Development of a Porous Ceramic Tablet Embedded with Silver Nanopatches for Low-cost Point-of-Use Water Purification

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ABSTRACT

Waterborne pathogens are a major cause of diarrheal diseases in developing communities. The World Health Organization (WHO) recognizes point-of-use (POU) technologies as effective methods to improve water quality and prevent diarrheal diseases at the household level. This work describes a novel method to embed silver in ceramic porous media in the form of metallic silver nanopatches. This method has been applied to develop a new POU technology, a silver-embedded ceramic tablet (SCT) that provides long-term water disinfection. The work presented here investigates the development, technical performance, social acceptance and economic sustainability of this novel POU technology.

When dropped into a household water storage container, the SCT releases silver ions at a controlled rate that in turn disinfect microbial pathogens. Characterization of the silver-embedded ceramic media was performed using transmission electron microscopy. Spherical-shaped patches of metallic silver were observed at 1– 6 nm diameters and confirmed to be silver with energy dispersive spectroscopy. Disinfection experiments in a 10 L water volume demonstrated a 3-log reduction of *Escherichia coli (E. coli)* within 8 h while silver levels remained below the WHO drinking water standard (100 μg/L). Silver release rate varied with clay mineralogy, sawdust particle size, and initial silver mass. Silver release was repeatable for daily 10 L volumes for 179 days. Results suggest the ceramic tablet can be used to treat a range of water volumes.

Field performance of the technology was evaluated among 79 rural households in Limpopo Province, South Africa over one year. In 50 households, the SCT was evaluated as a secondary POU method in combination with the ceramic water filter (CWF). Twenty-five households were given CWFs with lower plastic receptacles and spigots, and the other half was given CWFs with receptacles and a SCT for the lower receptacle reservoir. The effectiveness of the SCT as the primary POU technology was evaluated among 29 households in a blinded study. For households evaluating the SCT as the primary POU method, each household received two 20-L plastic water-storage containers with a cover and spigot. One container per household held a SCT, and the other container in each household held a ceramic tablet without any silver. This latter container and tablet served as a control. Both tablets appeared to be identical, and the residents could not distinguish between the SCT and the control tablet. Residents were instructed to fill both containers at night before going to bed and using water from both containers equally throughout the following day. All 79 households were visited weekly over the ensuing 5-week period and again at weeks 37 and 52. Water samples were collected from the source water and spigot of each container for analysis of turbidity, total silver, coliform bacteria, and *E. coli*.

Results demonstrated that all three approaches significantly reduced total coliform bacteria and *E. coli* relative to the controls (for silver-ceramic-tablet

households) or the source water (for filter and filter-plus-tablet households). The SCT's performance was comparable to current inexpensive, single-use POU methods and worked best when used in combination with the CWF to provide a 100% reduction in *E. coli* after 1 year. Silver levels in all treated water samples were less than 20 μg/L, significantly below the drinking water standard of 100 μg/L. User surveys indicated that all the technologies were simple to use and culturally appropriate.

In addition to being effective against bacteria, the disinfection efficiency of the SCT against other harmful waterborne pathogens, such as *Cryptosporidium parvum (C. parvum)* and MS2 phage, was also evaluated. Results showed excystation of *C. parvum* ocysts reduced to 14% from 74% among samples treated with ceramic tablets embedded with 500 mg of silver, and 89% reduction of MS2 bacteriophage. Silver concentrations ranged from 85.7 to 172.9 μg/L, demonstrating that silver is an effective disinfecting agent against these pathogens where current methods such as chlorination are ineffective.

Finally, market demand and operational costs for a start-up venture based on the technology was investigated to determine the economic sustainability of the SCT. Through the NSF I-Corp program, 100 customer discovery interviews were conducted to determine market demand, and a prototype manufacturing facility at the University of Virginia was established to evaluate operational costs.

Results suggest that the SCT has a competitive advantage. The ease of use, reusability, effectiveness against waterborne pathogens and ease of transport and distribution make it a promising and affordable technology that could improve human health. The work described here provides a fundamental understanding of this novel method to impregnate silver in porous ceramic media, which has great potential to provide safe drinking water for billions of people who are in need of it around the world.

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Abbreviations

- POU – Point-of-Use
- POUWT – Point-of-Use Water Treatment
- CWF – Ceramic water filter
- SCT – Silver-embedded ceramic tablet
- CWF+SCT – Ceramic water filter and silver-embedded ceramic tablet
- WTP – Willingness to Pay
- GFAA – Graphite Furnace Atomic Absorption Spectrometry
- IMWTS – Impaired Municipal Water Treatment System
- I-Corps – NSF Innovations Corps

Publications and Presentations

The work presented in this dissertation will ultimately result in three journal articles. Preliminary data collected for this project and described in Chapter 1 was published in collaboration with authors Mellor, J.E., Shawel, L., Dillingham R. and Smith J. in the Journal of Water Research in 2013. Work presented in Chapter 2 has been published in the Journal of Environmental Science and Technology in December 2014. Manuscripts are in preparation for work described in Chapters 3 and 4.

- **Chapter 1:** Mellor J E., Shawel L., Ehdaie B., Dillingham R., Smith J., 2013, Modeling the Sustainability of a Ceramic Water Filter Intervention. Water Research, v. 49, p. 286-299.

- **Chapter 2:** Ehdaie B, Krause C, Smith JA. Porous ceramic tablet embedded with silver nanopatches for low-cost point-of-use water purification. *Environ Sci Technol*. 2014; 48(23):13901-13908.
- **Chapter 2:** Ehdaie B, Kahler DM, Smith JA. Mechanisms regulating silver disinfection by porous ceramic tablet embedded with silver nanopatches. 2015, In preparation

- **Chapter 3:** Ehdaie B, Rento CT, Son V, Turner SS, Samie A, Dillingham RA, Smith JA. Evaluation of silver-embedded ceramic tablet as a primary and secondary point-of-use water purification technology in Limpopo Province, S. Africa. 2015, in preparation.
- **Chapter 4:** Ehdaie B, Su Y-H, Swami NS, Smith JA. Disinfection of protozoa and viruses by novel porous ceramic tablets embedded with silver and copper nanopatches for point-of-use water purification. 2015, In preparation.

The following work has been presented at the following conferences:

- **Chapter 2:** Ehdaie B., Smith J., 2013 (accepted). “The MadiDrop: A novel silver-embedded, ceramic water purifier for point-of-use water treatment.” Verbal presentation. 2013 UNC Water and Health Conference: Where Science Meets Policy, UNC: The Water Institute, October 2013, Chapel Hill, NC.

Chapter 1

Introduction

Over 780 million people do not have access to an improved drinking water supply and for many with access to an improved water sanitation system drinking water quality declines at the household level due to poor sanitation and hygiene conditions[1,2] . Waterborne pathogens found in contaminated water are a major cause of diarrheal diseases[1,3] . Therefore, research to develop innovative, versatile, and sustainable water treatment technologies at the household level is urgently needed to improve drinking water in vulnerable communities and reduce the associated burden of disease. The World Health Organization (WHO) recognizes point-of-use (POU) technologies as effective methods to improve water quality and prevent diarrheal diseases at the household level [4,5] . However, field performance among existing POU methods can be limited due to recontamination, high cost and poor social acceptance. This chapter discusses the current challenges with access to safe drinking water in developing countries at the household level, and evaluates technologies being used to address these challenges.

1.1 Background

1.1.1 Challenges with Access to Safe Drinking Water in the Developing World

Health disparities associated with poor water quality are severe and widespread. Each year, more than 3.4 million cases of diarrheal diseases are linked to unsafe drinking water, poor sanitation and hygiene[6] . Exposure to diarrheal diseases at an early age (< 5 years) can increase rates of malnutrition, resulting in growth stunting and impaired cognitive development[2,7] . Untreated water is particularly problematic for individuals living with AIDS, as their weakened immune systems cannot combat gastrointestinal infections[8,9] . In many parts of the world, including Limpopo province, there is an unfortunate confluence of low-quality water and high HIV infection rates[10,11] , making the consequences of poor water quality even more severe and sometimes fatal. While the disinfection or removal of coliform bacteria and *E. coli* can greatly improve drinking water quality, its impact on human health is limited by the prevalence of other harmful waterborne pathogens resistant to current water treatment methods. In fact, the most harmful waterborne pathogens, such as protozoa and viruses, are unaffected by common water treatment methods like chlorination and filtration. Both are resistant to chlorination, and in the case of viruses, too small for filtration[12,13] . This is even more problematic regarding *Cryptosporidium parvum* because it requires a low infectious dose and is commonly found in surface water, a common source of drinking water for those living in developing communities[12,14-16] .

Through the Millennium Development Goals, the United Nations aims to reduce this global burden by improving access to clean water. Many projects have taken centralized approaches to this problem, by successfully installing boreholes and protected wells to increase access to clean water[1,2] . However, the impact on human health has been hindered due to recontamination between the point-of-collection to the point-of-consumption. In a recent study, 43.6% of water samples from household water storage containers did not meet WHO water quality standards when water was collected from an improved water source[6,17] . These findings are consistent with other studies demonstrating occurrences of extensive contamination during collection, storage and use[18,19] . As a result, post-source contamination has motivated development of water treatment technologies at the household level.

1.1.2 Review of Literature: Point-of-Use (POU) Water Treatment Technologies

POU technologies are simple and inexpensive water treatment methods that can be used at the household level. The WHO identifies POU technologies as an effective means to improve water quality and human health in communities with impaired public health infrastructures[4,20] . In a recent meta-analysis, the most common and effective POU technologies were boiling water, solar disinfection, plain sedimentation, ceramic filters, and natural coagulants[21] . These technologies perform very well in the laboratory, however their field performance is limited due to recontamination, social acceptance, and economic sustainability[5,22-26] .

Regardless of the POU technology, recontamination is a major issue because water storage receptacles at the household level are at high risk of contamination due to poor sanitation and hygiene conditions. For example, an 8-month study in Limpopo province, South Africa, showed water quality significantly declines from source water to household water. Mean bacterial concentrations increased from 197 cfu/100 mL to 1046 cfu/100 mL[27] . In addition to recontamination, many POU technologies are not effective due to low social acceptance, high cost, and distribution challenges[26] . POU technologies, such as chlorine or bleach tablets, alter the taste and odor of water, and therefore has shown to hinder social acceptance[24-26,28-30] . Another example of poor social acceptance and economic sustainability is PUR, one of the POU methods with the lowest initial capital cost ($0.10/ sachet) on the market. It is a powder mixture of calcium hypochlorite (disinfectant) and ferric sulfate (flocculant) [31] . Its limitations are that a single packet can only disinfect 10 L of water, and it requires multiple steps with recommendation of additional materials, such as fabric filtration. If the user has the supplies and time to complete all these steps, then there is the complication of access to the product. PUR cannot be produced locally, therefore Procter & Gamble (P&G), who owns and distributes the product, has to work through local retailers to reach the consumer. The laborious instructions and complex distribution system has hindered its everyday use in homes. P&G addressed some of these challenges by significantly changing their market strategies and distribution channels to develop a sustainable business model including partnerships with key NGOs, who have already established relationships with potential end-users of PUR[32] . Other POU methods are not environmentally sustainable, such as boiling water where 1 L of water requires 1 kg of firewood, emitting 1625 g of carbon dioxide[33] . In many parts of the developing world (especially Africa), firewood is also a limited resource and boiling water represents an unsustainable method to clean water[34]

. As living conditions become more severe, such as in refugees camps and emergency settings, the challenges facing POU technologies are amplified. In these scenarios, local production and ease of distribution become critical to make POU technologies accessible to these communities.

Given these challenges, ceramic water filters (CWF) represent a promising POU method. CWFs are pot-shaped ceramic containers, made from clay, water and a combustible organic material, such as cornhusk, sawdust or flour. During kiln firing, the organic material combusts while the clay hardens, creating a porous ceramic media. The pores of the ceramic media are small enough to remove most pathogens and particulates from contaminated water[6,35] . Laboratory studies have shown CWFs to effectively remove waterborne pathogens such as bacteria (99.99-100%), and sufficient filtration of protozoa (99%)[5,20,36,37] . They are also economically sustainable because they can be produced locally and with fairly high social acceptance rates. However, they are still fairly expensive for many, and there are challenges associated with distribution, filter breakage, and recontamination. Ceramic water filters cost US$20-40 per filter, which often puts them out of reach for families whose average monthly income is below US$100 in regions similar to Limpopo, South Africa[38,39] . Also, their size and shape make them hard to handle, as 23.8% of ceramic filters were shown to have broken over three years[40] . Finally, ceramic filters require relatively precise manufacturing protocols in order to produce filters with acceptable flow rates. This can be a challenging endeavor for developing-world potters and thereby limit filter effectiveness and factory production capabilities[41] .

Recontamination is one of the most significant problems associated with CWFs. In a water intervention study conducted in Guatemala over 23 months, recontamination was observed among 25% of ceramic water filters. After the study, recontaminated filters and collection reservoirs were cleaned, and retested in a laboratory setting where their microbial removal efficiency returned to be greater than 95%. When the cleaned CWFs were returned to participants, recontamination resurfaced within only 26 days, indicating that the recontamination was due to the lower collection reservoir[22] . Similarly, in a 3-month study in Cambodia, recontamination was observed among 17-19% of CWF users across three different provinces[42-44] . I found similar results when investigating technical performance of ceramic water filters in Limpopo, South Africa 3-years post-intervention. During July 2012, I conducted a field study re-evaluating the performance and social acceptance of ceramic filters from a previous water intervention study. Of the 80 original study participants, I was able to visit 20 households. Technical performance of 26.7% of the filters was inhibited by recontamination of the lower reservoir. Recontamination was considered when effluent microbial concentration levels were higher than influent levels. Also, 20% of working filters had their microbial removal efficiencies decline from 99.9% to 90% suggesting early signs of recontamination[40,45] . These results further support the need for a POU technology that provides continual disinfection to reduce recontamination, easy to use, easy to distribute and socially acceptable at the household level in order to improve water quality and reduce waterborne diseases.

1.1.3 Silver-based POU methods.

Some of the most promising POU technologies include the application of silver and silver nanoparticles as a disinfecting agent. For centuries, the bactericidal effects of silver have been well known and it has been shown to be effective in disinfection of viruses and protozoa as well[11,46,47] . Recently, it had been shown that silver-treated water reduces infectivity of *C. parvum* by 99.99%[46] . Silver, when used with copper, has shown to be effective against viruses as well[48,49] . Furthermore, silver is safe to consume at low levels (<0.1 mg/L) according to the drinking water standards recommended by the US Environmental Protection Agency (EPA) and the World Health Organization. Silver does not change the odor, color, or taste of water, unlike other chemical-based POU methods, such as chlorine and iodine tablets. In the realm of POU technologies, silver nanoparticles have been shown to be an effective disinfecting agent. Perhaps the most common POU technology that uses silver nanoparticles is CWFs. For disinfection, an aqueous suspension of silver nanoparticles is painted onto the CWF, embedding silver within the ceramic pores to promote continual disinfection. A prior study has shown that the silver application benefits filter performance by providing additional 1-2 log reduction in *E. coli*[36] . There are, however, certain limitations to the use of silver nanoparticles in CWFs. First, silver nanoparticles are rarely available in developing world markets and therefore must be imported. Nano-silver is more expensive than bulk silver or even molecular silver (e.g. silver nitrate or silver chloride). A recent study has revealed that silver nanoparticles are relatively mobile in ceramic porous media, suggesting that a significant fraction of the silver nanoparticles may be washed from the filter over time, reducing the long-term effectiveness of the filter[50] . Some organizations paint an aqueous solution of silver nitrate onto fired filters to address these challenges, but a recent study has shown that the ionic silver is not well-retained by the porous ceramic compared to filters painted with silver nanoparticles [51] .

Other approaches for delivering silver to ceramic porous media include coating ceramic bricks with commercially available colloidal silver solution (SilverDYNE) by first dipping the brick in the solution, then firing it, followed by air-drying and another firing for 48 hours[52] . This method is more time-consuming and expensive compared to current methods. Mohan et al. developed a synthetic oxyhydroxide-chitosan granular polymer base where silver nanoparticles are bound to aluminum oxyhydroxide[53] . This method is effective due to high microbial disinfection efficiency and reusability. However production costs and technical skills are fairly demanding and not feasible for POU users in developing communities. Finally, none of these methods provide a passive silver delivery method where silver is released in a controlled rate that eventually reaches a steady state, assuring silver levels remain below the drinking water standard of 0.1 mg/L.

1.2 Dissertation Aims

This dissertation discusses the development and evaluation of a new methodology to embed silver in porous ceramic media and its applications as a novel silver-embedded ceramic POU technology. This research was completed in four parts. Chapter 2 focuses on developing the novel methodology to infuse silver in porous ceramic media in the form of silver nanopatches. It also investigates the mechanisms and processes regulating silver formation and silver release from the media for development of a novel point-of-use water purification, a silver-embedded porous ceramic tablet. Chapter 3 evaluates field performance and social acceptance of the silver-embedded ceramic tablet as a primary and secondary POU method along with CWFs. Disinfection efficiency against various waterborne pathogens is evaluated in Chapter 4. In Chapter 5, the market demand and costs for a start-up venture based off of this novel technology is investigated. To date this novel method of embedding silver in ceramic has not been investigated. The results of this project will contribute significantly towards future development of the technology, and potentially provide an effective, socially acceptable and affordable means for the millions of people around the world to have access to safe drinking water.

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Chapter 2

Development of a Ceramic Porous Tablet Embedded with Silver Nanopatches for Point-of-use Water Purification

The work presented in this chapter resulted in two papers. The first paper has been published and accepted in the Journal of Environmental Science & Technology. The second manuscript is in preparation.

Ehdaie B, Krause C, Smith JA. Porous ceramic tablet embedded with silver nanopatches for low-cost point-of-use water purification. *Environ Sci Technol*. 2014; 48(23):13901-13908.

Ehdaie B, Kahler DM, Smith JA. Mechanisms regulating silver disinfection by porous ceramic tablet embedded with silver nanopatches, 2015, in preparation.

2.1 Introduction

1.87 million deaths result from unsafe drinking water and poor sanitation annually among children under the age of 5 years [1-3]. An estimated 780 million people lack access to an improved water supply[1,2]. The World Health Organization (WHO) suggests that one potential solution to poor-quality household drinking water is treatment at the point of use (POU) [4,5]. A recent meta-analysis reported that household water interventions can be more effective in improving water quality compared to interventions at the source, however this is dependent on the user compliance[6]. Ease of use, affordability, and long-term effectiveness are key factors but also make development of POU technologies an extremely difficult design problem. Current conventional methods are labor intensive, such as fabric filtration and boiling, or dependent on variable factors such as availability of sunlight for solar disinfection. A common theme among a majority of POU methods is recontamination due to poor sanitation. Therefore, successful designs must be technologically effective with respect to removal and/or deactivation of waterborne pathogens under a wide range of water chemistries, and simple to use to ensure user compliance, long-term effectiveness, and reduce risk of recontamination[5,6]. They must also be socially acceptable, scalable and affordable, which likely requires local materials, labor, and/or ease of transport [7-9].

Some of the most promising POU technologies include the application of silver as a disinfecting agent. The antimicrobial effects of silver are well known and recent studies have shown its effectiveness against bacteria[10-14], viruses [15], and protozoa[16,17]. At low levels (< 0.1 mg/L) silver is considered safe for human consumption by the US Environmental Protection Agency (EPA) and WHO [18]. Also, silver maintains the natural odor, color, and taste of water, making it more appealing than other chemical-based POU methods, such as chlorine and iodine tablets/sachets. In the realm of POU technologies, silver has often been used in the form of nanoparticles as an effective disinfecting agent[11,15]. Mohan et al. have developed a synthetic oxyhydroxide-chitosan granular polymer base where silver nanoparticles are bound to aluminum oxyhydroxide[14]. This technology appears to be effective for microbial disinfection and demonstrates reusability. However there are limitations due to material costs and manufacturing, making it challenging to manufacture in a developing-world setting.

Another example is the ceramic water filter (CWF), a pot-shaped ceramic porous media painted with an aqueous silver nanoparticle solution[19-21]. The porous media physically removes waterborne pathogens, while the silver nanoparticles deactivate microorganisms by chemical disinfection[22]. Limitations of this technology include relatively high capital costs, a somewhat difficult manufacturing process, the large filter size and weight, and lack of filter durability (making them difficult to transport). Additionally, silver nanoparticles are expensive and scarce in developing world markets, and have been shown to be relatively mobile in ceramic porous media, suggesting that a significant fraction may be washed off over time, reducing the long-term effectiveness of CWFs [23].

This research describes two entirely new innovations. First, a new synthesis methodology that produces a porous ceramic media interspersed with metallic silver "nanopatches" (with diameters ranging from 1-6 nm). This method uses silver nitrate as a precursor (rather than silver nanoparticles) and does not require any added capping or reducing agents. Second, we have used this synthesis methodology to create an entirely new POU water treatment technology in the form of a silver-infused ceramic tablet. When the ceramic tablet is placed in a household water-storage container, metallic silver is oxidized to ionic silver in the ceramic pore space and diffuses through the porous ceramic into the bulk solution. The ionic silver release rate is effective for continual disinfection of waterborne pathogens while remaining below the silver drinking water standard. The silver release is replicable day after day for several months. Herein, we present results of nanopatch synthesis and characterization in a ceramic porous media, design variables that influence silver nanopatch morphology, silver release, and *E. coli* disinfection rates in different water volumes for silver-infused ceramic tablets.

2.2 Experimental Materials and methods

2.2.1 Materials. The following types of clay were used to fabricate ceramic porous media: (1) a commercially available Redart clay (Resco Products, Inc.) and (2) clay from a natural deposit in the village of Mukondeni in Limpopo Province, South Africa. The 200-mesh Redart clay is pottery clay produced by Cedar Heights Clay Company and was used as received. The predominant clay minerals are illite and kaolinite. The clay has a particle-size distribution (PSD) of 30.7%, 54.9% and 14.4% for particles < 2 μm, 2-20 μm, and > 20 μm, respectively [22] . The clay from South Africa was chosen because it has a different mineralogy and PSD. Also, it could be used to produce ceramic tablets in South Africa. The South African clay was air-dried and ground using a hammer mill at a local ceramic water filter factory. X-ray diffraction analyses indicate that the predominant clay mineral is smectite. PSD for the South African clay was determined using the Saturn DigiSizer II, a light-scattering-based method that was performed by Micromeritics Laboratories (Norcross, GA, USA). The clay has a PSD of 8.9%, 44.8% and 46.3% for particles <10 μm, 10-80 μm, and > 80 μm.

