally, a smaller particle size is associated with higher bacteria removal, thus it is recommended to use a smaller mesh (0.6 mm opening) to process burn-out material.

Ratio. It is recommended that the ratio of burn-out material to clay be controlled to achieve the desired flow rate but that LRV and strength performance criteria are monitored to verify the proportion of burn-out material added achieves a balance whereby all three criteria are met.

Firing. While the firing temperature range will be confined by the clay characteristics, increasing firing temperature may be a way to increase flow rate and strength without compromising LRV. It is recommended that filters fired at the selected temperature be tested for bacteria removal to confirm this recommendation is transferrable to the local materials.

Silver. It is recommended to apply 0.03-0.3 mg/g of nAg to fired filters by coating both the inside and outside of filters with a silver solution. nAg application is recommended over silver nitrate as it appears to be retained better and thus may provide longer-term performance than silver nitrate.

6.5.5 Research recommendations

Recommendations for further research into clay, burn-out material, firing conditions, and silver on flow rate, LRV and strength performance criteria are discussed below by manufacturing variable. Additionally, there is a need for a standardized test method and criteria for evaluating filter strength.

Clay: Factories may not have much control over the mineralogy of the local clays, and factories typically select clays with higher plasticity; however, some factories include grog (previously fired, ground clay) or sand in the clay body. Investigation into the influence of clay characteristics on filter characteristics and performance is recommended, including the use of commonly included additives, such as sand, grog and laterite.

Burn-out material: While factories typically use a single burn-out material type (rice husk or sawdust), at least one factory uses both rice husk and sawdust (Matthies et al. 2015) and some factories rely on sawdust from a variety of woods (Rayner, Skinner, and Lantagne 2013). Once study found a difference in flow rate and LRV in disks manufactured with rice husk or sawdust; however, the characteristics of the burn-out material that contribute to these differences were not investigated. Research to evaluate the effects of different burn-out materials, including hard and soft woods, on filter characteristics (including pore morphology) and performance is recommended.

Firing conditions: The study that evaluated filters fired to different temperatures found that with increased firing temperature a small impact on LRV was measured but flow rate increased substantially; however, only one clay and burn-out material was tested. Further research is recommended to investigate the use of firing temperature to optimize flow rate and LRV.

One study evaluated the effect of firing filters in a reduced oxygen atmosphere and filters achieved close to the WHO ‘two-star’ performance target for virus removal (mean 1.27-2.98 LRV MS2 and 2.86-3.54 LRV HAdV). Further research is needed to evaluate filters fired by this method against representative control filters fired in oxidation.

Silver: Further research is recommended to investigate sustained improved bacteriological removal performance of full-sized filters with nAg and the form of silver in filtered water (whether nanoparticle or ionic). Further research is recommended to understand the influence of silver during filtration and in filtered water.

6.5.6 Limitations

This systematic review limited inclusion to peer-reviewed, published manuscripts, with the exception of seminal unpublished reports (>20 citations) that have influenced the literature, in order to limit the studies to high-quality research. However, some studies contained methodological weaknesses such as a lack of appropriate statistical test selection or results interpretation (e.g. reporting statistical significance where implications are not relevant or reporting a lack of statistical significance without presenting whether the study was sufficiently powered to detect a difference). Presentation of methods and/or results, for example, sample size, number of replicates or measures of dispersion, was unclear or incomplete in multiple publications. While studies classified as high-risk of bias were not included in the synthesis, some of the studies still had a moderate possibility of bias. The synthesis of results given the presence of these limitations may put the conclusions of the present review at risk for suggesting validity in the absence of evidence.

6.6 Conclusions

A systematic review of the literature on CWFs was conducted, with a specific focus on manufacturing materials and methods, to synthesize research findings, provide manufacturing recommendations and identify future research needs. CWF researchers did not commonly document materials or manufacturing methods, with the exception of studies that specifically evaluated manufacturing variables. The results from laboratory testing of factory-manufactured filters suggest that filters should meet WHO ‘two-star’ performance target for bacteria and protozoa but not viruses. Results from manufacturing variable investigations are limited by the materials, methods and parameters investigated.