Sawdust used for fabrication was obtained from two different sources, a commercial lumberyard in Earlysville, Virginia (USA) and a ceramic water filter factory in Limpopo Province, South Africa. The Virginia sawdust was processed in the laboratory by sieving at the following three mesh sizes: 16 (1.190 mm), 20 (0.841mm) and 30 mesh (0.595 mm). South African sawdust was used as received, having previously been sieved through a 16-mesh screen. During the sieving process, any particles that passed through the sieve were used. Silver nitrate was purchased from Acros Organics with a purity of 99.5% and used in ceramic tablet fabrication and preparing standards.

A non-pathogenic strain of *E. coli* was purchased from IDEXX Laboratories (cat. 982900700, Lot 042313) and cultured using sterilized Luria-Bertani (LB) broth. LB broth was made with 0.5 g yeast extract, 0.5 g sodium chloride, 0.25 g Bacto-Tryptone and 50 mL deionized water. The *E. coli* culture was thawed and mixed at room temperature for 15 min and then incubated in 6 mL of LB broth for 12 h at 37°C while mixing in a VWR Scientific Orbital Shaker (Model 980001). Cultures were aliquoted and diluted with 40% glycerol for long-term storage at -20°C.

For each disinfection experiment, an *E. coli* culture was prepared from the frozen stock. After a 12-hr incubation, the culture was centrifuged for 20 min at 1363 x *g* using a Thermo Fisher Scientific Laboratory Centrifuge (Model Sorvall Legend XTR) [24] . Then re-suspended in 50 mL of 10 mM phosphate buffer (PB) solution and stored at 4°C. The PB solution was used to preserve viability of *E. coli* in solution while preventing growth, prior to any POU treatment. The PB solution comprised of 11.2 g/L of dipotassium phosphate, 4.8 g/L of potassium phosphate monobasic, 0.02 g/L of ethylenediaminetetraacetic acid and deionized, organic-free water [25] . Sodium thiosulfate was used in microbial testing to stop silver disinfection. A 60 g/L solution of sodium thiosulfate was prepared by dissolving anhydrous sodium thiosulfate (Fisher Scientific) in deionized water. All solutions used in microbial analyses were sterilized before use.

2.2.2 Ceramic Porous Media. Ceramic tablets were made by preparing a dry mixture of clay and sawdust (62.5 g) with 19.2 mL of a silver nitrate solution. The mixture was molded and pressed for 1 minute at 6,895 kPa using a hydraulic manual press. After air-drying for 72 h, tablets were fired in an electric kiln (Evenflow) at 150°C/h until 600°C and then at 300^{o}C/h until 900^{o}C and held for 3 h. Porosity of ceramic media was analyzed using an AutoPore IV 9500 Automatic Mercury Porosimeter (Micromeritics). Fabrication components were varied to produce different types of ceramic tablets. The components that varied were: (i) clay type, (ii) source of sawdust, (iii) weight percent of sawdust, (iv) PSD of sawdust, (v) embedded mass of silver, and (vi) tablet volume. The different combinations of ceramic tablets are shown in Tables 2.1 and 2.2.

Table 2.1. Composition of ceramic tablets fabricated for use in this study.

Clay source/type	Sawdust Source	Percent Mass of Sawdust	Sawdust Mesh size	Initial Silver Mass (mg)
South Africa	South Africa	10	16	50
Redart	South Africa	10	16	50
Redart	Virginia	10	16	50
Redart	Virginia	15	16	50
Redart	Virginia	20	16	50
Redart	Virginia	1	16	50
Redart	Virginia	0	-	50
Redart	Virginia	10	30	50
Redart	Virginia	10	20	50
Redart	Virginia	10	20	500
Redart	Virginia	10	20	1000
Redart	Virginia	10	20	3000

Table 2.2. Dimensions, volumes and macroscopic surface areas of ceramic tablets.

	Diameter (mm)	Thickness (mm)	Volume (cm^3)	Exterior Surface Area (cm^2)
A	65	15	50	97
B	65	30	100	128
C	65	45	149	158
E	130	7	93	294

To test the impact of clay type and source of sawdust on silver release kinetics, ceramic tablets were fabricated using Redart clay, South African clay, Virginia sawdust and South African sawdust. Weight-percent sawdust compositions studied were: 0%, 1%, 10%, 15% and 20% Virginia sawdust in the dry mix. To study sawdust PSD, ceramic tablets were made with Virginia sawdust sieved at three different mesh sizes. Ceramic tablets were made with different masses of silver (50 mg, 500 mg, 1 g and 3 g) and in different shapes to study the impact the initial silver mass and the tablet volume had on silver release. Ceramic tablets were molded in different cylindrical volumes using polyvinylchloride cylindrical molds, and prepared with higher silver content (1 g) in order to be used in larger (10 L) water volume experiments, which is more representative of household water storage containers. For all experiments, control ceramic tablets were prepared using the exact same methods, however, the silver nitrate solution was replaced with19.2 mL of deionized water.

Ceramic tablets for sorption experiments were prepared as described above, however without any silver therefore 19.2 mL of deionized water was used instead of silver nitrate solution. Ceramic tablets were also crushed into smaller pieces using a hammer and weighed out for each isotherm sample that had 1 g of ceramic media. Fabrication components were varied to study the impact of (i) clay type, (ii) source of sawdust, (iii) weight percent of sawdust and (iv) PSD of sawdust on silver sorption. Experiments to investigate diffusion path length on silver release used ceramic tablets, as described as above, and granular pieces of ceramic media. Granular pieces were prepared exactly the same as ceramic tablets with an additional final step where tablets were crushed using a hammer, and sieved at various mesh-sizes for experiments evaluating the optimal particle granular size for silver release.

2.2.3 Characterization of Silver in Ceramic Media using TEM. Transmission electron microscopy (TEM) was used to characterize the formation of silver nanopatches in the ceramic tablets. Samples were prepared by lightly scraping the ceramic surface into a solution of deionized water. TEM grids (Ted Pella Item No. 01822 Ultrathin Carbon A) were prepared with a drop of sample and allowed to dry under a laboratory fume hood. Grids were examined on an FEI Titan TEM at 300 kV. Silver was chemically verified using energy dispersive spectroscopy (EDS) elemental analysis in scanning transmission electron microscopy (STEM) mode. Micrographs were created using a CCD digital camera (Gatan). Size distribution and density of silver nanopatches were quantified using ImageJ processing software.

2.2.4 Quantifying silver in ceramic media via acid digestion. Silver embedded within the ceramic media was extracted and quantified post-firing through acid digestion. Samples were prepared by lightly scraping the surface of the ceramic surface into 50-mL conical tube. Mass of ceramic in each sample was recorded. Samples were digested with 10 mL of 70% nitric acid for 18 h in a sand bath at 40^{o}C. An additional 5 mL of 70% nitric acid was added to 8 mL of the sample. Samples were incubated for another 56 h in the sand bath set at 40^{o}C. Deionized water was added to each sample for a final volume of 50 mL. Samples were incubated at room temperature overnight. Samples were then analyzed for total silver concentrations. A sample of ceramic media without any silver was run in parallel as a control. All samples were run in duplicate.

2.2.5 Batch Reactor Experiments. Silver release and *E. coli* disinfection kinetics were conducted using 200-mL and 10-L batch reactors. Small-volume batch-reactor experiments were prepared by filling a sterile 500-mL plastic container with 200 mL of 10 mM PB solution. Each water sample was inoculated with viable *E. coli*, and the solution was stirred for a few minutes prior to adding the ceramic tablet to suspend the bacteria uniformly. Then a ceramic tablet was placed in each batch reactor. Reactors were sacrificed over time and water samples were collected for analysis of ionic silver, total silver, and *E. coli* concentration. All experiments were conducted in duplicate and at room temperature.

Large-volume (10-L) batch-reactor experiments were conducted to optimize the ceramic tablet for real-world water-storage-and-use applications. 10- or 20-L plastic, open-top containers are often used in rural communities to collect and store water[26] . For these experiments, 20-L plastic open-top buckets were cleaned with soap and boiling water, then filled with 10 L of either tap water or 10 mM PB solution. Tap water was used in these experiments to determine whether residual chlorine impacts silver release kinetics of ceramic tablets, because interrupted municipal water sources are common occurrences in developing world communities and as a result chlorinated treatment of the municipal tap is unpredictable. The residual chlorine in tap water was measured using the Free Chlorine Micro Check Test Strips (HF Scientific). Results were compared to silver release rates in microbial disinfection experiments that were conducted in 10mM PB solution to maintain viability of bacteria in suspension while not providing a carbon source for growth. Each 10-L sample was spiked with *E. coli*, and all experiments were conducted in duplicate at room temperature.

Reusability of the ceramic tablet was tested by measuring changes in silver release over time in large-volume batch-reactor experiments. Ceramic tablets (65 mm diameter x 45 mm width) were prepared using 90% Redart clay (by weight), 20-mesh sawdust and 1 g of silver. The water was sampled every 24 h for 179 d and replaced daily to mimic everyday use. Experiments were run in triplicate and samples were measured for total silver. The silver concentrations were normalized to the average silver concentration measured during the first three days to quantify changes in silver release overtime.

2.2.6 Inorganic Chemical Analysis. Ionic and total silver concentrations were measured at 4, 6, 8 and 24 hr. Ionic silver was measured using a Thermo Scientific Orion Ion-Selective Electrode for silver/sulfide ions. Samples and standards were prepared with 1 mL of low ionic-strength adjuster solution (Thermo Scientific) per 100 mL of sample. Total silver concentrations were measured using an acetylene-air flame atomic absorption (AA) spectrometer (Perkin-Elmer AA2100), and a graphite furnace atomic absorption spectrometer (GFAA) (Perkin-Elmer HGA 900) for low silver levels, ensuring they were in the detectable range. GFAA was also used to measure copper, zinc, lead, chromium and cadmium levels in samples. AA and GFAA samples were prepared with nitric acid (1%), to reduce chelation of ions, and were analyzed using cathode lamps specific to the element being measured.

Nitrate was quantified in 10-L tap water batch reactor experiments treated with ceramic tablets embedded with 1 g of silver using the Hach TNT835 Kit with the DR 3900 Benchtop Spectrophotometer.

2.2.7 Microbial Disinfection. Samples were taken at 4, 6, 8 and 24 h to quantify levels of viable *E. coli*. Each sample was treated with sodium thiosulfate (26.4 μL per 1 mL of sample) and then kept at room temperature for 2 min to stop the disinfection caused by silver ions[10]. Additional experiments were performed to ensure thiosulfate addition effectively stopped disinfection (refer to Figures 2.1 and Appendix A for methods and discussion). Viable *E. coli* were quantified in each sample using the Colilert Defined-

Substrate Technology System, a method approved by the U.S. EPA and recommended by the WHO for microbiological testing[27-29] . Colilert media (cat. WP200I) were added to 100 mL of the sample and mixed thoroughly. The solution was poured into the IDEXX Quanti-trays (cat. WQT-2K) and incubated for 24 h at 37 °C. Using a fluorescent UV lamp, the number of fluorescing wells in the tray were counted and correlated to *E. coli* concentrations using a most-probable-number table provided by the manufacturer.

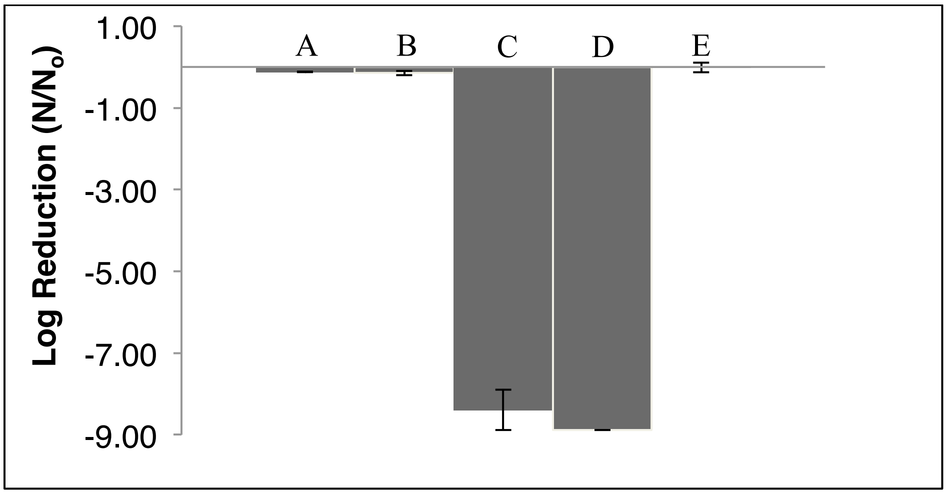

Figure 2.1. *Preliminary experiments on sodium thiosulfate treatment of samples for ceramic tablet experiments. Log reduction in E. coli concentration (with standard error) for the following treatments: (A) E. coli with control ceramic tablet, (B) E. coli with control ceramic tablet and $Na_2S_2O_3$ (neutralizer) treatment, (C) E. coli with silver ceramic table without neutralizer treatment, (D) E. coli with silver ceramic tablet and $Na_2S_2O_3$ treatment and (E) silver ceramic tablet with $Na_2S_2O_3$ treatment prior to addition of E. coli. All samples were incubated for 6 hr at room temperature in 200 mL of 10 mM phosphate buffer solution with 10^9 cfu/100 mL of E. coli. Samples treated with $Na_2S_2O_3$ neutralizer were incubated for 2 minutes.*

2.2.8 Isotherm sorption experiments for ceramic tablets. Silver sorption to ceramic media was measured over time among ceramic tablets with different clay mineralogies to determine sorption equilibrium time-point. Immediately following firing, ceramic tablets were broken into small pieces using a hammer. In a 50-mL conical tube, 1 g of ceramic was added to 40mL of 10ppm silver. The 10 ppm silver was prepared using phosphate buffer and silver nitrate. Tubes were stirred constantly in a shaker at room temperature and sacrificed over time. Water samples were collected at the following time points: 1,4, 6,10, 20 and 24 h. Samples were centrifuged for 15 min at 2,500 rpm, and analyzed for total residual silver concentrations using the flame AA as described in 2.2.6. These concentrations were subtracted from the initial concentration in solution to determine amount of silver sorbed to ceramic media.

For the isotherm experiment, samples were prepared for each condition as described above. In a 50-mL conical tube, 1 g of ceramic was added to 40mL of phosphate buffer, however silver concentrations varied among samples. Samples were prepared with the following silver concentrations: 0.5 ppm, 1.0 ppm, 5.0 ppm and 10 ppm. Then samples were kept at room temperature in a shaking incubator for 20 h. Samples were centrifuged for 15 min at 2,500 rpm and then analyzed for total silver concentrations using flame AA. Final silver concentrations were subtracted from the initial and multiplied by the volume of the solution to determine mass of absorbed silver. This amount was then divided by the ceramic mass to determine silver absorbed per kilogram of ceramic sample. Positive and negative controls were used for each isotherm experiment. Positive controls consisted of a 50-mL conical tube with phosphate buffer and silver, but no ceramic, and handled identically to the samples containing ceramic. Negative controls consisted of samples with only PB and PB with ceramic media.

Cation ion exchange capacity was measured among ceramic tablets with variations in clay mineralogy, source of sawdust, percent composition of sawdust, and sawdust particle size. Redart clay and S. African clay were also tested as a control. Samples were analyzed by Midwest Laboratories, Inc. using the EPA 9081 method. Samples were mixed with sodium acetate and extracted with isopropyl alcohol and then washed with ammonium acetate. Cation ion capacity was measured by quantifying the increase in residual sodium acetate concentrations when ammonium acetate was introduced into solution. Sodium acetate was measured using inductively coupled plasma-atomic emission spectrometry (ICP) methods.

2.3 RESULTS

2.3.1 Characterization of silver retained in ceramic media. Figure 2.2 displays a TEM micrograph of nano-sized patches of metallic silver within the ceramic matrix. Samples were taken from the center of a ceramic tablet embedded with 500 mg of silver and prepared with 90% Redart clay, 20-mesh Virginia sawdust. Silver nanopatches were confirmed to be metallic silver using EDS (Figure 2.3), and are spherical in morphology (Figure 2.2) with an average diameter of 2.71 ± 0.51nm (Figure 2.4).

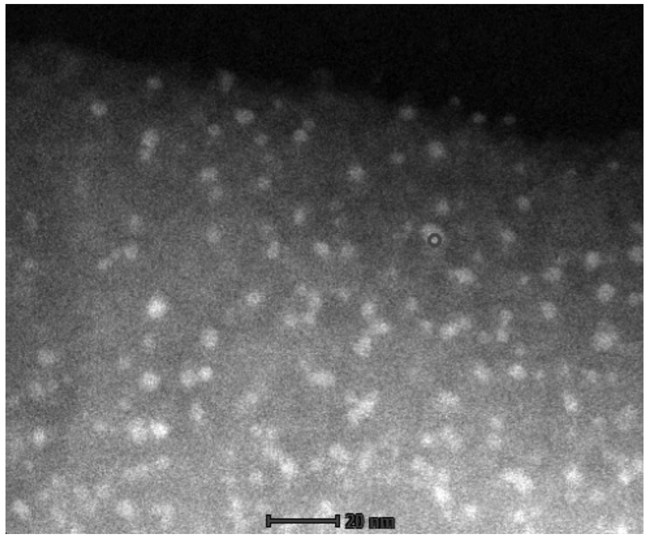

Figure 2.2. *Transmission electron microscopy image taken of silver nanopatches observed in the center of a ceramic tablet using scanning electron microscopy mode. The scale bar represents 20 nm in distance. Ceramic tablets were fabricated using 90% Redart clay, 20-mesh Virginia sawdust and 500 mg of silver.*

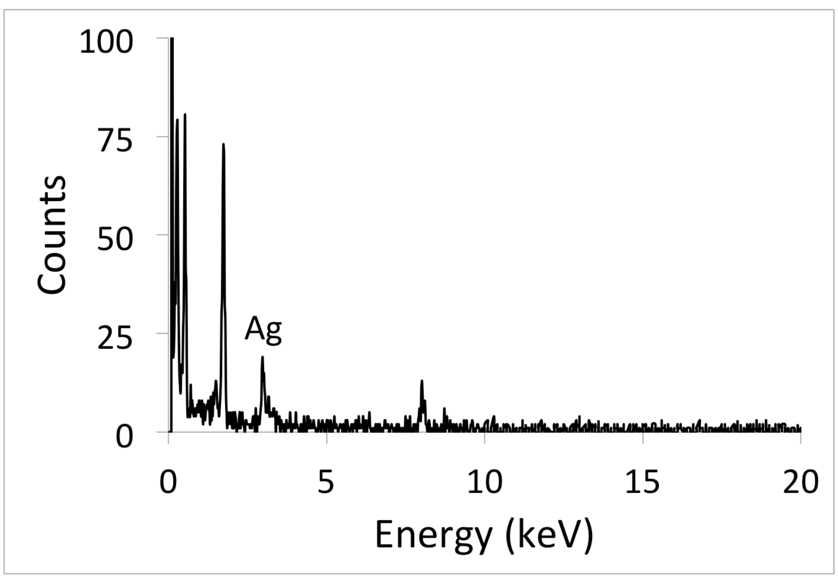

Figure 2.3. *Elemental analysis of ceramic tablet for verification of silver. Energy dispersive spectroscopy (EDS) graph of ceramic tablet made with 90% Redart clay, 20-mesh sawdust and 500 mg of silver*

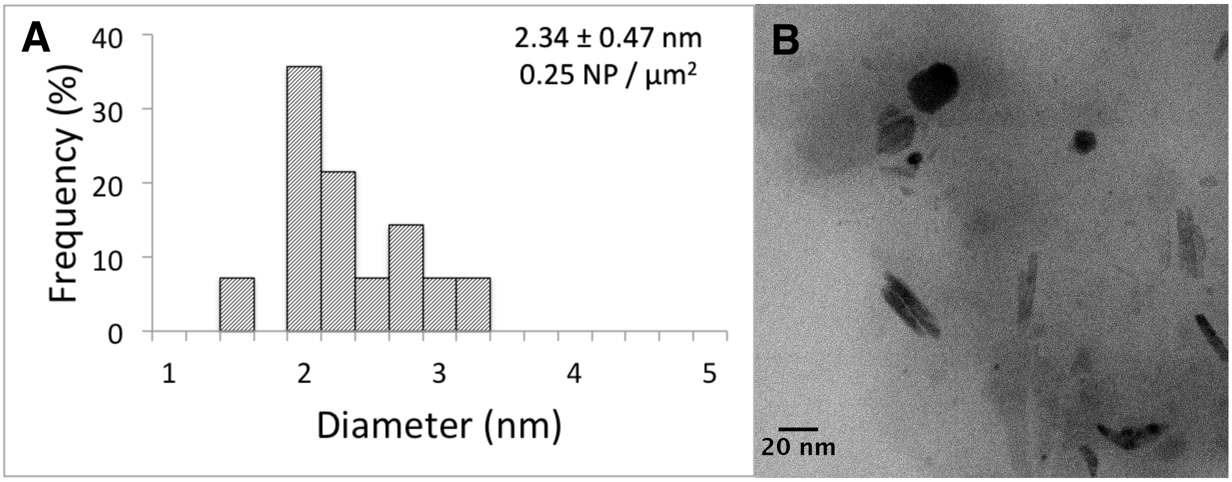

Figure 2.4. *Distribution of nanopatch diameters and number of silver nanopatches in center of ceramic tablet embedded with 50 mg of silver. (A) Histogram of the particle-size distribution of silver nanopatches (B) Transmission electron microscopy image of silver nanopatches in center of ceramic tablet.*

Ceramic tablets embedded with 50 mg, 500 mg and 3 g of silver were further characterized for nanopatch size distribution and number of nanopatches per unit area at the center and exterior edge using TEM (Figures 2.4, 2.5, and 2.6). Ceramic tablets embedded with 50 mg, 500 mg and 3 g of silver had 0.25, 13.61 and 34.05 nanopatches/μm^2, respectively, for samples taken from the center (Figures 2.4, 2.5, and 2.6). As the mass of embedded silver increased from 50 mg to 3 g the average diameters of the nanopatches ranged from 2.34 ± 0.47 nm to 2.90 ± 0.83 nm.