Given these limitations, a synthesis of the results suggest that an increased proportion of burn-out material or firing temperature can increase flow rate and may not substantially compromise bacteria removal performance, particle size of burn-out material is important to control for consistent bacteria removal, an increase in firing temperature can increase filter strength while increased proportions or size or rice husk reduces strength and silver nitrate application to fired filters may not result in sustained improved performance. nAg appears to be retained better in the filter, thus may provide sustained improved performance. Thus, it is recommended to optimize filter recipes to meet the three quality criteria based on local materials and methods, to test filters for LRV prior to silver application, control manufacturing with attention to particle size of burn-out material during manufacture and monitor and evaluate production consistency. Recommended areas for further research include: the influence of clay characteristics, burn-out material type and particle size and firing temperature on filter characteristics, including pore morphology, and the three performance criteria; the potential for sustained improved bacteria removal performance with nAg application; and the development of a strength testing protocol. While the review has identified limitations in the existing studies of CWFs and many knowledge gaps remain, these, and other HWT technologies remain important components of safe drinking water provision and diarrheal disease reduction where access to safe water supply is limited.

6.7 Supporting information

Table 23: Summary of studies

#	First Author Surname	Title	Year
Outcome			
General Filter			
1	Abebe	Chitosan Coagulation to Improve Microbial and Turbidity Removal by Ceramic Water Filtration for Household Drinking Water Treatment.	2016
2	Adeyemo	Comparing the Effectiveness of Five Low-Cost Home Water Treatment Devices for Cryptosporidium, Giardia and Somatic Coliphages Removal from Water Sources	2014
3	Baumgartner	Reconsidering 'Appropriate Technology': The Effects of Operating Conditions on the Bacterial Removal Performance of Two Household Drinking-Water Filter Systems.	2007
4	Bielefeldt	Bacterial treatment effectiveness of point of use ceramic water filters	2009
5	Bielefeldt	Removal of virus to protozoan sized particles in point-of-use ceramic water filters	2010
6	Brown	Microbiological Effectiveness of Locally Produced Ceramic Filters for Drinking Water Treatment in Cambodia.	2010
7	Clark	Bacteria Removal Effectiveness of Ceramic Pot Filters Not Applied with Colloidal Silver.	2011
8	Farrow	Virus Removal Efficiency of Ceramic Water Filters: Effects of Bentonite Turbidity	2014
9	Lantagne	Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 1: Intrinsic Effectiveness	2001
10	Lantagne	Effect of Production Variables on Microbiological Removal in Locally-Produced Ceramic Filters for Household Water Treatment	2010
11	Matthies	Morphology, composition, and performance of a ceramic filter for household water treatment in Indonesia	2015
12	Mikelonis	Multilevel modeling of retention and disinfection efficacy of silver nanoparticles on ceramic water filters	2016
13	Murphy	Influence of household practices on the performance of clay pot water filters in rural Cambodia	2009
14	Mwabi	Household Water Treatment Systems: A Solution to the Production of Safe Drinking Water by the Low-Income Communities of Southern Africa.	2011