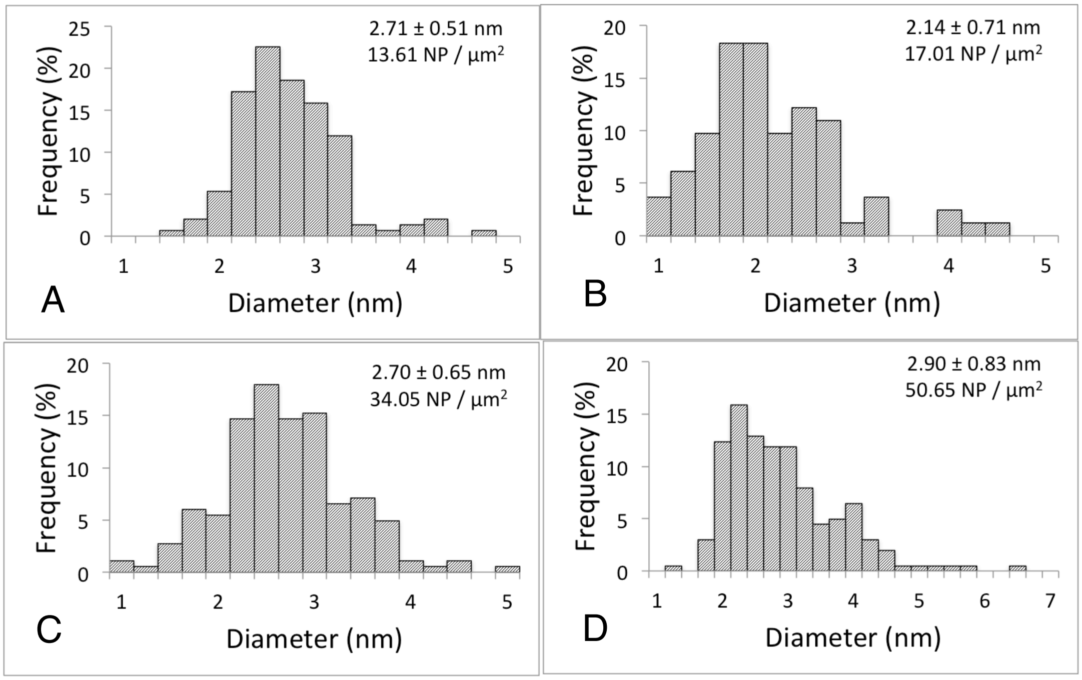

Figure 2.5. *Distribution of nanopatch diameter size and density throughout ceramic tablets with different initial silver masses. (A) Distribution of nanopatch diameters and number of silver nanopatches in center of ceramic tablet embedded with 500 mg of silver, (B) Distribution of nanopatch diameters and number of silver nanopatches at exterior edge of ceramic tablet embedded with 500 mg of silver, (C) Distribution of nanopatch diameters and number of silver nanopatches in center of ceramic tablet embedded with 3 g of silver, (E) Distribution of nanopatch diameters and number of silver nanopatches in edge of ceramic tablet embedded with 3 g of silver.*

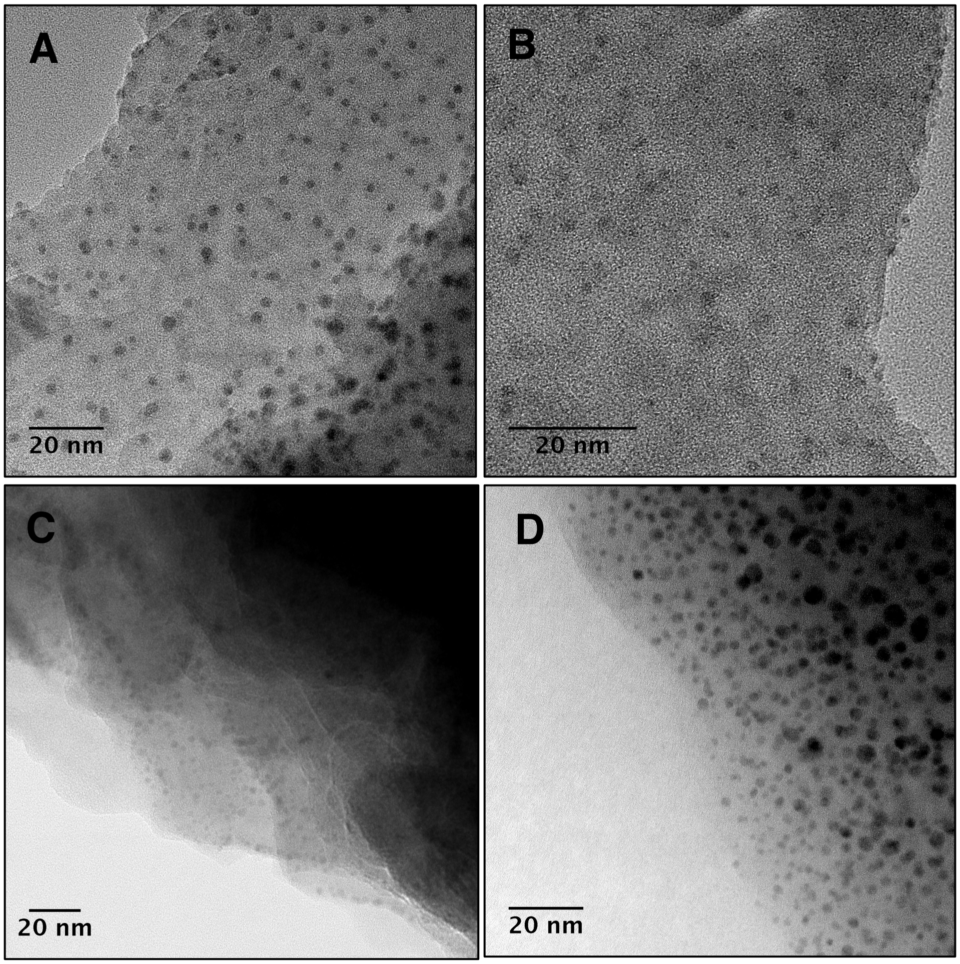

Figure 2.6. *Transmission electron microscopy images of the center and exterior edge of silver embedded ceramic tablets. (A) Center and (B) Exterior images of silver nanopatches in a 0.5 g silver-embedded ceramic tablet. (C) Center and (D) Exterior images of silver nanopatches in a ceramic tablet embedded with 3 g of silver.*

Figures 2.5 and 2.6 compares the number of metallic silver nanopatches per unit area between the exterior edge and center of ceramic tablets. A ceramic tablet embedded with 500 mg of silver had 13.61 nanopatches /μm^2 at the center and 17.01 nanopatches /μm^2 at the edge. A ceramic tablet embedded with 3 g of silver had 34.05 nanopatches /μm^2 at the center compared to 50.65 nanopatches /μm^2 at the edge. Silver extraction was performed using acid digestion methods and on ceramic tablets prepared with Redart clay, 10% Virginia sawdust sieved at 20 mesh and embedded with 50 mg of silver. Silver embedded within the ceramic media was extracted using nitric acid, and only 45% of the initial amount of silver embedded was able to be extracted from the ceramic. No silver was detected in the control samples.

2.3.2 Characterization of silver released from ceramic media. Figure 2.7 disinfection efficiency and ionic silver (Ag^{+1}) release from ceramic tablets. Ceramic tablets caused a 3.8-log reduction of *E. coli* within 6 h (Figure 2.7A) while Ag^{+1} concentrations remained below the drinking water standard (Figure 2.7B). The oxidation state of silver released from the tablet was characterized by comparing total and Ag^{+1} concentrations among 83 samples. Total silver concentrations represent the sum of zero-valent and Ag^{+1} concentrations in solution. Total silver concentrations were plotted against Ag^{+1} concentrations (Figure 2.8). The resulting slope is approximately equal to unity, indicating that approximately all the silver released into solution is in the ionic form.

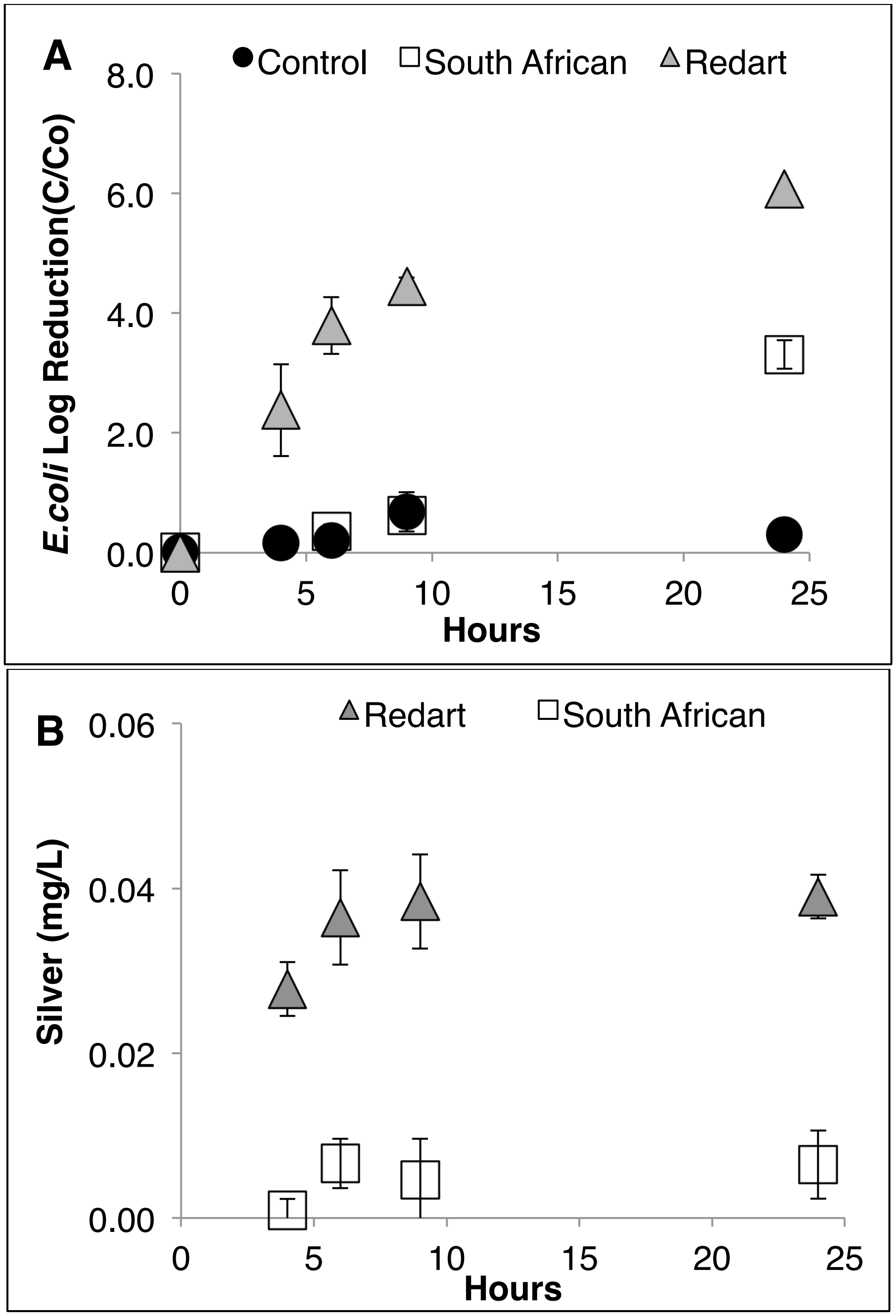

Figure 2.7. (A) *Disinfection efficiency of ceramic tablets with different clay mineralogies. Ceramic tablets were prepared with 16-mesh South African sawdust and 90% clay, and PB solution and E. coli was added at time zero to produce a concentration of 10^6 cfu/100 mL. Error bars represent standard error based on quadruplicate experiments. (**B)** Total silver concentration as a function of time in 200 mL of PB solution with the same ceramic tablets made with different types of clay. Error bars represent standard error of quadruplicate experiments.*

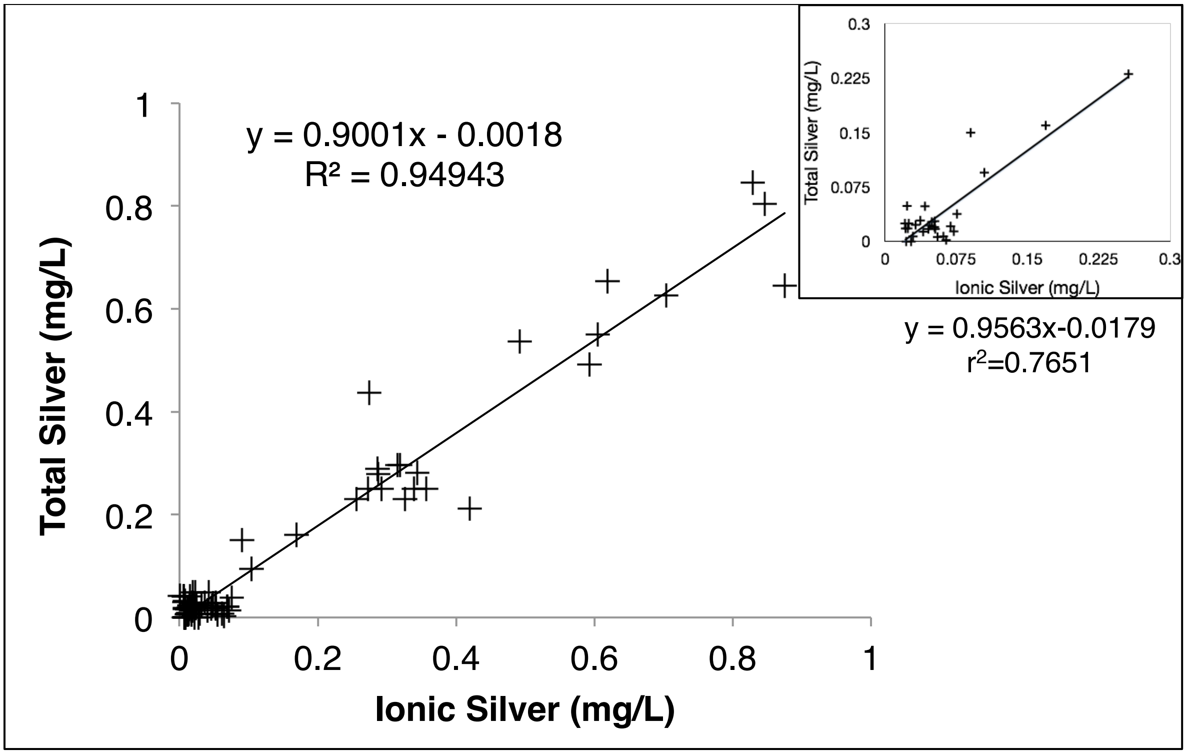

Figure 2.8. *Total silver concentration as a function of ionic silver concentration. Data are for 83 ceramic tablets of varying amounts of silver in 200mL of PB solution after 24h. Top right corner shows the total silver concentration as a function of ionic silver concentration for 32 of the 83 samples that fall within the lower range of silver levels (< 0.3 mg/L). Trend is similar at low and high silver concentrations.*

2.3.3 Evaluating fabrication materials. The role of design variables on Ag^{+1} release was studied by fabricating different ceramic tablets (Tables 2.1 and 2.2). Figure 2.7A shows disinfection of *E. coli* using ceramic tablets made with different clay samples. Ceramic tablets made with Redart clay performed the best with average log reductions of 2.4, 3.8, 4.4 and 6.1 sampled at 4, 6, 8 and 24 h. Ceramic tablets made with South African clay resulted in a 3.3 log reduction of *E. coli* after 24 h. Total residual silver concentrations were higher for ceramic tablets made with Redart clay (0.028, 0.036, 0.038 and 0.039 mg/L) compared to those made with South African clay (0.001, 0.007, 0.005 and 0.006 mg/L) (Figure 2.7B). No differences in microbial disinfection efficiency

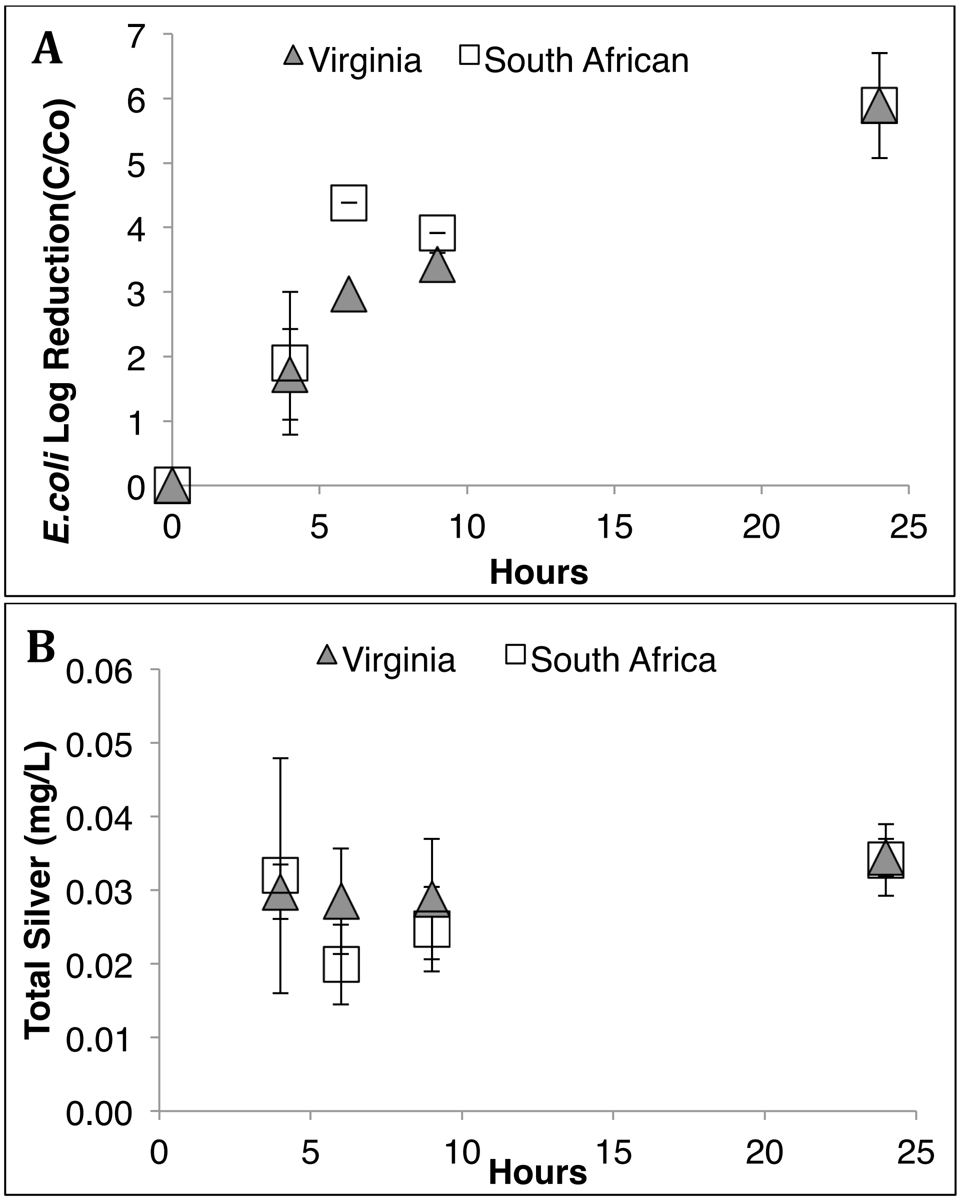

Figure 2.9. (A) *Disinfection efficiency of ceramic tablets with different sources of sawdust. Ceramic tablets were prepared with 16-mesh sawdust and 90% Redart clay, and PB solution and E. coli was added at time zero to produce a concentration of 10^6 cfu/100 mL. Error bars represent standard error based on quadruplicate experiments. (**B**) Total silver concentration as a function of time in 200 mL of PB solution with the same ceramic tablets made with different sources of sawdust. Error bars represent standard error of quadruplicate experiments.*

and silver release were observed among ceramic tablets prepared with two different sources of sawdust (Figure 2.9). Porosity differed among ceramic tablets made with different clay mineralogies (Figure 2.10). Ceramic tablets made with Redart clay had smaller pores overall where 40% of pores were between 0.1 to 1 μm in diameter. Ceramic tablets made with South African clay had larger pores where 53% of the available pores ranged from 10 to 50 μm in diameter. Porosity among ceramic tablets made with different particle sizes of sawdust was also analyzed in Figure 2.11. Ceramic tablets prepared using sawdust particles with diameters less than 0.841 mm (20-mesh) had 50% of pores ranging between 10-25 μm in diameter. Ceramic tablets prepared with slightly larger sawdust particles, diameters at least 1.190 mm, had less larger pores (10 -25 μm) but more smaller pores with 43% of pores ranging 0.1-1 μm in diameter.

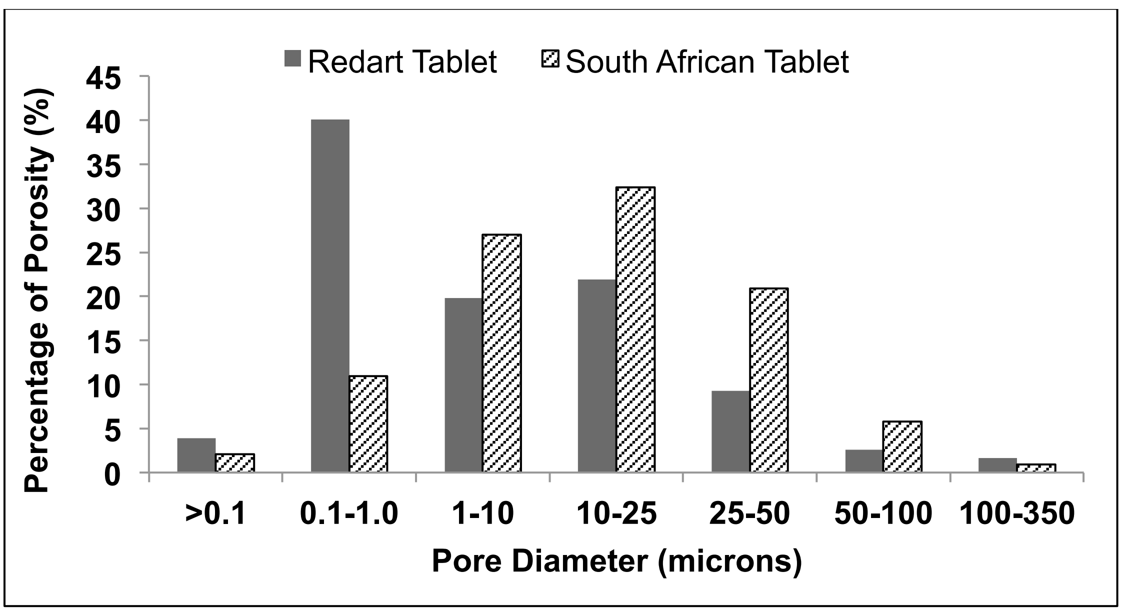

Figure 2.10. *Pore-size distribution of two ceramic tablets prepared with different clays and embedded with 50 mg of silver with 10%, 16-mesh South African sawdust. Ceramic tablets made with Redart clay were compared to those made with South African clay. Percent porosity was determined comparing incremental pore volume to total available pore volume using a mercury porosimeter.*

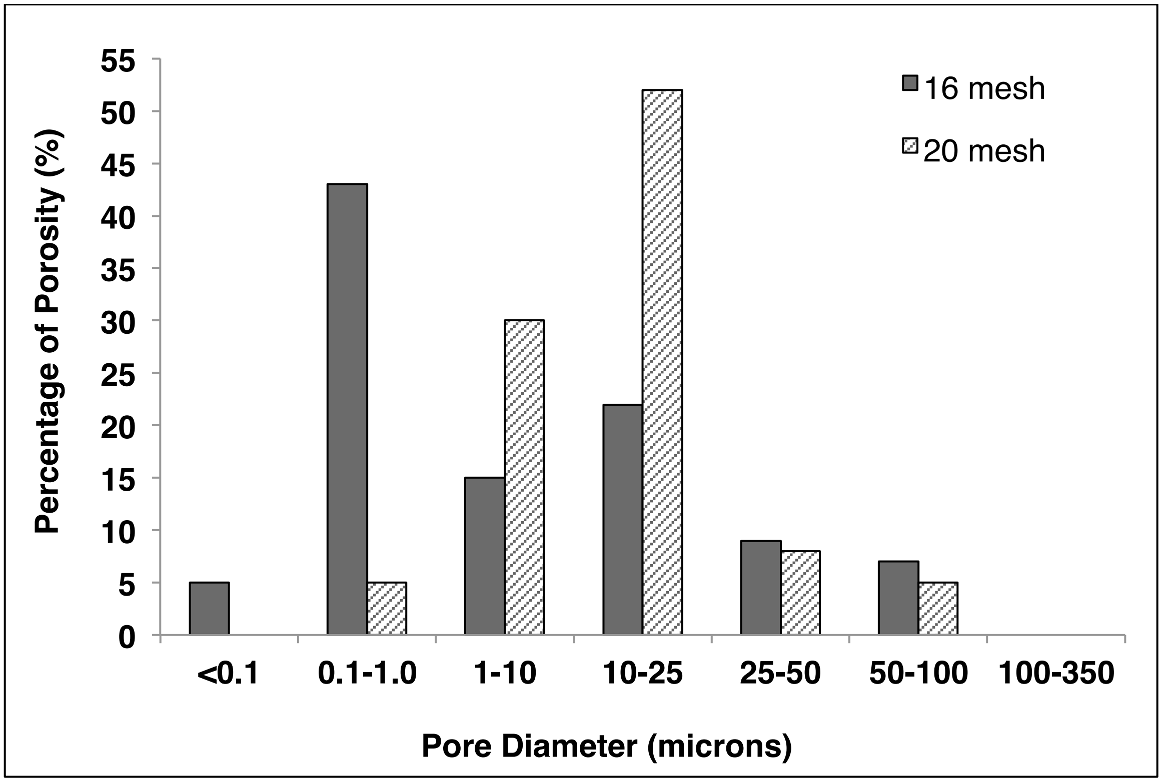

Figure 2.11. *Pore-size distribution of two ceramic tablets prepared with sawdust sieved at two different mesh sizes, 16 and 20. Ceramic tablets made with Redart clay, 10% Virginia sawdust and 50 mg of silver. Percent porosity was determined comparing incremental pore volume to total available pore volume using a mercury porosimeter.*

Figure 2.12 shows the effect of sawdust particle size on silver release for ceramic tablets. Ceramic tablets made with sawdust sieved at 16-mesh and 20-mesh produced the highest residual silver concentration (0.054 mg/L and 0.025 mg/L) after 24 h, compared to ceramic tablets made with 30-mesh sawdust that did not release detectable levels of silver.

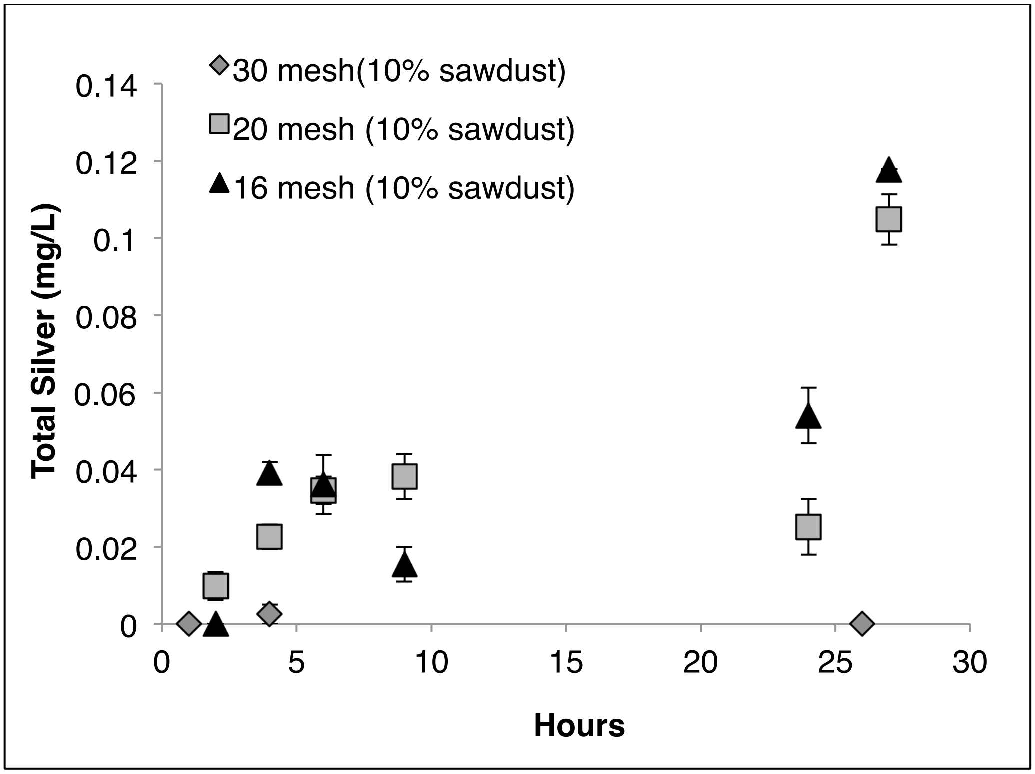

Figure 2.12. *Total silver concentration in water (with standard error) as a function of time for ceramic tablets fabricated using 90% Redart clay, 50 mg of silver, and sawdust passed through different sieve sizes. Each data point represents the average of duplicate experiments and error bars represent standard error.*

The effect of percent composition of sawdust on silver release is shown in Figure 2.13B. Silver release was completely inhibited among ceramic tablets comprised of 1% sawdust. Silver release increased incrementally for ceramic tablets made with 10%, 15%, and 20% sawdust, reaching 0.21, 0.24 and 0.30 mg/L, respectively, after 48 h. Differences in silver release from ceramic tablets with sawdust compositions ranging from 10-20% were not enough to provide a difference in microbial disinfection (Figure 2.13A).

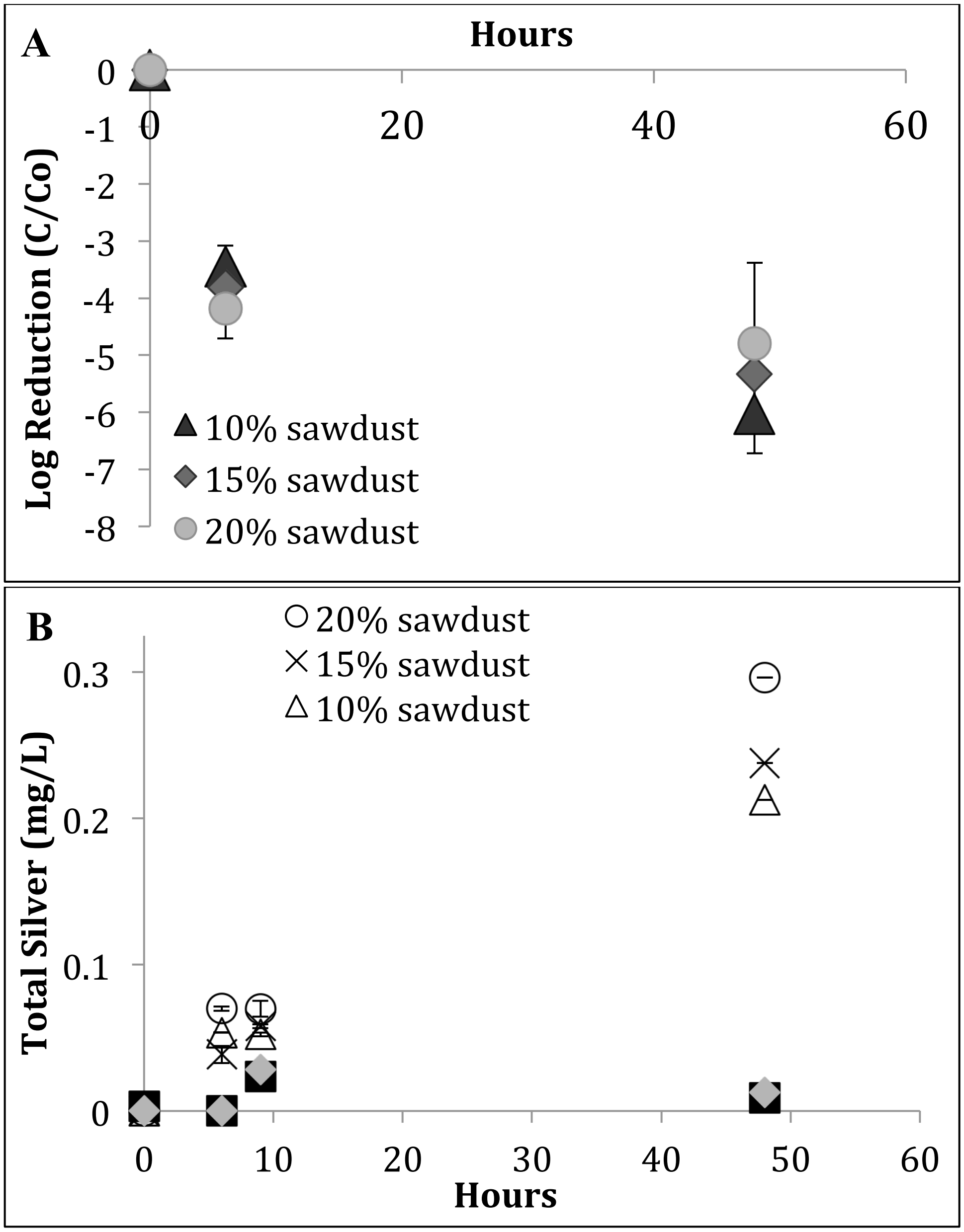

Figure 2.13. *Total silver release and microbial disinfection of ceramic tablets made with different clay to sawdust ratios. (A) Log reduction in E. coli concentration as a function of time for ceramic tablets fabricated with different percentages of sawdust and with Redart clay, 20-mesh sawdust, and 50 mg of silver. The aqueous phase was 200mL of phosphate buffer solution with 10^8 cfu/100mL E. coli. Standard error was used to calculate error bars and each data point represents the average of duplicate experiments. (B) Plot of total silver concentration in water as a function of time for ceramic tablets fabricated with different percentages of sawdust. Each tablet was prepared with Redart clay 20-mesh sawdust, and 50 mg of silver.*

Figure 2.14 show silver release and disinfection efficiency of ceramic tablets embedded with different masses of silver. When 500 mg of silver is embedded in the ceramic tablets, silver concentrations reached 0.60 mg/L within 4 h (Figure 2.14B) and resulted in a 7.6 log reduction of *E. coli* (Figure 2.14A). These aqueous silver concentrations are higher than the EPA recommended silver standard for drinking water, but demonstrate that increasing the silver mass in the tablet causes an increase in aqueous silver concentrations in the treated water (Figure 2.14B).

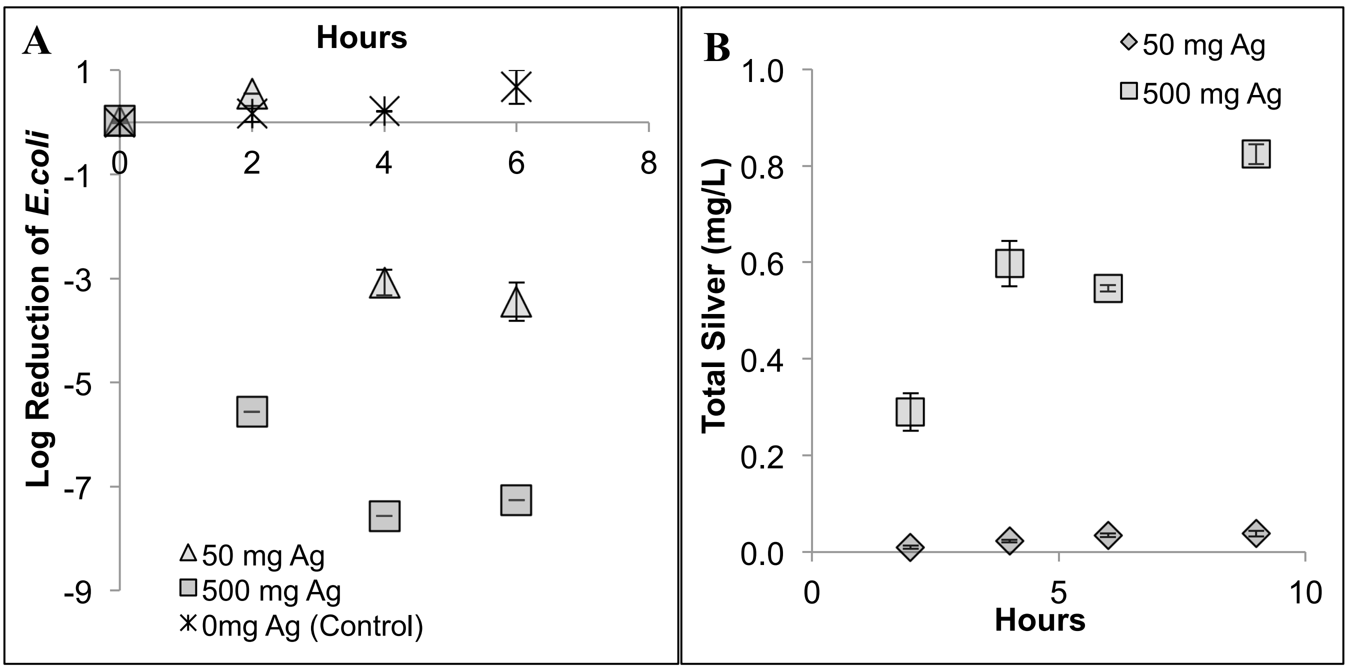

Figure 2.14. *Total silver concentration and microbial disinfection as a function of time for ceramic tablets fabricated with 50 and 500 mg silver. (A) Total silver concentration in water for ceramic tablets fabricated with 50 and 500 mg silver, prepared with Redart clay (90%) and 20-mesh sawdust. Standard error was used to calculate error bars and each data point represents the average of duplicate run. (B) Log reduction of E. coli for ceramic tablets with 0, 50, and 500 mg silver. Ceramic tablets were prepared with Redart clay (90%) and 20-mesh sawdust. A 200-mL phosphate buffer solution was used with 10^8 cfu/100 mL E. coli. Standard error was used to calculate error bars and each data point represents the average of duplicate experiments.*

2.3.4 Investigating mechanistic processes dictating silver release. Effects of diffusion path length on silver release are shown in Figure 2.15. Silver release increased with shortened diffusion length. Using granular pieces of silver-embedded ceramic media shorter diffusion paths for silver release were created. Silver release among granular pieces was compared to that of the solid ceramic tablet. To ensure the same mass of silver and ceramic were present in each condition, equal masses of silver were used in preparing the ceramic media and equal masses of ceramic media were used in each condition. Silver levels were 3.76 times higher in 10 L of tap water exposed to the granular ceramic compared to the solid tablet.

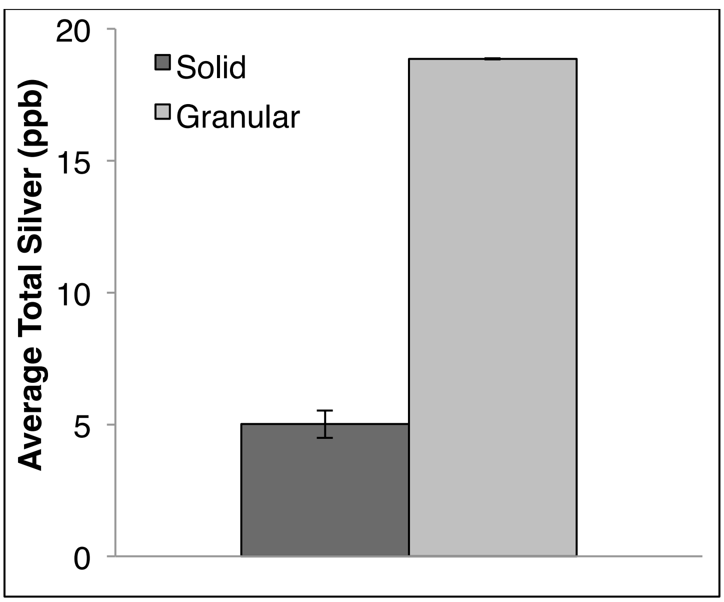

Figure 2.15. *Total silver concentrations of solid and granular ceramic media embedded with 1g of silver. Ceramic media was placed in 10 L of tap water as a solid tablet or as non-uniformal granular pieces. Granular pieces were made by breaking the solid tablet into pieces. Samples were taken at 24 h and run in parallel. Error bars represent standard error.*

The effects of particle size distribution of granular ceramic media on silver release are shown in Figure 2.16. Granular pieces ranging in 0.841 to 0.42 μm in diameter had the highest silver release levels, with residual silver concentrations reaching 34.6 μm/L.

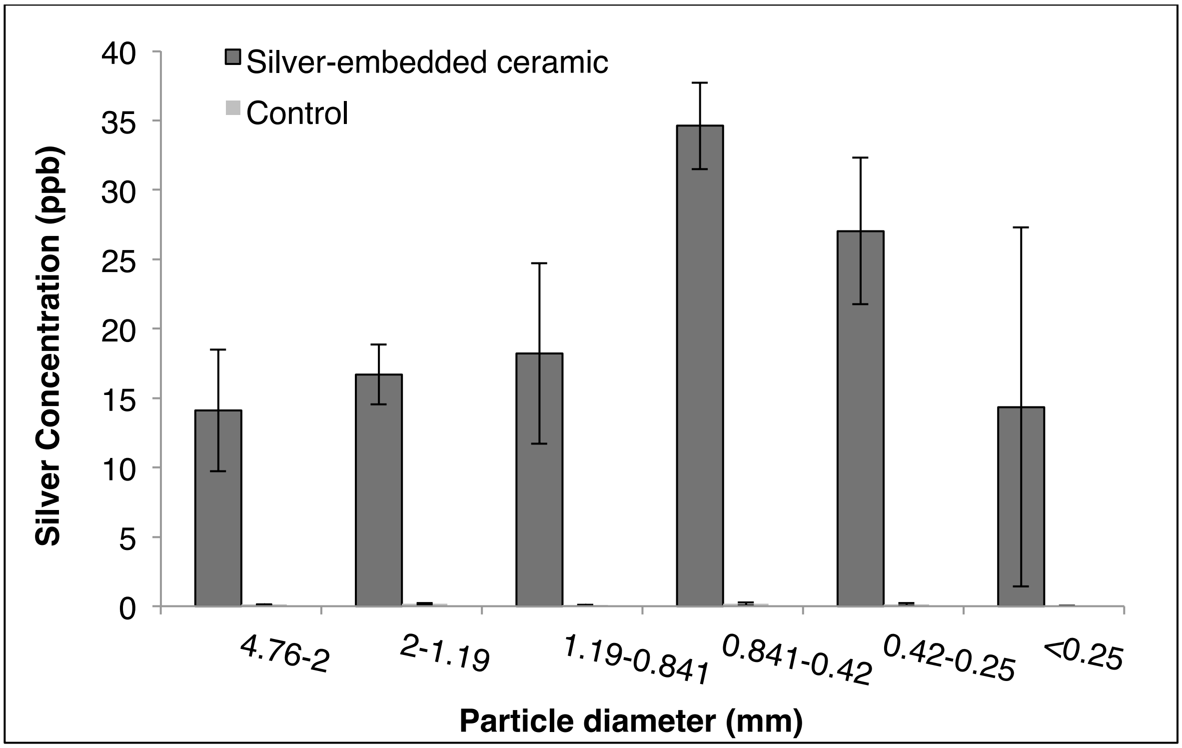

Figure 2.16. *Effects of granular particle size distribution on silver release. Ceramic media was prepared with 1 g of silver. Silver-embedded granular media (10g) was placed in 300 mL of tap water. Samples were run in duplicate and taken at 24 h. Data points represent average with standard error representing error bars.*

The granular material was tested in two different forms (dispersed and contained) in order to further evaluate diffusion length. In one form factor, granular pieces were freely dispersed at the bottom of the container, providing the shortest diffusion length for silver ions. In the second form factor, granular pieces were contained in a bag, lengthening the diffusion length of silver ions synthetically. Figure 2.17 compares silver release among granular pieces freely dispersed to those contained in a permeable bag. Figure 2.18 compares silver release among dispersed granular pieces to those contained in a non-permeable bag. In Figure 2.18, only the top of the non-permeable bag is open and in contact with the water. Silver levels were measured after 24 hours and at 0 hours, which represented silver levels before adding the ceramic pieces to the water. Silver release declined to 23.6 and 1.37 μm/L from 38.2 and 20.1 μm/L among granular pieces contained in a permeable bag and non-permeable bag, respectively.