15	Mwabi	Removal of Escherichia Coli and Faecal Coliforms from Surface Water and Groundwater by Household Water Treatment Devices/Systems: A Sustainable Solution for Improving Water Quality in Rural Communities of the Southern African Development Community Region.	2012
16	Mwabi	Removal of Waterborne Bacteria from Surface Water and Groundwater by Cost-Effective Household Water Treatment Systems (HWTS): A Sustainable Solution for Improving Water Quality in Rural Communities of Africa.	2013
17	Pérez-Vidal	Long-Term Evaluation of the Performance of Four Point-of-Use Water Filters	2016
18	Pérez-Vidal	Evaluación Del Tratamiento De Agua Para Consumo Humano Mediante Filtros Lifestraw® Y Olla Cerámica.	2016
19	Plappally	A field study on the use of clay ceramic water filters and influences on the general health in Nigeria	2011
20	Salsali	Virus removal efficiency of Cambodian ceramic pot water purifiers	2011
21	Salvinelli	Assessment of the impact of water parameters on the flow rate of ceramic pot filters in a long-term experiment	2015
22	van Halem	Ceramic Silver-Impregnated Pot Filters for Household Drinking Water Treatment in Developing Countries: Material Characterization and Performance Study.	2007
Manufacturing Variable Investigations			
1	Abebe	Point-of-Use Removal of Cryptosporidium Parvum from Water: Independent Effects of Disinfection by Silver Nanoparticles and Silver Ions and by Physical Filtration in Ceramic Porous Media	2015
2	Abiriga	Effect of Grogs on in the Performance of Ceramic Water Filters	2014
3	Goodwin	An optical method for characterizing carbon content in ceramic pot filters	2017
4	Guerrero-Latorre	Development of Improved Low-Cost Ceramic Water Filters for Viral Removal in the Haitian Context	2015
5	Kallman	Ceramic Filters Impregnated with Silver Nanoparticles for Point-of-Use Water Treatment in Rural Guatemala	2011
6	Lantagne	Effect of Production Variables on Microbiological Removal in Locally-Produced Ceramic Filters for Household Water Treatment	2010
7	Oyanedel-Craver	Sustainable Colloidal-Silver-Impregnated Ceramic Filter for Point-of-Use Water Treatment	2008

8	Plappally	A field study on the use of clay ceramic water filters and influences on the general health in Nigeria	2011
9	Rayner	Laboratory Investigation into the Effect of Silver Application on the Bacterial Removal Efficacy of Filter Material for Use on Locally Produced Ceramic Water Filters for Household Drinking Water Treatment.	2013
10	Rayner	The effects of input materials on ceramic water filter efficacy for household drinking water treatment	2017
11	Soppe	Critical Parameters in the Production of Ceramic Pot Filters for Household Water Treatment in Developing Countries.	2015
12	Varkey	Point-of-use water purification using clay pot water filters and copper mesh	2012
13	Yakub	Porosity, Flow, and Filtration Characteristics of Frustum-Shaped Ceramic Water Filters.	2013
Silver Investigations			
1	Adeyemo	Comparing the Effectiveness of Five Low-Cost Home Water Treatment Devices for Cryptosporidium, Giardia and Somatic Coliphages Removal from Water Sources	2014
2	Bielefeldt	Bacterial treatment effectiveness of point of use ceramic water filters	2009
3	Bielefeldt	Removal of virus to protozoan sized particles in point-of-use ceramic water filters	2010
4	Brown	Microbiological Effectiveness of Locally Produced Ceramic Filters for Drinking Water Treatment in Cambodia.	2010
5	Kallman	Ceramic Filters Impregnated with Silver Nanoparticles for Point-of-Use Water Treatment in Rural Guatemala	2011
6	Lantagne	Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 1: Intrinsic Effectiveness	2001
7	Lantagne	Effect of Production Variables on Microbiological Removal in Locally-Produced Ceramic Filters for Household Water Treatment	2010
8	Mikelonis	Multilevel modeling of retention and disinfection efficacy of silver nanoparticles on ceramic water filters	2016
9	Mwabi	Removal of Escherichia Coli and Faecal Coliforms from Surface Water and Groundwater by Household Water Treatment Devices/Systems: A Sustainable Solution for Improving Water Quality in Rural Communities of the Southern African Development Community Region.	2012