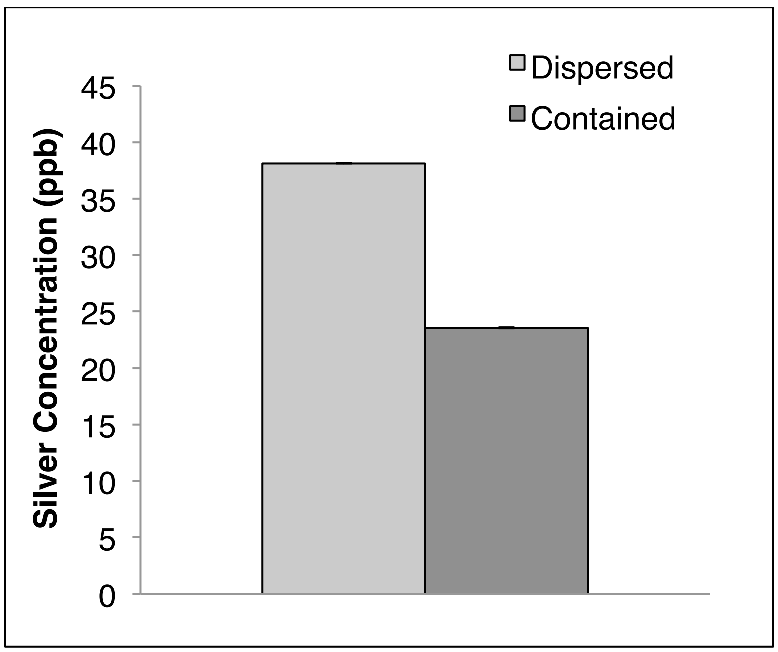

Figure 2.17. *Effects of dispersed and contained form factors of silver-embedded granular media on silver release. Ceramic media was embedded with 1 g of silver and crushed into pellets 0.841 to 0.42-mm in diameter. In the dispersed condition, 10 g of pellets were spread out at the bottom of 500 mL-container with 300 mL of tap water. In the contained condition, 10g of pellets were placed in empty tea bags in 300mL of tap water. Samples were run in duplicate and sampled at 24 h. Data points represent average and error bars represent standard error.*

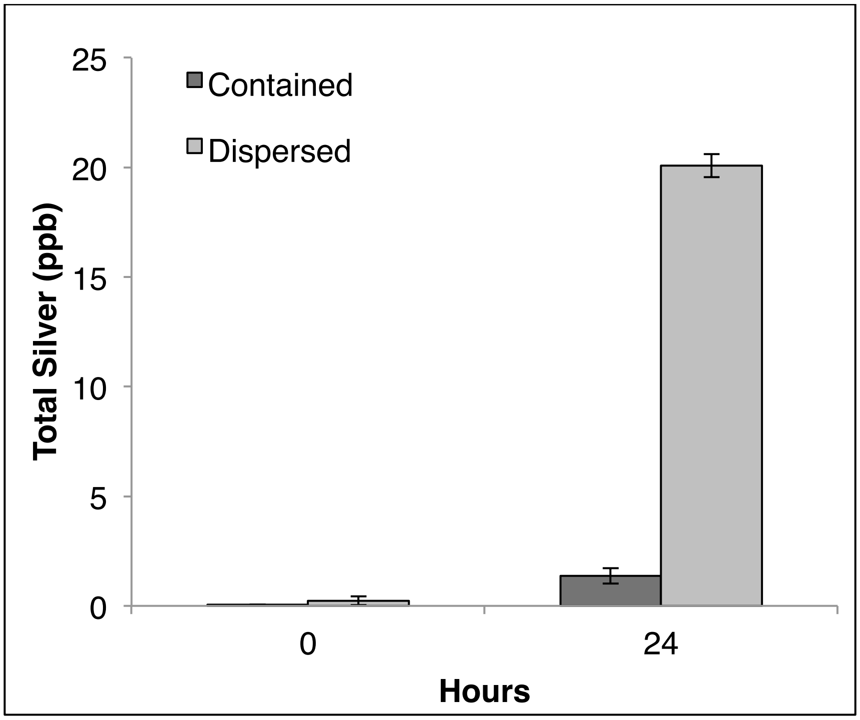

Figure 2.18. *Total silver concentrations for silver-embedded granular material as dispersed and contained form factors. Granular ceramic pellets were embedded with 1g of silver and passed through 0.841-mm sieve and retained at 0.42-mm sieve. Dispersed condition consisted of 150 g of pellets dispersed in 10 L of tap water and contained condition consisted of a 500-mL plastic sample bag placed in 10 L of tap water with top of the bag open. Samples were run in duplicate and sampled at 0 h and 24 h. Average silver concentrations represented by bar graphs with error bars representing standard error.*

Isotherm experiments were conducted to evaluate the sorption coefficient among ceramic porous media with variation in fabrication materials. The equilibrium time-point for isotherm experiments was determined to be 20 h (Figure 2.19).

Sorption coefficients and cation ion exchange capacity among ceramic porous media with variation in clay mineralogy, source of sawdust, percent composition of sawdust and sawdust PSD are summarized in Table 2.3 and shown in Figures 2.20-2.23. Sorption did not differ among ceramic porous media with different mineralogy.

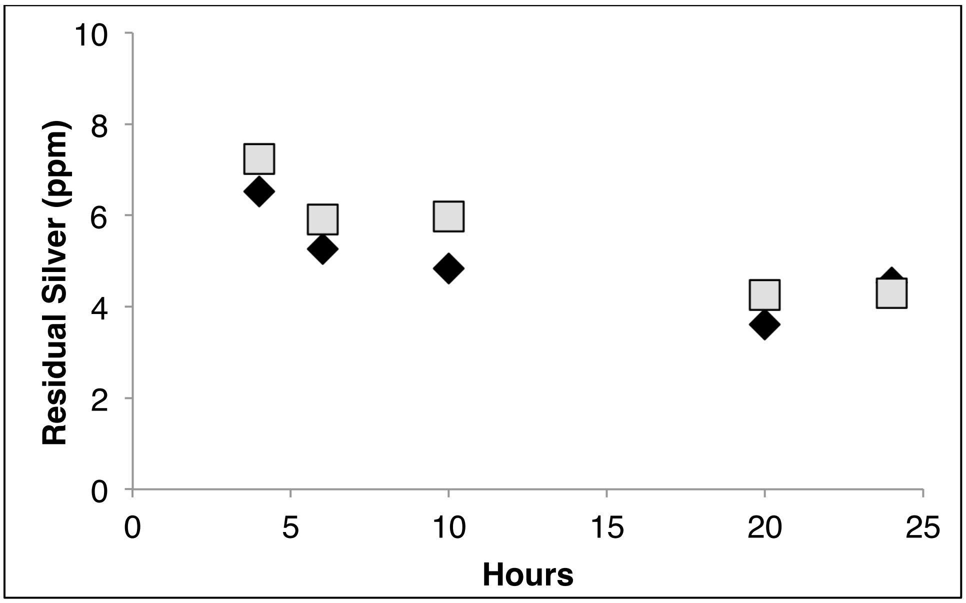

Figure 2.19. *Residual silver concentrations over time among samples with S. African ceramic (☐) and redart ceramic (◆). S. African ceramic was prepared with S. African clay, 10% S. African sawdust and no silver. Redart ceramic was prepared with redart clay with 10% Virginia sawdust.*

Table 2.3. Sorption coefficient and cation ion exchange capacity of ceramic tablets

Ceramic tablet composition				Sorption coefficient	Cation exchange capacity
Clay source/type	Sawdust source	Percent mass of sawdust	Sawdust mesh size	K_d (L/kg)	**meq/100g**
S. African	S. African	10	16	97.0	4.8
S. African	Virginia	10	16	66.2	4.8
Redart	Virginia	10	16	64.3	4.9
Redart	Virginia	10	20	54.4	5.2
Redart	Virginia	5	20	71.4	6.5
Redart	-	-	-	-	14.2
S.African	-	-	-	-	29.8

The biggest difference in sorption coefficients was observed among ceramic porous media made with different sources of sawdust, and followed by ceramic porous media prepared with different ratios of clay to sawdust. Ceramic pieces used from sorption experiments did vary in size, however a total mass of 1g of ceramic media was used in each sample. Variations in size and shapes of ceramic pieces may impact sorption results. Cation ion exchange capacity was similar among all ceramic samples. Samples for cation ion exchange capacity analysis were grinded into fine pieces. Redart clay and S. African clay were analyzed as control, where cation ion exchange capacity was higher, 14.2 and 29.8 meq/100g respectively. As expected, clay samples had higher cation ion exchange capacity compared to porous ceramic media.

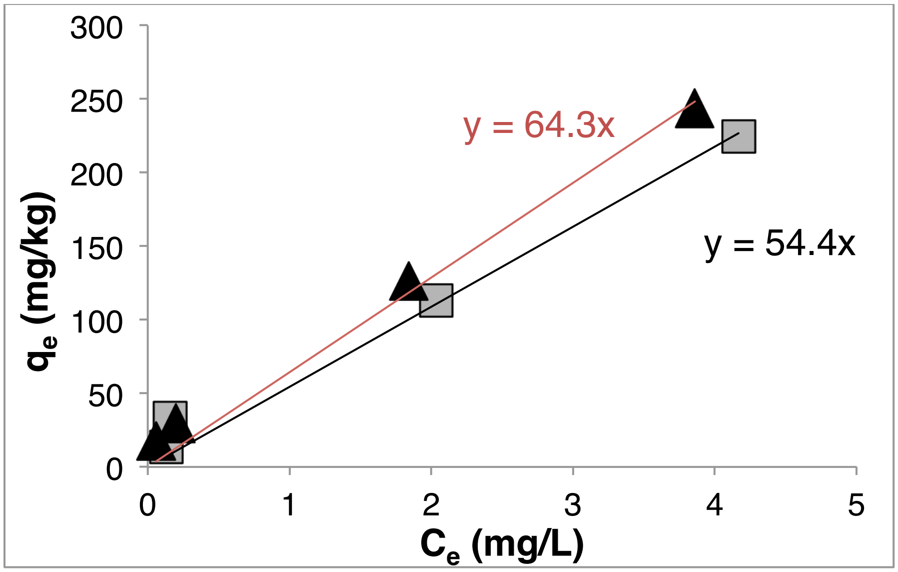

Figure 2.20. *Sorption of silver to ceramic media prepared with different particle sizes distributions of Virginia sawdust. Ceramic media was prepared using Redart clay with 10% Virginia sawdust and either sawdust passed through 16-mesh sieve (▲) or 20-mesh sieve (◻). Samples were continuously shaking at room temperature for 20h.*

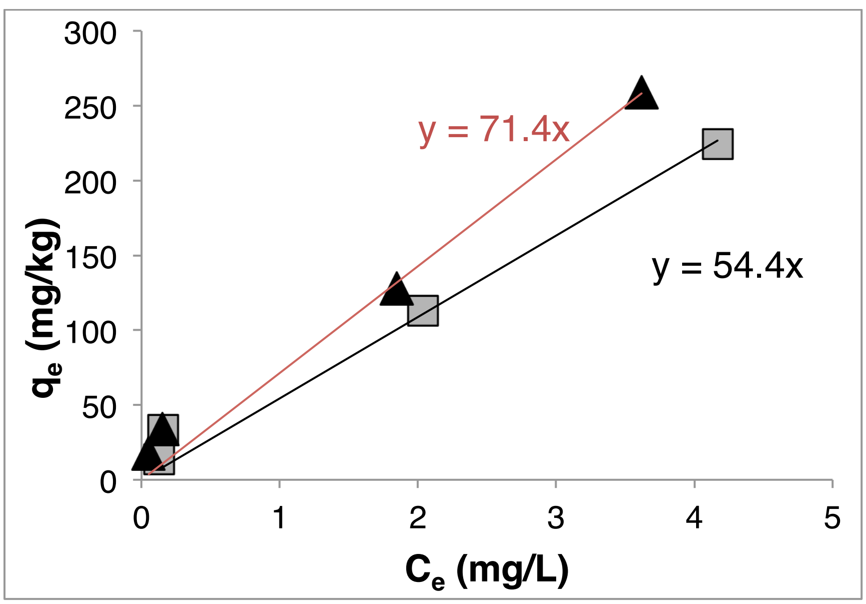

Figure 2.21. *Sorption of silver to ceramic media prepared with different compositions of sawdust. Ceramic media was prepared using Redart clay with Virginia sawdust sieved with a 20-mesh screen and either 5% (▲) or 10% (◻) sawdust based of off mass. Samples were continuously shaking at room temperature for 20h.*

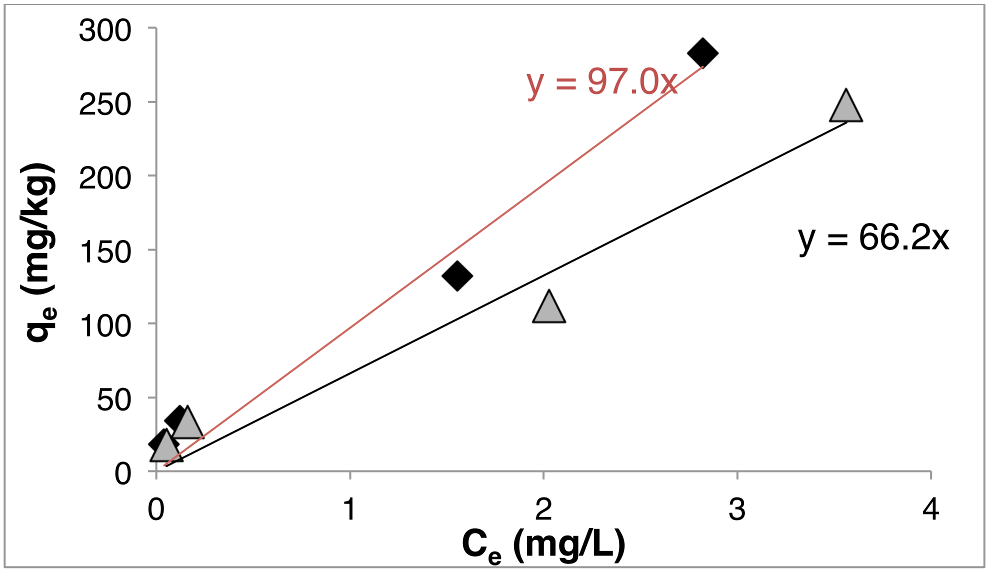

Figure 2.22 *Sorption of silver to ceramic media prepared with different sources of sawdust. Ceramic media was prepared using Redart clay and 10% sawdust sieved with a 16-mesh screen Two types of sawdust were tested that were collected from South Africa(◆) and Virginia (△). Samples were continuously shaking at room temperature for 20h.*

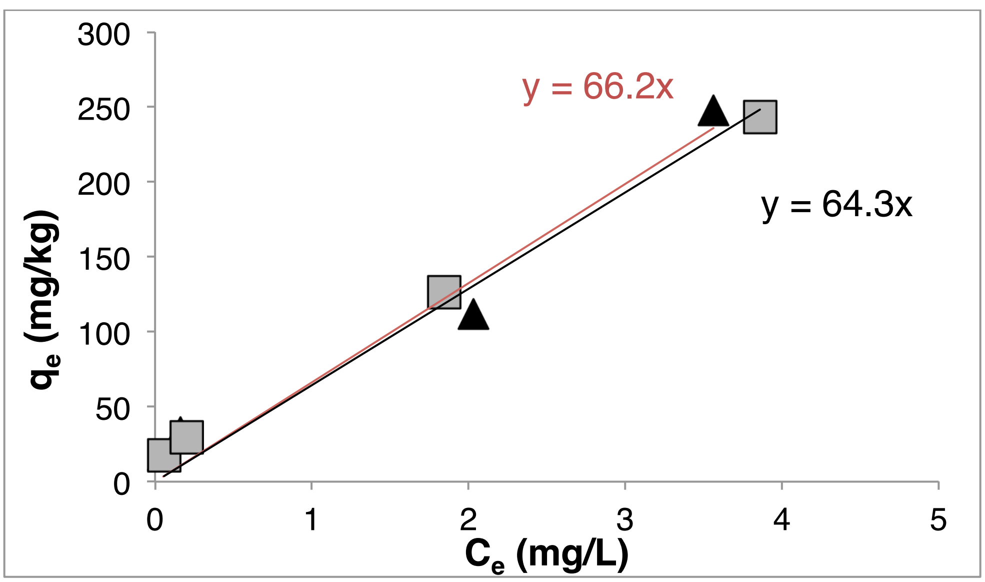

Figure 2.23. *Sorption of silver to ceramic media prepared with different clay mineralogies. Ceramic media was prepared using 10% Virginia sawdust sieved with a 16-mesh screen Two types of clays were tested, South African (▲) and Redart (□). Samples were continuously shaking at room temperature for 20h.*

2.3.5 Optimization of ceramic tablet for POU applications. A series of experiments were conducted to design ceramic tablets for disinfection of larger water volumes (10 L). The embedded silver mass was found to be one of the most important factors regulating silver release, thus three silver mass conditions were tested to treat 10 L of tap water: a ceramic tablet embedded with 1 g of silver, another embedded with 3 g of silver and six ceramic tablets, each embedded with 500 mg of silver. The ceramic tablets embedded with 1 g and 3 g resulted in residual silver concentrations of 0.01 mg/L after 24 hr. For the six 500 mg silver ceramic tablets the silver concentration reached 0.05 mg/L after 24h (Figure 2.24). These data indicate that simply increasing the silver content of the ceramic tablet does not necessarily improve performance.

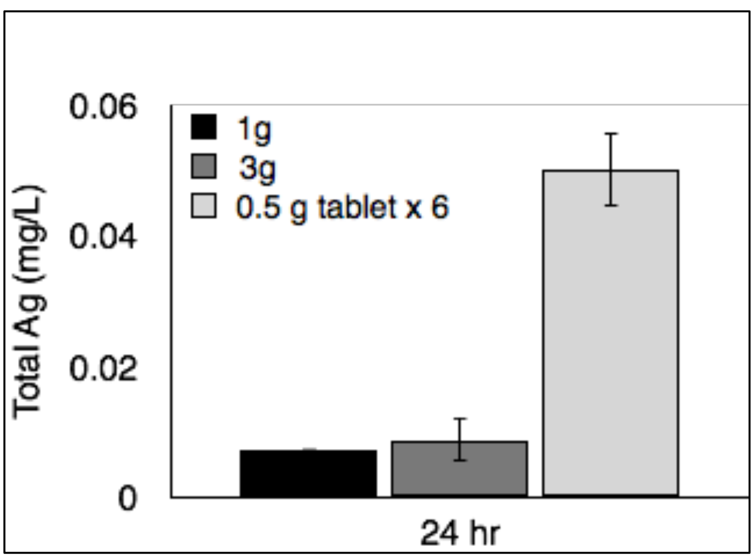

Figure 2.24. *Total silver concentrations in a 10-L water volume after 24-hr exposure to ceramic tablets fabricated using different masses of silver. Three different ceramic tablets were prepared: (i) a single ceramic tablet with 1 g silver; (ii) a single ceramic tablet with 3 g silver; (iii) six ceramic tablets with 500 mg silver per tablet. Ceramic tablets were fabricated with 90% (by weight) Redart clay and 20-mesh sawdust.*

Figure 2.25 shows the effect of the ceramic tablet geometry on silver release. The cylindrical-shaped tablet with a 65-mm diameter and 45-mm height had the highest silver release of the tested geometries: 0.04 mg/L at 24 h (Figure 2.25) with a 4.6-log reduction of *E. coli* in 10 L of PB solution (Figure 2.26). In Figure 2.27, performance in more real-world water chemistries was compared to laboratory conditions and no difference was seen in silver release among tablets placed in PB solution and tap water (with residual chlorine levels of 0.3 mg/L). Table 2.4 shows total levels of other inorganic chemicals, aside from silver, in treated water being undetectable or below the EPA drinking water standard.