10	Mwabi	Removal of Waterborne Bacteria from Surface Water and Groundwater by Cost-Effective Household Water Treatment Systems (HWTS): A Sustainable Solution for Improving Water Quality in Rural Communities of Africa.	2013
11	Oyanedel-Craver	Sustainable Colloidal-Silver-Impregnated Ceramic Filter for Point-of-Use Water Treatment	2008
12	Rayner	Laboratory Investigation into the Effect of Silver Application on the Bacterial Removal Efficacy of Filter Material for Use on Locally Produced Ceramic Water Filters for Household Drinking Water Treatment.	2013
13	van der Laan	Bacteria and Virus Removal Effectiveness of Ceramic Pot Filters with Different Silver Applications in a Long Term Experiment.	2014
14	van Halem	Ceramic Silver-Impregnated Pot Filters for Household Drinking Water Treatment in Developing Countries: Material Characterization and Performance Study.	2007
15	Zhang	Comparison of the bacterial removal performance of silver nanoparticles and a polymer based quaternary amine functionalized silsesquioxane coated point-of-use ceramic water filters	2013
Outcome Evaluations			
1	Abebe	Ceramic water Filters Impregnated with Silver Nanoparticles as a Point-of-Use Water-Treatment Intervention	2014
2	Brown	Local Drinking Water Filters Reduce Diarrheal Disease in Cambodia: A Randomized, Controlled Trail of the Ceramic Water Purifier	2008
3	Casanova	A Post-Implementation Evaluation of Ceramic Water Filters Distributed to Tsunami-Affected Communities in Sri Lanka.	2012
4	Casanova	Factors Affecting Continued Use of Ceramic Water Purifiers Distributed to Tsunami-Affected Communities in Sri Lanka	2012
5	Kallman	Ceramic Filters Impregnated with Silver Nanoparticles for Point-of-Use Water Treatment in Rural Guatemala	2011
6	Lantagne	Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 2: Field Investigations	2001
7	Lemons	Assessment of the Quality, Effectiveness, and Acceptability of Ceramic Water Filters in Tanzania.	2016
8	Mellor	Comparison of Three Household Water Treatment Technologies in San Mateo Ixtatán, Guatemala	2015

9	Mohamed	Microbiological Effectiveness of Household Water Treatment Technologies under Field Use Conditions in Rural Tanzania	2016
10	Murphy	Influence of household practices on the performance of clay pot water filters in rural Cambodia	2009
11	Murphy	Microbial and chemical assessment of ceramic and biosand water filters in rural Cambodia	2010
12	Murphy	A Critical Evaluation of Two Point-of-Use Water Treatment Technologies: Can They Provide Water That Meets WHO Drinking Water Guidelines?	2010
13	Rayner	Evaluation of Household Drinking Water Filter Distribution Programs in Haiti.	2016
14	Salvinelli	Ceramic Pot Filters Lifetime Study in Coastal Guatemala	2017
Impact Evaluations			
1	Abebe	Ceramic water Filters Impregnated with Silver Nanoparticles as a Point-of-Use Water-Treatment Intervention	2014
2	Brown	Local Drinking Water Filters Reduce Diarrheal Disease in Cambodia: A Randomized, Controlled Trail of the Ceramic Water Purifier	2008
3	Plappally	A field study on the use of clay ceramic water filters and influences on the general health in Nigeria	2011

7 Research Summary

The laboratory, field and secondary research presented in this dissertation investigated the influence of manufacturing variables on filter quality, evaluated in situ filter use, evaluated quality control protocols for filter production, and synthesized available research on filter effectiveness from laboratory investigations, household evaluations and health impact studies. The overarching aims of this thesis were to: 1) fill some research gaps in the CWF literature; and, 2) further guide manufacturing recommendations to support the consistent production of high-quality filters.

This was carried out by: 1) conducting a laboratory investigation to evaluate the influence of different silver species and silver application dose on effluent silver concentration, *E. coli* removal and viable bacteria retained in ceramic filter disks (as surrogates for full-sized filters) manufactured with different clays and burn-out materials; the effect of different influent water chemistries was also evaluated; 2) conducting a laboratory investigation into the influence of different manufacturing variables on *E. coli* removal and filter characteristics of filter disks; 3) evaluating the effectiveness of five filter distribution programs that had provided biosand, ceramic or Sawyer filters in Haiti; 4) developing a framework for evaluating quality control protocols in ceramic water filter manufacturing; and lastly, 5) conducting a systematic review of the literature on ceramic water filter quality in laboratory, household evaluations and health impact studies. Summaries of each of these components of the thesis (Chapters 2-6) are presented below.