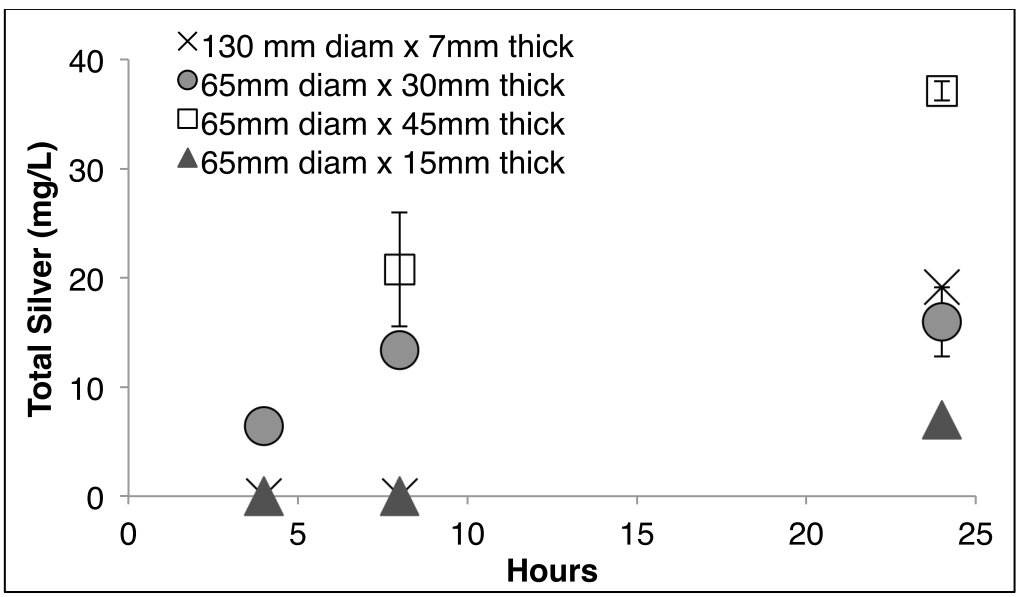

Figure 2.25. *Aqueous silver concentration as a function of time for ceramic tablets with different volumes and surface areas. Ceramic tablets were prepared with 90% Redart clay 90%, 20-mesh sawdust, and 1 g of silver. Each tablet was placed in 10 L of PB solution. Error bars were calculated using standard error, and data points represent average concentrations of duplicate measurements.*

Table 2.4. Total levels of inorganic chemicals in10-L of ceramic tablet-treated tap water compared to EPA drinking water standards.

Inorganic Chemical	Silver Ceramic Tablet Average (ppb)	Silver Ceramic Tablet Std Error	EPA drinking water standard (ppb)
Cd	0	0	5
Cu	1.72	0.189	1300
Cr	1.56	0.125	100
Pb	0.221	0.162	15
Zn	0	0	5000
NO_3	0.816	0.0216	10000

The reusability of this tablet was also investigated over 179 d in 10 L of tap water (Figure 2.28). There was minimal difference in silver release over time as demonstrated by the linear regression analysis, indicating that the ceramic tablets can be reused for at least 179 days without major changes in performance.

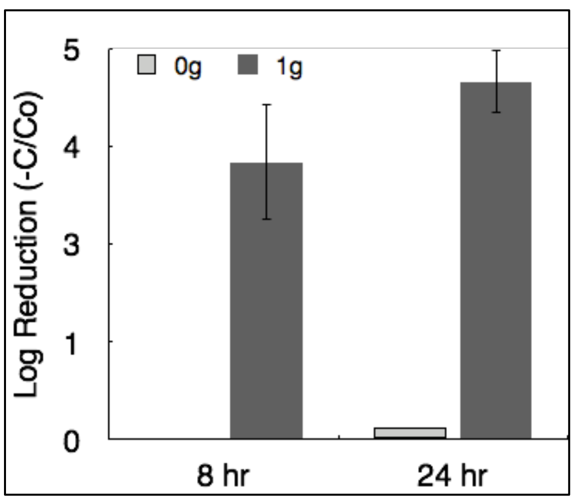

Figure 2.26. *Log reduction in E. coli concentration after 8 and 24 hr in a 10-L of PB solution for a single ceramic tablet with dimensions 65 mm X 45 mm and either 0 g or 1 g of silver. The ceramic tablet is fabricated from 90% (weight basis) Redart clay and 20-mesh sawdust. Standard error was used to calculate error bars and each data point represents the average of duplicate experiments. 10 L of a phosphate buffer solution was inoculated with* 10^8 *cfu/100mL E. coli.*

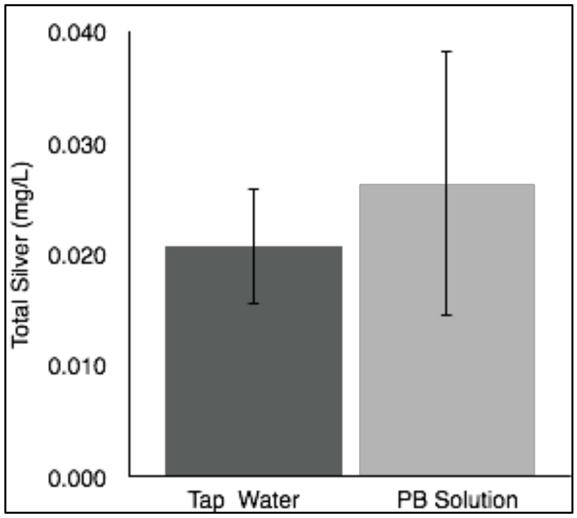

Figure 2.27. *Silver release of ceramic tablets in different water chemistries, chlorinated versus non-chlorinated. The ceramic tablet is fabricated from 90% Redart clay and 20-mesh sawdust and 1 g of silver. They were placed in 10 L of tap water, containing free chlorine, and 10 L of deionized water, the control with no chlorine. Standard error was used to calculate error bars and each data point represents the average of duplicate experiments.*

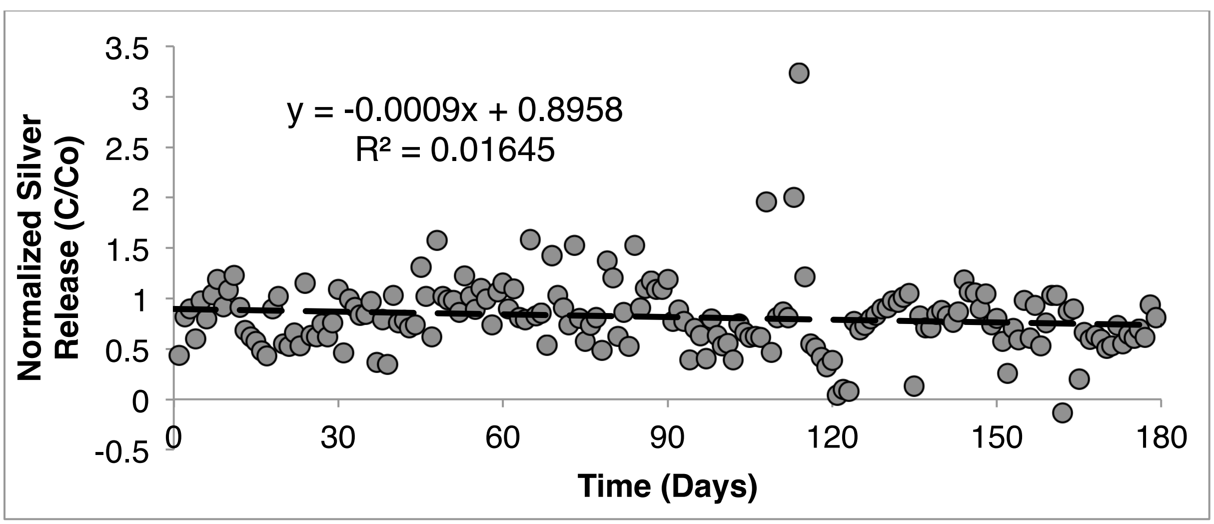

Figure 2.28. *Silver concentrations in water repeatedly exposed to the same ceramic tablets for 179 consecutive days. Concentrations are normalized to the silver concentration averaged over the first three days. The water was replaced every 24h, but the silver level returns to about the same level every day.*

2.4 Discussion

In this study, we have demonstrated a new method for the synthesis of metallic silver "nanopatches" in a ceramic porous media. The silver-impregnated ceramic media is formed using only clay, sawdust, water, and silver nitrate. No external capping or reducing agent is required for formation of silver nanopatches. Using a Redart clay and 20-mesh sawdust in a 9:1 weight ratio, silver nanopatches are produced with average diameters of 1-6 nm (Figures 2.4 and 2.5). Silver nanopatch formation likely occurs during the firing process; water evaporates first from the largest pores, concentrating the Ag^{+1} in smaller pores. As the remaining water evaporates and the temperature continues to rise, the Ag^{+1} is reduced to metallic nanopatches throughout the porous ceramic tablet, most likely existing in the smallest pore channels. Although we cannot be certain the silver nanopatches are in the zero-valent form, several observations support the reduction of Ag^{+1} to zero-valent silver.

First, we visually observe the presence of silver nanopatches through TEM imaging (Figs 2.2 and 2.12) and EDS (Fig 2.3). Assuming each patch has a hemispherical geometry, the silver is in the lattice solid crystalline form with four silver atoms per unit cell and the silver lattice spacing is 0.4087 nm, then a silver patch with a diameter of 3 nm would have 414.17 silver atoms per patch. Given this, it is unlikely that the surface charge density of the ceramic could accommodate that large number of negatively charged sites so as to result in Ag^{+1} sorption by ion exchange, as charges are more widely distributed through typical aluminosilicate clays through isomorphous substitutions in the clay lattice.

Second, heat is commonly used to reduce Ag^{+1} to form zero-valent silver nanoparticles. Piccione and Urbanic [30] developed a process to form metallic silver in the pores of powdered activated carbon following the application of heat and silver nitrate. Dankovich and Grey[12] and Dankovich and Smith[31] have formed silver and copper nanoparticles, respectively, on cellulose-fiber paper using silver and copper ions as a precursor with 3 minutes of microwave heating and glucose as the reducing agent to produce relatively homogeneous particles with diameters less than 10 nm. Other studies have demonstrated the importance of heat to the silver reduction process[32]. However, no study to date has shown the reduction of Ag^{+1} to metallic silver under such simple conditions as presented here.

Third, the slow and repeatable release of silver from the tablet shown in Figure 2.28 over a 179-d period is unlikely to result from silver in an ionic form, as repeated washing would likely deplete the silver into solution within a few days or weeks and silver release rates would be expected to decrease with time. Silver nitrate applied to ceramic filter post-firing is released relatively quickly, as reported by Rayner et al [21,33]. Collectively, these observations support the reduction of Ag^{+1} to metallic silver in ceramic porous media. We should also note that nitrate and other inorganic chemicals were not detected above background levels in the treated water and is likely the nitrate is converted to nitrogen gas and water vapor during the firing process (Table 2.4).

Figure 2.7 demonstrates that this new method of porous-media nanopatch formation can be applied to produce a silver-impregnated ceramic tablet for effective POU water disinfection. Using a 200-mL water volume, a 3 to 5-log reduction in *E. coli* is obtained with exposure times ranging from 5-10 h (Figure 2.7A). Corresponding aqueous silver concentrations remain well below the drinking water standard of 0.1 mg/L (Figure 2.7B). These results suggest that a silver-embedded ceramic tablet could be placed in a water storage container at night and the following morning, after 8 hours of contact time, the microbial water quality will be significantly improved which could in turn improve the health of the household members. Following subsequent design modifications, a silver-ceramic tablet that functions well in 10 L of water has been developed (Figures 2.25 and 2.26). Although not necessarily fully optimized, this prototype functions well with regard to *E. coli* disinfection and aqueous ionic silver levels in a water volume typical of household storage. If needed, the ceramic tablet can be optimized for disinfection of larger volumes by simply varying fabrication components. Also, Figure 2.27 demonstrates that the presence of free chlorine does not impact silver release, thus ensuring the safety and longevity of the product under different water chemistries.

Silver that is released into solution from the ceramic tablet is approximately all in the ionic form (Figure 2.8). This observation is in contrast to the release mechanism of silver from ceramic water filters, where the silver painted on to the ceramic is released in the form of zero-valent silver and dissociates to ionic silver based off of the capping agent and composition of the nanoparticle [19,20,23] . Xiu et al. have demonstrated that the benefits of silver-nanoparticle-specific effects are negligible in the disinfection of waterborne pathogens[13] . The antimicrobial effects of silver nanoparticles are primarily derived from the amount of silver that can be oxidized to Ag^{+1} and released into solution in the presence of dissolved oxygen, along with some potentially beneficial effects of reactive oxygen species (ROS) [34] . It is likely some ROS would be produced by the oxidation of silver and this would contribute to disinfection, however ROS levels and their contribution to disinfection have not been quantified at this time.

Previous studies have also demonstrated that Ag^{+1} disinfects bacterial cells by various mechanisms, such as damaging cell wall vacuoles, interfering with thiol groups, disrupting the cytoplasm and damaging nucleic acids[35-38] . Although it is unclear whether the Ag^{+1} is released back into solution or not, calculations made based off of chemisorption studies conducted by Hwang et al [37,38] demonstrate that 3.68 μg of the 10.8 μg Ag^{+1} released into the system by the ceramic tablet would be chemisorbed to the bacterial cells, leaving most of the Ag^{+1} for continual disinfection. Of course these rates of chemisorption are contact time and bacterial concentration dependent. However, it is believed the silver-embedded ceramic tablets described in this work are more efficient with regard to Ag^{+1} release into bulk solution, and thus also in disinfection compared to conventional methods of silver application to ceramic media.

We believe the mechanistic processes regulating Ag^{+1} release into the bulk solution are two-fold. The first step is the oxidation of metallic silver to Ag^{+1}. The second step is the diffusion of Ag^{+1} through the porous ceramic media. Although we have not quantitatively determined the relative roles of silver oxidation, the role of Ag^{+1} diffusion through the media and Ag^{+1} sorption to ceramic pore walls has been investigated and results suggest that Ag^{+1} release is regulated by the ceramic tablet's clay mineralogy, sawdust PSD, sawdust source, initial silver mass, and tablet volume. These fabrication components are most likely impacting the available surface area of silver nanopatches and the pore structure of the ceramic through which Ag^{+1} diffusion and sorption occurs. This is supported by the increase in silver levels observed among ceramic media with shortened diffusion lengths, where there is also less sorption, and the differences seen in sorption by variations in the fabrication materials (Table 2.3 and Fig 2.15).

The significant differences in Ag^{+1} release for ceramic tablets fabricated with Redart and South African clays (Figure 2.7B) suggest that clay mineralogy and PSD cause different pore-networks and pore-surface chemistries related to diffusion through the media. The South African clay consists of larger particles, creating larger and perhaps more isolated pores, resulting in less available porous space. Redart clay consists of smaller particles and more interconnected pores providing more available pore space. Also, they consist of different minerals; therefore, diffusion path and rates are expected to vary between these clays. Sorption did not vary that much between the two different clays (Fig 2.23). However, it did increase among ceramic tablets prepared with S. African sawdust compared to Virginia sawdust (Fig 2.22) suggesting the combination of different clay and sawdust causes difference in silver release. Sawdust PSD most likely impacts silver release due to its role in the formation of the porous network (Figure 2.11), therefore impacting the diffusion paths for Ag^{+1} and ultimately the release into solution (Figure 2.12).

Figures 2.2, 2.5 and 2.6 show that increasing the amount of silver in the ceramic will increase the number of silver nanopatches, while decreasing the distance between nanopatches and perhaps increasing the silver-water interfacial area. The increased interfacial area likely increases the silver oxidation rate and release rate into the bulk solution. However, at a certain point the increased number of nanopatches causes only a small increase in silver concentrations for a given ceramic volume. When tablet volume is increased, the silver release increases as well (Figure 2.25). This most likely pertains to the oxidative mass transfer of silver from the solid phase to the dissolved phase. Increasing the silver nanopatch density provides higher silver-ion concentrations in the pore space, especially if diffusion of Ag^{+1} is slow relative to metallic silver oxidation rates. However, if Ag^{+1} concentrations in the pore space become high enough, it may significantly reduce oxidation rates and saturating the liquid phase faster since concentration gradients driving the mass-transfer from bulk silver to Ag^{+1} in solution become relatively small as seen in Figure 2.25.

Furthermore, based on the data in Figure 2.28, it is apparent that the silver-embedded ceramic tablet performs in an identical manner day after day for at least 179 days. A few simple calculations can be used to estimate the lifespan of a silver-ceramic tablet. If the tablet contained an initial mass of silver of 1 g, and assuming the tablet could be designed to produce a concentration of 0.1 mg/L (the drinking-water standard) in a 20-L volume of water each day (a daily release of 2 mg of Ag^{+1}), then the lifespan of the tablet would be 1.4-year. Of course, we do not know if the tablet will continue to perform as shown in Figure 2.28 for a 1.4-year period. It is likely that some of the silver in the tablet is in pore space that is not in hydraulic contact with the bulk solution, therefore would not be available for release. Also, as Ag^{+1} is released and the morphology of the nanopatches change, the silver oxidation and subsequent release rates may also change. Depending on whether the Ag^{+1} release rate increases or decreases, this would change the silver concentrations in water and the tablet's effective lifespan. Nevertheless, the data in Figure 2.28 suggest that the ceramic tablets can function effectively for 6 months, and thus would only cost $0.002 per liter of treated water (assuming a US$7.5 retail price), making it the least-expensive POU method currently on the market [7,39,40] .

The ceramic tablets described in this paper show potential in addressing some of the challenges associated with current POU methods. Aside from effectively improving water quality, these ceramic tablets can be made with local materials for under US$2 potentially making them more affordable than to current products on the market [40-42] . Ceramic tablets are easy to transport because of their small size and durability, which we believe will make them more appealing to local distribution channels. With partnerships with local NGOs and aid agencies, we believe strong distribution channels can be established. Ceramic tablets are easy to use, as the tablet is just placed into a household water storage container and functions effectively for at least 179 d, making it more user-compliant and effective long-term. Use of local raw materials and simplicity of production make it feasible to scale production and manage quality assurance of the ceramic tablet. Aside from being used by itself, the ceramic tablet can also be used with existing POU methods to reduce rates of recontamination. Examples include biosand filters or boiling water methods where performance declines in the field due to recontamination of the treated water from poor sanitation and the lack of a residual disinfectant[43] .

Further investigation of the ceramic tablet needs to be performed to better understand the mechanistic process regulating silver release, such as disinfection efficiency with varying initial bacterial concentrations, performance in varying water chemistries and against various waterborne pathogens as technical performance may vary under these different conditions. Additionally, field studies need to be conducted to evaluate performance under real-world conditions and social acceptance. Overall though, we believe this technology shows great potential to provide safe drinking water to underserved components of our global population.

2.5 Acknowledgements

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Chapter 3

Field Evaluation of the Silver-embedded Ceramic Tablet as a POU water purification Technology in Limpopo Province, South Africa.

This chapter is in preparation for publication.

Ehdaie B, Rento CT, Son V, Turner SS, Samie A, Dillingham RA, Smith JA. Evaluation of silver-embedded ceramic tablet as a primary and secondary point-of-use water purification technology in Limpopo Province, S. Africa. 2015, In preparation.

3.1 Introduction

Drinking water quality for approximately 1.8 billion people around the world is contaminated with fecal bacteria, and thus contributing to the 2 million deaths that are associated to diarrheal diseases [1]. Furthermore, water-related diseases can cause cognitive impairment and growth stunting in children [2], and among those less than five years in age, accounts for 21 percent of all deaths [3]. Lack of access to safe water is a significant barrier to improvement in human health and development of the global community. Households may have access to public taps monitored by the municipal government, however, they often face water shortages and impaired municipal water systems leading to poor drinking water quality [4]. Point-of-use (POU) methods have shown great promise in improving water quality at the point of consumption with laboratory testing demonstrating up to 6-7 log reductions in bacteria. However, often times performance declines when tested in a field setting [5,6]. The decline in performance is due to a combination of many factors, such as user-compliance, ease of use of the technology, cost of the POU method, and poor sanitation and hygiene conditions.

Recent studies have demonstrated that recontamination of drinking water occurs among 17-25% of households using ceramic water within a month to a year of use. Ceramic water filters are considered one of the more socially acceptable and effective POU methods currently available. The recontamination is thought to be a result of poor sanitation conditions and lack of a residual disinfectant in the filtered water. Other POU methods, such as chlorine-based methods, perform even worse in the field due to low compliance and social acceptance. Chlorine-based methods usually alter the taste and odor of water, which is unappealing to many end-users [7-10]. POU methods such as flocculent/disinfecting powders have short lifespans or require multiple operating steps and supplies. Boiling is effective but not cost-effective and treated water is easily recontaminated [11,12].

Evaluation of POU methods has been limited to short-term evaluations of field performance, where POU methods have shown promise. Only limited studies have evaluated their long-term efficacy and these studies have generally shown a decline in effectivieness [13,14]. In a paper published by Mellor et al [15], safe drinking water was correlated to community health through an agent-based model (ABM) model. When applied to POU interventions, it demonstrated that improvements on health within communities is seen among POU interventions where at least a 3-log reduction in total coliform is achieved consistently over 3 years. This further provides support for long-term field evaluations in order to provide sufficient safe drinking water to improve human health [15].

In addition to longevity, there can be high variability between samples and bias in user compliance that cannot be accounted for due to a lack of a true blind control for many POU methods. Until now, only chlorine-based POU methods have been eligible for blinded field studies [10,16-18], however given the residual taste of chlorine-treated water these studies may not represent a truly blinded test. Although these studies account for user compliance, there are limitations to chlorine based POU methods, such as being ineffective against protozoa and low social acceptance due to changes in taste and odor of water [7,17]. Studies have shown around 30% adherence for chlorine-based POU methods [7,18]. Therefore, blinded studies have been restricted to POU methods that already perform rather poorly due to technical performance and social acceptance.

The ceramic tablets described in this paper and developed in Chapter 2, show potential in addressing some of the challenges seen in field studies associated with current POU methods. It is the first ceramic-based POU method that can be tested in a blinded study. The novel silver-embedded ceramic tablet in this paper is designed to make drinking water microbiologically safe, thus we see its applications in two ways: (1) as a primary POU method for individuals in need of a low-cost, reusable and portable POU method and (2) as a secondary POU method to provide continual disinfection to reduce risks of recontamination. Examples of secondary applications include ceramic water filters, biosand filters or boiling water methods where performance declines in the field due to recontamination of the treated water from poor sanitation and the lack of a residual disinfectant [11]. Furthermore, this paper evaluates the novel silver-embedded ceramic tablet over 12 months, allowing evaluation of both short and long term performance.