Chapter 2: The goal of this investigation was to provide evidence-based recommendations for silver application to ceramic water filters. The effects of three concentrations of two silver species on effluent silver concentration, *E. coli* removal and viable bacteria retained on the surface and contained in the pores of ceramic disks manufactured with clay imported from three CWF factories using sawdust as the burn-out material were evaluated. Additionally, filter performance using water with three chemistry characteristics (Na^+-NaCl, Ca^{2+}-$CaCl_2$ and humic acid as natural organic matter) with disks manufactured with the different clays using either sawdust or rice husk as burn-out material was evaluated. Results showed: 1) silver desorption from disks coated with silver nitrate (Ag^+) was greater than desorption of silver nanoparticles (nAg) for all disks; 2) effluent concentration, *E. coli* removal and viable bacteria retained inside the disks were dose-dependent on the amount of silver applied; and, 3) at the silver concentration tested (0.003mg/g) neither water chemistry conditions nor burn-out material demonstrated an effect on the parameters evaluated. The recommendation from this research is for filter manufacturers to use nAg rather than silver nitrate and that the amount of nAg may be increased from the current recommendation (0.03mg/g) to 0.3mg/g to improve disinfection and increase expected longevity of the silver in the filter without exceeding guideline values for silver in drinking water.

Chapter 3: This investigation sought to improve the understanding of the relative influence of different input variables on bacteria removal ability and filter characteristics. Filter disks manufactured with different clays, burn-out materials, burn-out material sieved with different mesh sizes and burn-out material to clay ratios were tested for *E. coli* reduction. Filter characteristics including porosity, density, shrinkage and flow rates were calculated. Water was run through filters daily for four weeks, and flow rate and *E. coli* reduction, as measured by *E. coli* LRV, were tested twice weekly. The findings were: 1) there was not a strong correlation between the first and last LRV test results (R^2=0.38,

$p<0.010$); 2) there was not a strong association between flow rate and first, average, or last LRV results ($R^2=0.17$, $p=0.090$; $R^2=0.30$, $p=0.020$; $R^2=0.24$, $p=0.040$); and, 3) first and average LRV were associated with burn-out material type ($R^2=0.68$, $p<0.001$; $R^2=0.60$, $p<0.001$), and last LRV was associated with burn-out material and mesh size ($R^2=0.54$, $p<0.050$). Recommendations for filter manufacturers, are to: 1) verify filtration efficacy with repeated bacteria reduction tests when materials, processing, or filter characteristics vary; 2) carefully control production variables; and, 3) continue flow rate testing of each filter to evaluate within and across batch production consistency.

Chapter 4: The purpose of this investigation was to evaluate filter programs that distributed biosand, ceramic, or Sawyer filters in Haiti after the 2010 earthquake and cholera outbreak. Household surveys and water sampling was conducted at ~50 randomly selected households in each of the five program catchments. Stored untreated and treated samples were tested for *E. coli* and turbidity. Across programs, self-reported filter use ranged from 27-78%; confirmed use (participants with reported use who also showed the filter with water currently in it) ranged from 20-76%; and, effective use (participants who used the filter to improve water quality to international guideline values) ranged from 0-54%. Programs that more successfully met evaluation metrics featured the following attributes: 1) distributed an effective technology; 2) provided safe storage; 3) required cash investment in the technology; 4) provided initial training; 5) provided follow-up; 6) provided supply-chain access; 7) targeted households relying on contaminated water sources; and, 8) had experience working in the local context. Findings from this research support results of previous research on household water treatment and suggest that well implemented programs have the potential to result in sustained household filter use in Haiti.

Chapter 5: The goal of this project was to develop a framework to evaluate quality control protocols in ceramic water filter manufacturing. Site assessment tools were developed, four factories were visited, production protocols were documented, production processes observed, and filters were transported to Tufts University for flow rate and *E. coli* removal testing. Filters from two factories met *Best Practice* bacteria removal guidelines (≥2 LRV); however, none of the manufacturers consistently applied criteria to monitor production consistency. Two of the four factories documented production and promoted safe working environments. It is proposed that this framework for evaluating production protocols be incorporated into a future filter manufacturing quality control evaluation process. The following proposed metrics would constitute the main elements for quality control protocol assessment: 1) filters achieve ≥2 LRV of *E. coli*; 2) the quality control protocol in place applies criteria to verify production consistency; 3) factories document production; and 4) factories promote a safe working environment for employees. Recommended modifications to this framework include on-site filter testing.

Chapter 6: The aim of this review was to systematically evaluate research carried out on CWFs, with a specific focus on manufacturing materials and methods, to synthesize research findings, provide manufacturing recommendations and identify future research needs. A protocol was developed that defined: inclusion criteria, search strategy, selection and processing strategy, quality assessment strategy and an analysis plan. Data was extracted from 57 full-text manuscripts. In laboratory testing, full-sized factory-manufactured filters met WHO 'two-star' performance target for bacteria and protozoa, but not for virus removal; however, materials and manufacturing methods were not generally documented. Results from research that investigated manufacturing variables suggest that increased ratio and firing temperature may increase flow rate without substantially compromising LRV; control of burn-out material particle size is important for consistent LRV; and the proportion and size of burn-out material added to the filter mixture and firing temperature impact filter strength. There does not appear to be sustained improved performance with silver nitrate application. It is recommended that filters be tested for bacteriological effectiveness prior to silver application to ensure the filter itself, rather than the silver, is relied on for drinking water treatment. Recommended areas for further research include: the influence of clay characteristics, burn-out material type and particle size and firing temperature on the three performance criteria; the potential for sustained improved bacteria removal performance with nAg application; and the development of a strength testing protocol.

7.1 Overall conclusions

The aim of the work presented in this dissertation was to address research needs to further guide manufacturing recommendations and to facilitate and support the production of consistently high quality filters.

With initial silver application improved bacteria removal performance has been measured, but some studies that evaluated filter performance over time have found no difference in LRV by filters with or without silver application. This may be due to desorption of silver nitrate from filters, a finding in Chapter 1. While nAg appears to be retained better in the filter material, no long-term performance studies of full-sized filters were identified in the literature. Additionally, water chemistry conditions (inorganic or organic compounds) did not appear to influence silver release; however, the silver concentration applied (0.003 mg/g) may have been too low to measure an effect as other studies have measured a change in silver elution with varying in influent water characteristics (Mittelman et al. 2015).

Manufacturing is optimized at the factory level to balance performance criteria of flow rate, LRV and strength according to locally available materials. Manufacturers widely rely on flow rate as an indicator of filter quality and consistency. One study that evaluated the influence of manufacturing variables on flow rate and total coliform removal using natural waters (without controlled influent bacteria concentrations), identified a relationship between flow rate and bacteria removal; however, manufacturing variables including burn-out material type were not controlled for in the regression analysis (Lantagne et al. 2010). Results from Chapter 3 suggest that burn-out material type and mesh size used to sieve burn-out material are associated with LRV and a strong association between flow rate and LRV, controlling for input variables, was not identified in this study. Similarly, another study identified a relationship between control of burn-out material particle size and LRV but did not identify a correlation between flow rate and LRV in filters manufactured with different rice husk ratios.

Thus, while silver application improves initial bacteria removal performance, this improvement may not be sustained with silver nitrate application and long-term performance evaluations with nAg were not identified. Therefore, it is not recommended to rely on silver as the principal treatment mechanism and it is recommended that filters be tested before silver application to evaluate the bacteria removal performance of the filter material. Since it is not practical to test every filter for bacteria removal, and flow rate does not appear to be a reliable indicator for bacteriological removal, once a recipe has been established, input materials and processing should be carefully controlled and manufacturing consistency monitored and evaluated. Research findings suggest that particle size of burn-out material is an important variable to control for bacteria removal performance.