To evaluate the silver-embedded ceramic tablet as a primary and secondary POU method, the work described in this chapter compares three POU methods: the silver-embedded ceramic tablet when used alone, ceramic water filters used alone, and ceramic water filters with a silver-embedded ceramic tablet to provide continual disinfection as a secondary POU. We see these three POU method technologies classified in three categories: good, better and best. The good method comprises of the silver ceramic tablet (SCT) that will microbiologically improve water however not remove turbidity. The better method is the ceramic water filtration system, which will remove pathogens and particulates without any means of continual disinfection (CWF). The best method is the ceramic water filter used with the silver ceramic tablet (CWF+SCT), where the ceramic water filter removes microbial pathogens and turbidity then the silver-embedded ceramic tablet provides continual disinfection to reduce recontamination. This paper compares the technical performance and social acceptance of these three POU methods over one year.

3.2 Materials and Methods

3.2.1 Ethics

The protocol for this study was approved by the University of Virginia Institutional Review Board for Social and Behavioral Sciences. With the assistance of interpreters, verbal consent was obtained from each participant prior to the beginning of the study. Participants were informed of all details of the study. For those using the silver-embedded ceramic tablet as the primary POU method, participants were informed one of the ceramic tablets they were given was embedded with silver and the other was not but not told which was which. Participants were instructed to only use ceramic tablets and the corresponding containers for storage of untreated water. Prior to consumption, they should treat their water using whatever water treatment methods they currently use, since the efficacy of the silver-embedded ceramic tablet is still being evaluated in this study. All participants were informed that silver is a disinfecting agent and, when used to treat water, would disinfect waterborne pathogens. All participants were provided with a silver-embedded ceramic tablet and ceramic water filter at the end of the study.

3.2.2 Field site and enrollment eligibility

The field study was conducted in Limpopo Province, South Africa. Limpopo Province was selected as the location of the study because it is one of the least developed provinces in South Africa with the highest rates of HIV/AIDS and lowest rates of accessible drinking water (44%) [19]. It is home to the Water and Health in Limpopo (WHIL) program, an interdisciplinary collaboration between the University of Virginia and University of Venda. The WHIL project aims to bring safe drinking water to improve community health in the Limpopo Province. As a result of years of research in the community, the WHIL program has established strong relationships with the local community. Two villages in Limpopo Province were considered for testing the efficacy of the silver-embedded ceramic tablet. The village of Ha-Mashamba was selected to evaluate the silver-embedded ceramic tablet as the primary POU method (SCT), and in the village of Tshibvumo the silver-embedded ceramic tablet was evaluated as a secondary POU method (CWF+SCT).

A total of 79 households were selected to participate in the study. Participants were selected with the help of local community leaders in each village. To be eligible, participants had to be at least 18 years of age and without previous exposure to any of the POU intervention technologies. Prior to being enlisted, participants were screened for previous knowledge or exposure to any of the intervention technologies in the study. If households had previously owned or extensively used one of the intervention technologies they were not eligible to participate.

3.2.3 Intervention and design of study

In Ha-Mashamba, the performance of the silver-embedded ceramic tablet was evaluated as the primary POU method among 29 households. Each household was provided two 20-L water storage containers, one with a silver-embedded ceramic tablet (Figure 3.1A) and another with a control ceramic tablet (without silver). The container with the control ceramic tablet served as a blind control.

Participants were asked to use both containers equally to the best of their ability. Also, participants were instructed to only use containers for collection and storage of untreated water.

In Tshibvumo, the silver-embedded ceramic tablet was evaluated as a secondary POU method with CWFs. The silver-embedded ceramic tablet was used as part of a ceramic water purification system, ceramic water filter with silver-embedded ceramic tablet (CWF+SCT) as seen in Figure 3.1C. The CWF+SCT consists of a ceramic water filter with a 20-L, plastic lower reservoir. The CWF serves as the primary POU method by physically removing contaminants. The lower reservoir is used to collect and store treated water. Previous studies have shown that the water in the lower reservoir becomes prone to contamination over time. The silver-embedded ceramic tablet could be a potential solution to this problem as it can be placed in the lower reservoir of the CWF to provide continual disinfection as a secondary POU method. Fifty households were enlisted in Tshibvumo and each household was given a CWF. Half of the households were given silver-embedded ceramic tablets that were placed in the lower reservoir of the ceramic water purification systems, CWF+SCT (Figure 3.1C), and the other half only had the CWF (Figure 3.1B).

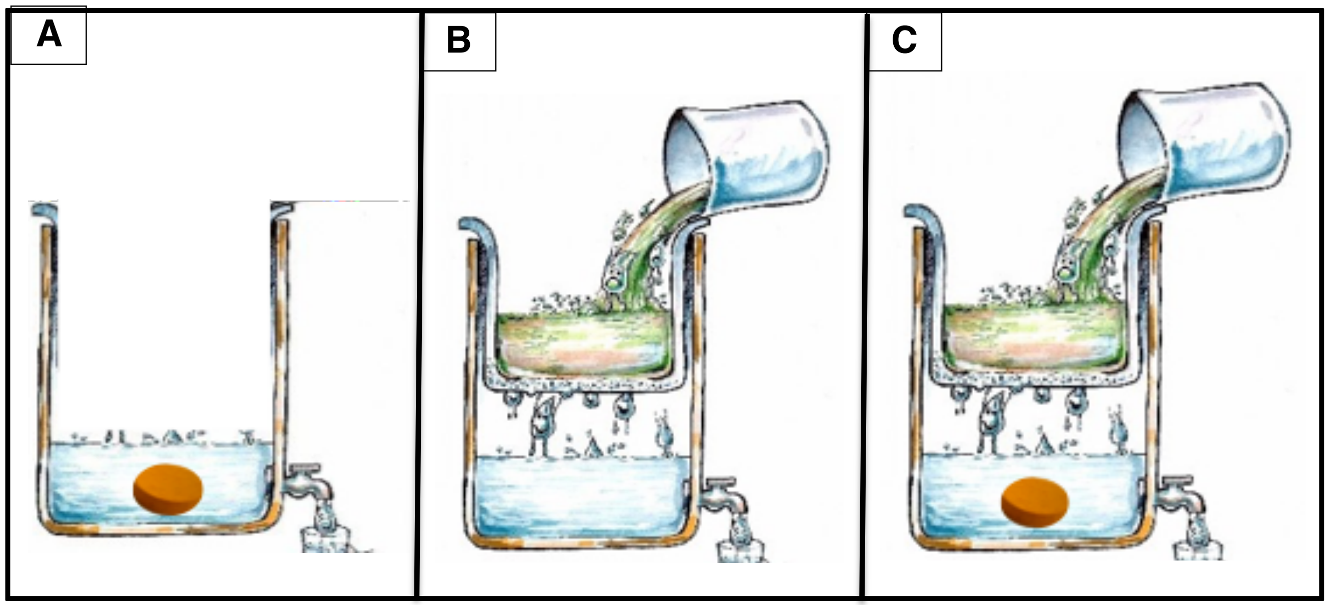

Figure 3.1. *Ceramic-based point-of-use water purification methods. (A) Silver-embedded ceramic tablet in 20-L lower reservoir (SCT). (B) Ceramic water purification system: ceramic water filter and lower reservoir (CWT). (C) Ceramic water purification system with silver-embedded ceramic tablet in lower reservoir (CWF+SCT).*

Households were visited weekly for five consecutive weeks and again at weeks 37 and 52 (June 2013-2014). Households were instructed not to clean the lower reservoirs and water storage containers in order to evaluate the continual disinfection capability of the SCTs. An outline of the field study is shown in Figure 3.2. Only 30 of the 79 households were sampled at week 37 due to time constraints. Households visited during week 37 and 52 with silver-embedded ceramic tablets were provided new silver-embedded ceramic tablets at that time and removed from the study. The original ceramic tablets were transported back to the University of Virginia for further laboratory testing.

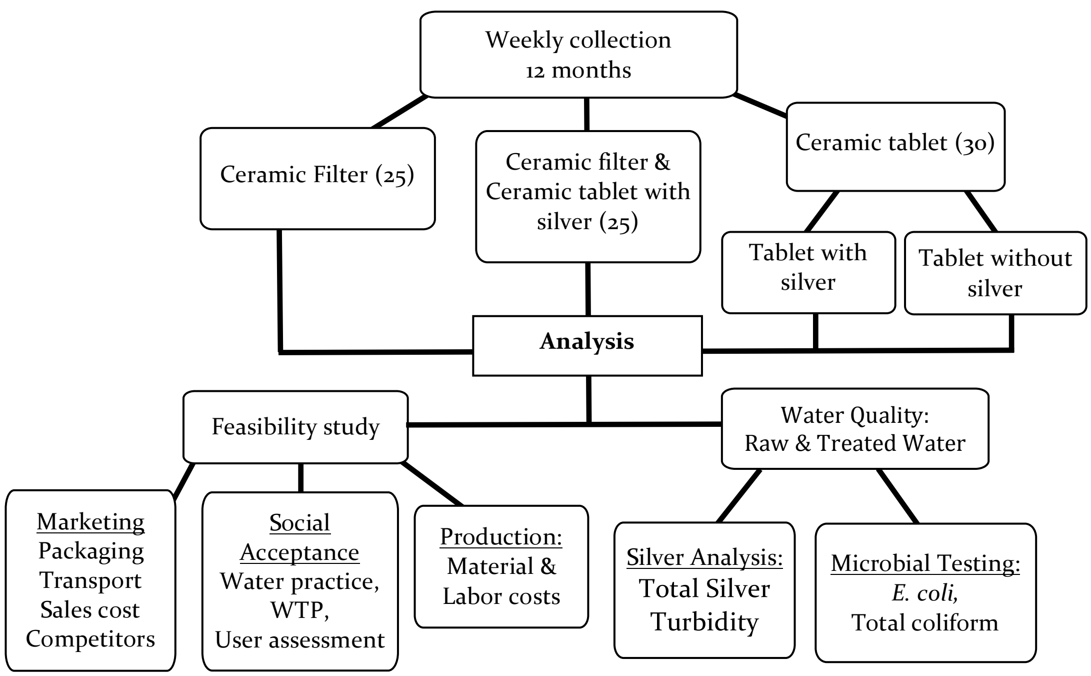

***Figure 3.2**. Outline of study to evaluate the technological performance of silver-embedded ceramic tablets, ceramic water filters, and ceramic water filters with ceramic tablets in the lower water reservoir in Limpopo Province, South Africa.*

3.2.4 Preparation of ceramic water filters and ceramic tablets

CWFs were provided by the UVA non-profit organization PureMadi, and were manufactured at the PureMadi filter factory located in Limpopo Province, S. Africa. The factory is a collaborative project between WHIL, the local Mukondeni Women's Pottery Cooperative and PureMadi. CWFs were made with local supplies: clay from a natural clay deposit, locally processed sawdust and water. Clay was processed at the factory using a hammer mill. Sawdust was passed through a 16-mesh sieve and water from a private borehole was used. 68 kg of clay and 8 kg of sawdust were mixed for 30 min then 28 L of water was added and mixed for another 30 min. The mixture was molded in to a pot shape using a filter press, and air-dried for three days. Filters were fired using a wood-fire kiln. To ensure filters are working properly, the flow rates of the filters were tested. Filters were soaked in a water bath and then filled to the rim. Water levels were measured after 1 h and confirmed to be between 1.5 L/h to 3 L/h. All working filters were painted with 300 mg/L of colloidal silver and allowed to dry. The factory also produces the lower reservoir that is used with the CWFs. Lower reservoirs were prepared by drilling a hole in a 20-L Evernu bucket to attach the spigot. The filter and lower reservoir are sold as a single unit as shown in Figure 3.1B.

Silver-embedded ceramic tablets were made in Charlottesville, Virginia in a pilot production facility. A dry clay-sawdust mix was prepared with 168.8 g of Redart clay and 18.8 g of sawdust, passed through 20-mesh sieve. Silver nitrate solution (27.2 g/L) was prepared using deionized water and 57.6 mL was added to the dry mix. The wet mixture was molded and pressed for 1 min at 6,895kPa using a hydraulic manual press, and air-dried for 72 h at room temperature. A total of 54 silver-embedded ceramic tablets were prepared and fired in an electric kiln (Evenflow). Ceramic tablets were fired at 150˚C/h until 600˚C and then at 300˚C/h until 900˚C and held for 3 h. For households in the village of Ha-Mashamba, control tablets were also provided that were prepared using deionized water in place of silver nitrate solution. All participants were given, a 20-L plastic water storage container with a spigot with each ceramic tablet. PureMadi provided the water storage containers, which were the same as the lower reservoirs used with CWFs and CWF+SCTs.

3.2.5 Sample collection

Sterile Whirlpak stand up sample bags were used to collect and transport 500 mL of each sample. Samples were stored in coolers with ice during transportation from sample site to the laboratory and analyzed same day of collection. In the village of Tshibvumo, two samples were taken at each house. Influent samples were collected from the water source to represent the untreated water. The second sample was the effluent sample collected directly from the spigot of CWFs and CWF+SCTs. In the village of Ha-Mashamba, three samples were collected. One sample was taken from the blind control.

One sample was taken from the water storage container containing the silver-embedded ceramic tablet (SCT). The third sample was taken from the water source where participants filled their water storage containers (source water). All samples in the village of Ha-Mashamba were collected in duplicate. Source water samples were collected on a weekly basis for weeks 1-5. Control- and SCT-treated samples were collected at weeks 1-5, 37 and 52.

The total number of houses visited each week varied due to availability of households. A few households dropped out of the study or were removed towards later time points. Total number of houses visited and samples collected for each week are recorded in Tables 3.1 and 3.2 for the villages of Tshibvumo and Ha-Mashamba.

Table 3.1. *Number of Households Sampled each week in Tshibvumo*

Week	Control Households	Intervention Households	Total Households
1	21	24	45
2	24	23	47
3	22	22	44
4	22	24	46
5	26	21	47
37	10	10	20
52	18	11	29

Table 3.2. *Number of houses visited and samples collected each week in Ha-Mashamba*

Week	Number of houses visited	Number of samples
1	29	57
2	25	48
3	29	58
4	29	58
5	27	53
37	10	20
52	15	30

3.2.6 Water-quality testing

Water samples were analyzed for total silver concentration, turbidity, total coliform bacteria (TC) and *Escherichia coli (E. coli)*. Total silver concentrations were measured using a PerkinElmer HGA 900 graphite furnace atomic absorption spectrometer (GFAA) with a silver cathode lamp. Prior to GFAA analysis, samples were acid digested using nitric acid for a final sample concentration of 1% HNO_3. Samples were prepared in South Africa and transported to the University of Virginia for GFAA analysis.

Turbidity was measured using the Hach 2100AN Turbidimeter. Samples were poured in glass vials, provided by the test kit, and shaken thoroughly to ensure particles were uniformly distributed. Prior to readings, the outer surface of the glass vial was wiped with silicone oil to ensure no scratches or smudges interfered with the reading. Results were measured in units of nephelometric turbidity units (NTU) using standards provided by the kit. In between samples, glass vials were rinsed three times with deionized water.

Membrane filtration techniques were used to quantify TC and *E. coli* in water samples. TC and *E. coli* were used as indicators of fecal contamination because they are commonly found in mammalian feces. 100 mL of sample, or diluted sample, was passed through a sterile 0.45-μm Millipore membrane filter using a vacuum pump. The filter paper was placed in a sterile Millipore petri dish containing m-Coliblue24 broth growth media (Millipore) and incubated overnight at 37^{o}C. After 24 hours the dishes were counted for TC colonies, indicated by a red dot, and *E. coli* colonies, indicated by a blue dot. During each membrane filtration analysis, a negative control sample was prepared, which was cooled boiled-water. Negative controls never had bacteria, as was expected, ensuring there was no contamination of samples or supplies.

3.2.7 Laboratory analysis of ceramic tablets

Ceramic tablets were collected from houses visited during week 37 and reanalyzed for silver release in the laboratory at the University of Virginia. Ceramic tablets were placed in 10 L of tap water in a 20-L plastic container, and sampled after 24 h. Silver-embedded ceramic tablets were run in parallel with corresponding control ceramic tablets. Samples were analyzed for total silver concentration using the GFAA, as described previously. Total silver concentrations in control samples were subtracted from total silver concentrations in samples treated with the silver-embedded ceramic tablets to calculate final silver concentrations among laboratory and field samples.

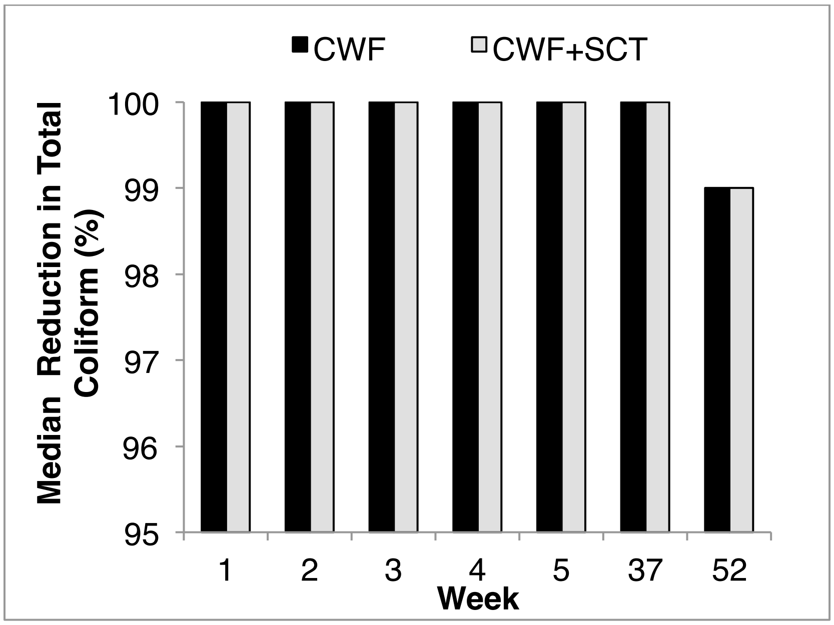

Figure 3.3. *Median percent reduction of total coliform bacteria over 12 months. The CWF group consisted of 25 households with only ceramic water purification systems. The CWF+SCT group consisted of 25 households with the ceramic water purification system and silver embedded ceramic tablet.*

3.2.8 Social acceptance

Social acceptance was evaluated through collection of survey data. Participants were asked to complete two surveys: entrance and exit surveys. Willingness to pay was evaluated through a series of questions in the exit survey using the binning method [20]. Interpreters were used to assist in language and literacy barriers. Entrance surveys were structured to collect demographic data and information on current water practices. Exit surveys were designed to collect information on performance and potential demand of the ceramic-based water purification technologies. Survey questions can be found in Appendix B.

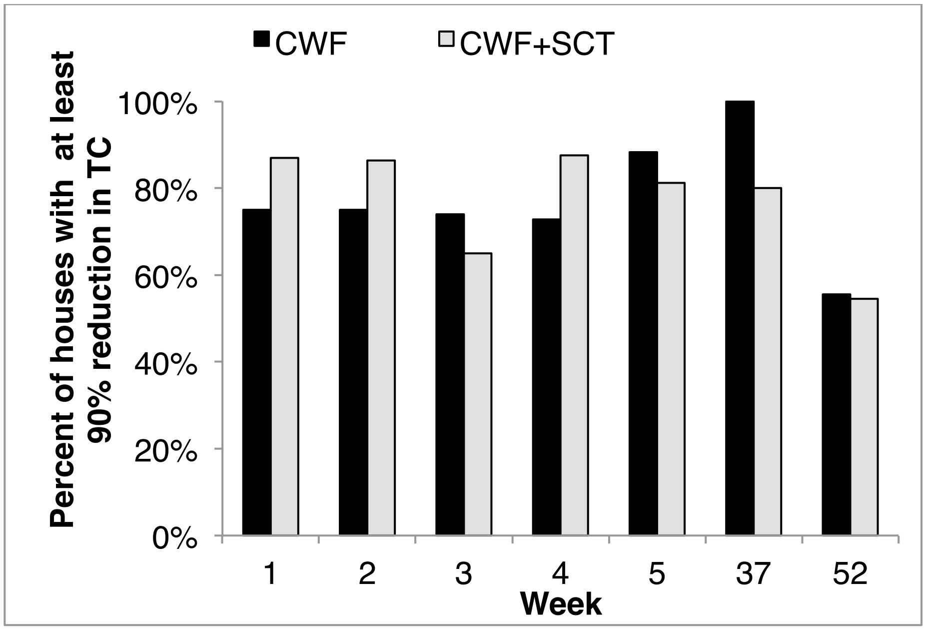

Figure 3.4. *Percent of households with at least 90% reduction in total coliform bacteria over 12 months. Samples were taken from CWF households and households using the ceramic water purification system with a silver-embedded ceramic tablet (CWF+SCT).*

3.3 Results

3.3.1 Evaluation of silver-embedded ceramic tablet as secondary POU method

Figure 3.3 shows the effect of the silver-embedded ceramic tablets on percent reduction of TC when used as a secondary POU with CWFs. Reduction in TC was calculated by subtracting bacterial concentrations in the influent samples from those in the effluent and then dividing by the TC levels in the influent sample. Results show median reductions of 100% during weeks 1-5 and 37 for both groups. At week 52, the median reduction in TC declined to 99% for both control and intervention groups.

Figure 3.4 shows the percent of households with at least 90% reduction in TC each week. In the CWF group, 75%, 75%, 74%, 73%, 81%, 100% and 56% of households had at least 90% reduction in TC at weeks 1-5, 37 and 52. Percent of households in the CWF+SCT group with high-performing ceramic water filtration systems (at least 90% reduction) was 87%, 86%, 65%, 88%, 81%, 80% and 55% for week 1-5,37 and 52.