Filter manufacturing recommendations. Filter manufacturing specifications are optimized at each factory to achieve performance criteria of flow rate, LRV and strength according to local materials. When a filter mixture recipe is developed, changed or materials or filter characteristics vary, it is recommended that filters be tested for bacteria removal performance. It is recommended that filters be tested and achieve ≥2LRV in bacteria before silver application to evaluate the quality of the filter material. During production it is recommended that input materials and manufacturing processes are controlled and manufacturing consistency monitored and evaluated. Furthermore it is recommended that production is documented and a safe working environment is promoted.

Recommendations for filter manufacturers by manufacturing variable are discussed below. Please note that these recommendations are based on a small number of, small, heterogeneous studies and are limited by the materials, methods and parameters tested in each study.

Clay. High clay content (high plasticity) has been associated with improved bacteria removal. Thus it is recommended that manufacturers seek clays with high plasticity, monitor clay consistency, and when clay characteristics vary additional bacteria removal testing is recommended.

Burn-out material type. It is recommended that manufacturers work with a single burn-out material type; however, where local resource availability requires working with different burn-out materials, additional monitoring for consistency and quality (bacteria removal testing) is recommended.

Burn-out material processing. Burn-out material may not be adequately controlled with a relatively large mesh depending on the characteristics of the burn-out material received (1 mm opening). Additionally, a smaller particle size is associated with better bacteria removal, thus it is recommended to use a smaller mesh (0.6 mm opening) to process burn-out material.

Ratio. It is recommended that the ratio of burn-out material to clay be controlled to achieve the desired flow rate but that LRV and strength performance criteria be monitored to verify the proportion of burn-out material added achieves a balance whereby all three criteria are met.

Firing. While the firing temperature range will be confined by the clay characteristics, an increase in firing temperature may increase flow rate and strength without compromising LRV. It is recommended that filters fired at the selected temperature be tested for bacteria removal to confirm this recommendation is transferrable to the local materials.

Silver. It is recommended to apply 0.03-0.3 mg/g of nAg to fired filters by coating both the inside and outside of filters with a silver solution. nAg application is recommended over silver nitrate as it appears to be retained better and thus may provide longer-term performance than silver nitrate.

Further research: The above recommendations are based on a small number of, small, heterogeneous studies limited by the materials, methods and parameters tested in each study; further research is recommended into the influence of manufacturing variables on key performance criteria including: flow rate, LRV and strength. Additionally, there is a need for a standardized test method and criteria for evaluating filter strength. These are presented below by manufacturing variable.

Clay. Investigation into the influence of clay characteristics on filter characteristics and performance is recommended, including the use of commonly included additives, such as sand, grog and laterite.

Burn-out material: Research to evaluate the effects of different burn-out materials, including rice husk and hard and soft wood sawdust, on filter characteristics (including pore morphology) and performance is recommended.

Firing conditions: Further research is recommended to investigate the effects of firing temperature on performance criteria and the use of firing temperature to optimize flow rate and LRV. Additionally, further research is recommended to evaluate the effects of firing filters in a reduced atmosphere.

Silver: Further research is needed to evaluate long-term LRV performance of nAg, predominant form of silver in filtered water from filters applied with nAg (as nAg or ionic silver), and silver performance during filtration. Research to evaluate the fired-in method of silver application on silver release and bacteriological performance is also recommended.

Strength: There is a need for a standardized test method and criteria for evaluating filter strength.

7.2 Closing

Diarrheal disease is preventable and treatable, yet it remains a leading cause of morbidity and mortality. Where access to safely managed water and sanitation infrastructure is limited, CWFs and other HWT technologies can improve the microbiological quality of drinking water and reduce diarrheal disease. Local CWF production has many advantages, including contributing to local business opportunity and supply chain access; however, with more than 50 independent factories worldwide and variability in resources, materials and methods, research and the dissemination of findings is challenging. Continued effort is needed to promote, improve and maintain the consistent production of high quality filters for drinking water treatment.

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