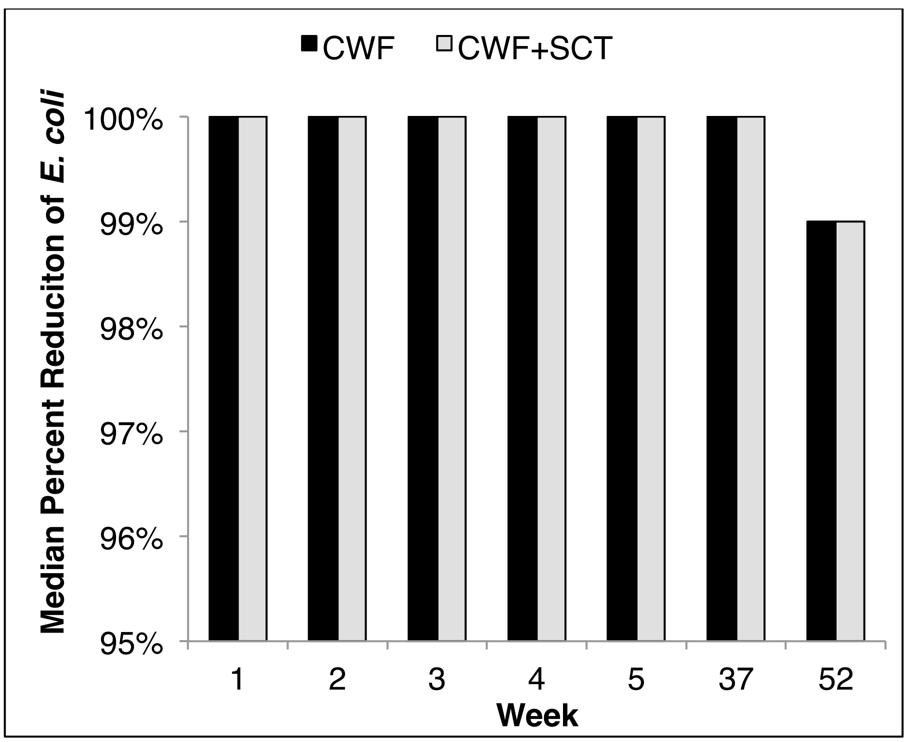

Figure 3.5. *Median percent reduction of E. coli among households using ceramic water purification systems over 12 months. 25 households were using ceramic water purification systems (CWF). 25 households were using the ceramic water purification system with the silver-embedded ceramic tablet (CWF+SCT).*

The efficiency of CWFs and CWF+SCT to reduce *E. coli* are displayed in Figures 3.5 and 3.6. Median percent removal of *E. coli* was 100% for weeks 1-5. At week 52, median percent reduction of *E. coli* was 99% for both groups (Figure 3.5). There was no difference in median percent reduction of *E. coli* between the two groups over 12 months. The distribution of high-performing ceramic water filter systems are shown in Figure 3.6 for *E. coli* reduction. At week 52, the CWF+SCT group had a higher number of CWF+SCTs providing 100% reduction in *E. coli* compared to the control group. The percent of households in the CWF group with 100% reduction in *E. coli* was 100%, 79%, 100%, 100%, 86%, 100% and 60% at weeks 1-5, 37 and 52, respectively. Among the CWF+SCT households, 100% of samples were completely free of *E. coli* at weeks 3,4, 37 and 52, and 92%, 80% and 86% during weeks 1,2 and 5, respectively (Figure 3.6).

Table 3.3. *WHO risk category of samples in Tshibvumo between CWF (control) and CWF+SCT (intervention) households.*

WHO Risk Category	*E. coli* (CFU/100mL)	Week						
Control		1	2	3	4	5	37	52
No risk	<1	100%	87%	100%	100%	95%	100%	63%
Low risk	1-10	0%	9%	0%	0%	5%	0%	38%
Medium risk	11-100	0%	4%	0%	0%	0%	0%	0%
High risk	>100	0%	0%	0%	0%	0%	0%	0%
Intervention								
No risk	<1	96%	73%	100%	100%	95%	100%	100%
Low risk	1-10	4%	5%	0%	0%	5%	0%	0%
Medium risk	11-100	0%	23%	0%	0%	0%	0%	0%
High risk	>100	0%	0%	0%	0%	0%	0%	0%

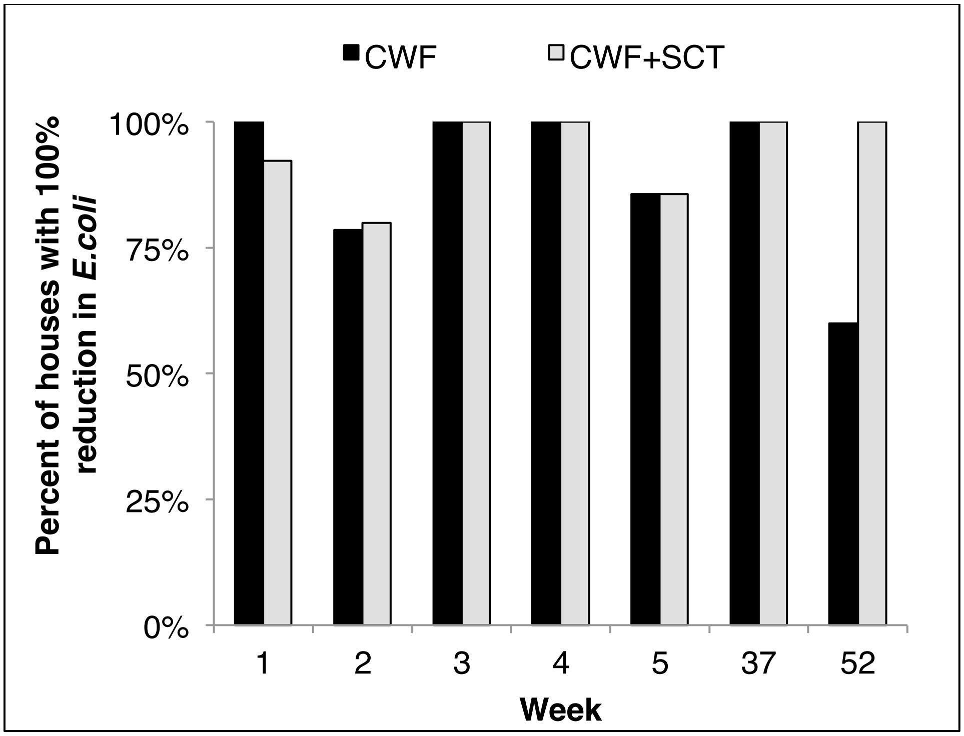

Figure 3.6. *Percent of households with 100% reduction in E. coli over time. Households were using ceramic water purification systems (CWF) or ceramic water purification systems with the silver-embedded ceramic tablet (CWF+SCT).*

Figure 3.7 and 3.8 demonstrate the average reduction in bacteria among CWF and CWF+SCT groups. No difference in reduction of TC was seen between households using the CWF and CWF+SCT (Figure 3.7). A difference in percent reduction of *E. coli* was observed at week 52, with an average of 60% and 100% reduction in *E. coli* among the CWF and CWF+SCT group, respectively (Figure 3.8). Table 3.3 displays the number of CWF and CWF+SCT-treated samples that met WHO risk category requirements.

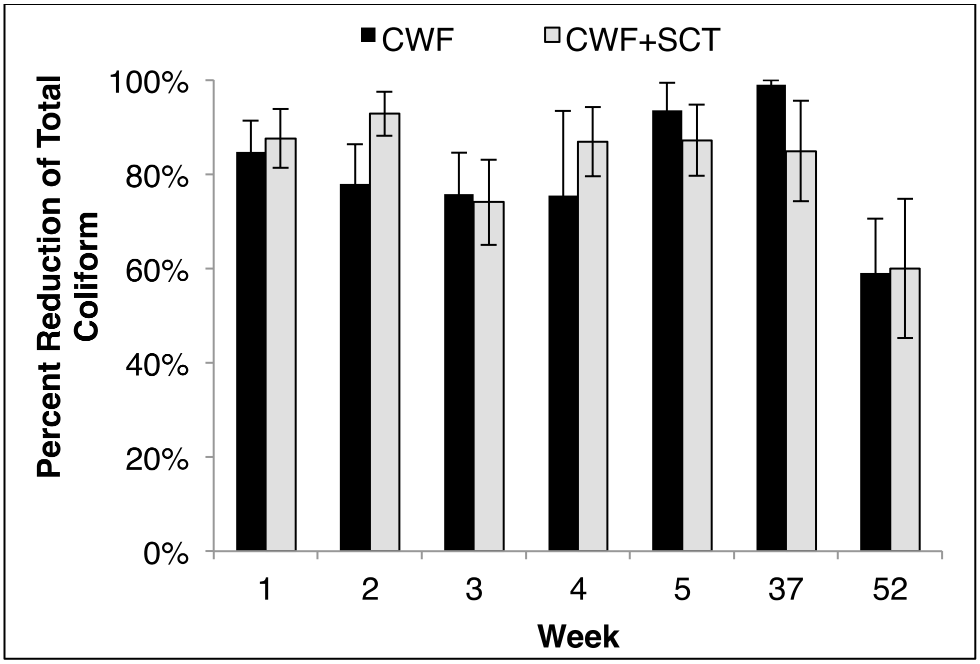

Figure 3.7. *Percent reduction of total coliform over time. Households were using ceramic water purification systems (CWF) or ceramic water purification systems with the silver-embedded ceramic tablet (CWF+SCT). Data points represent average and error bars represent standard error.*

Total silver released into solution by the POU technologies is shown in Figure 3.9. Silver released into solution was determined by subtracting silver concentrations in the influent sample from those in the effluent sample. Average silver levels in the control group were 46.4, 33.6, 30.5, 31.4, 19.8, 6.94 and 28.3 μg/L for weeks 1-5, 37 and 52. Among the intervention group, average silver concentrations were 54.8, 38.0, 24.8, 31.8, 15.5, 10.8 and 17.1 μg/L at weeks 1-5, 37 and 52.

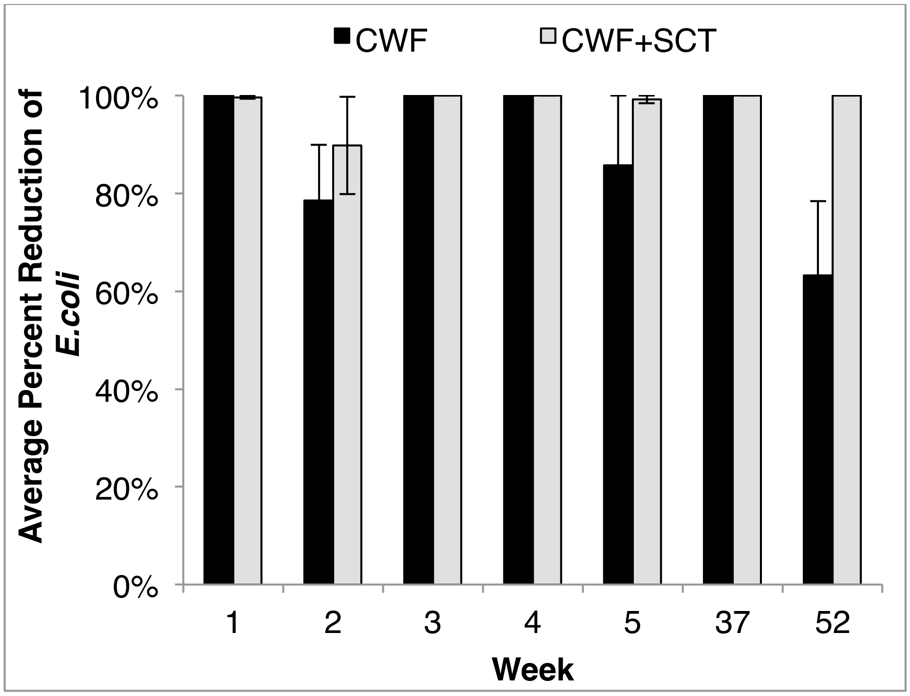

Figure 3.8. *Percent reduction of E. coli over time. Households were using ceramic water purification systems (CWF) or ceramic water purification systems with the silver-embedded ceramic tablet (CWF+SCT). Data points represent average and error bars represent standard error.*

3.3.2 Evaluation of silver-embedded ceramic tablet as primary POU method

Figure 3.10 shows the decline in water quality at the household level over time. Samples were collected at the water source of each household in the village of Ha-Mashamba and compared against water quality in the control water storage container over 5 weeks. Average TC levels at the water source were 2.4E+03, 4.9E+02, 80, 2.2E+02 and 2.4E+02 cfu /100mL over 5 weeks. The average TC concentration among water storage containers was 6.0E+02, 3.0E+03, 2.8E+03, 1.9E+02 and 3.8E+03 cfu/100 mL.

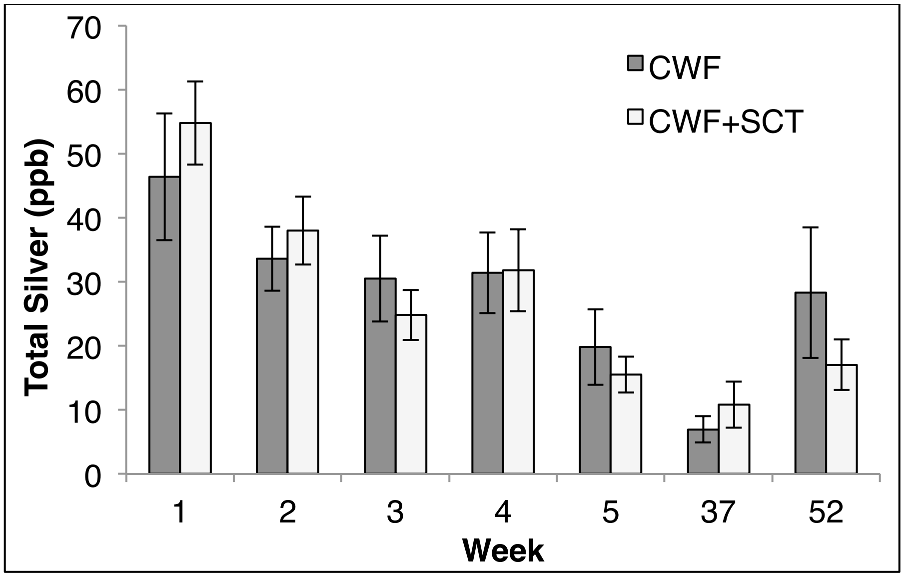

Figure 3.9. *Total silver levels among households using ceramic water purification systems over 12 months. Households were either using ceramic water purification system alone (CWF) or with the silver-embedded ceramic tablet (CWF+SCT). Data points represent the average of households sampled each week. Error bars represent the standard error.*

TC levels in the control water storage containers were compared to those in water storage containers with the silver-embedded ceramic tablet. Figure 3.11 demonstrates that TC levels remained lower in water storage containers when treated with silver-embedded ceramic tablets compared to the control. Average TC concentrations were 89, 35, 4.4E+02, 1.1E+02, 1.9E+02, 4.3E+02 and 2.1E+02 cfu/100 mL at weeks 1-5, 37 and 52, respectively, for SCT-treated samples. TC concentrations in the storage containers with the control tablet were always higher with 6.0E+02, 3.0E+03, 2.8E+03, 1.9E+02 and 3.8E+03, 2.8E+03 and 2.0E+03 cfu/100 mL at weeks 1-5, 37 and 52, respectively.

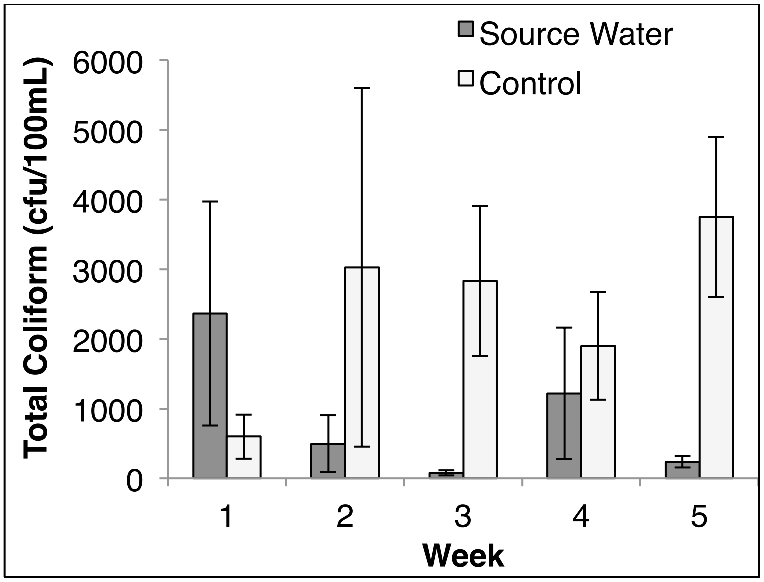

Figure 3.10. *Total coliform bacteria levels at the water source and in water storage containers at the household level over time. The water storage containers that were sampled had the control ceramic tablet that did not have silver (Control). Data points represent average total coliform bacteria of all samples taken each week. Error bars represent standard error.*

Figure 3.12 shows median percent reduction in TC and *E. coli* in drinking water treated with SCTs over 12 months. Percent reduction in bacteria was determined by taking the difference in bacteria concentrations between the blind control and SCT-treated samples, and dividing by the bacteria concentration in the control. Median percent reductions in TC were 75%, 100%, 91%, 80%, 75%, 93% and 72% for weeks 1-5, 37 and 52, respectively. The *E. coli* median reduction was 100% for weeks 1-3, 5 and 37, and dropped to 0% and 79% during weeks 4 and 57.

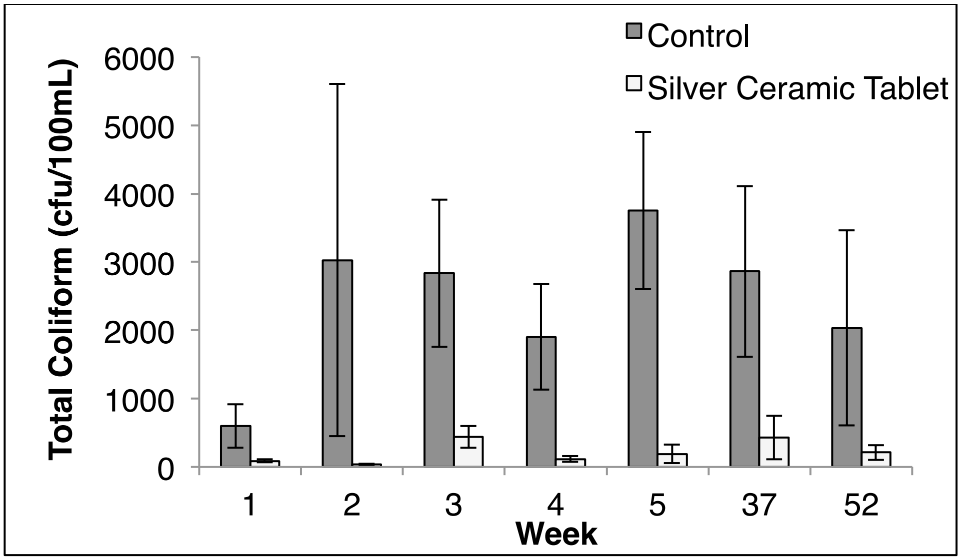

Figure 3.11. *Total coliform bacteria in water storage containers with ceramic tablets. Control samples represent samples taken from the water storage container with the control ceramic tablet. Silver ceramic tablet samples represent samples taken from water storage containers with the silver-embedded ceramic tablet. Data points represent average total coliform levels among all households per week. Standard error was used to calculate error bars.*

The distribution of high-performing SCTs is shown in Figures 3.13 and 3.14.

The efficacy of SCT declines over time for both TC (Figure 3.13) and *E. coli* (Figure 3.14). There was at least 80% reduction in TC among 47%, 88%, 60%, 50%, 45%, 67% and 33% of households at weeks 1-5, 37 and 52, respectively. At least 90% reduction in TC was observed among 39%, 79%, 53%, 42%, 32%, 67% and 27% of households at weeks 1-5, 37 and 52, respectively. There was 100% reduction in TC among 12%, 63%, 24%, 12%, 9% and 33% at weeks 1-5 and 37. None of the households had 100% reduction in TC at week 52.

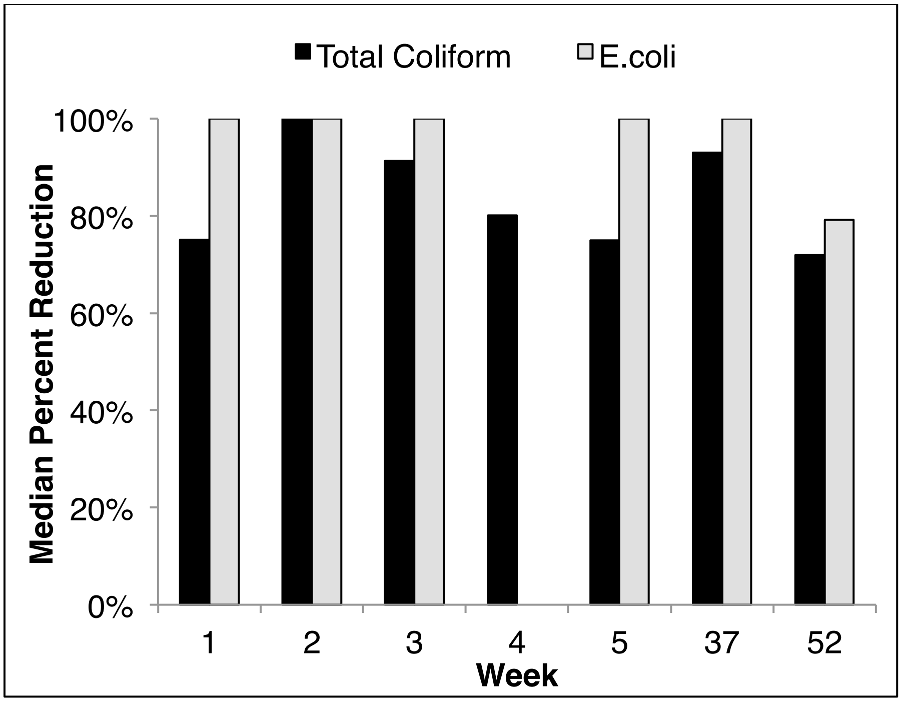

Figure 3.12. *Median percent reduction of total coliform bacteria and E. coli among ceramic tablet treated samples. Percent reduction was determined by comparing bacteria levels in water storage containers treated with control ceramic tablets to those treated with silver-embedded ceramic tablets. Samples were taken in duplicate among 29 households over 12 months. Data points represent the median of all samples.*

Figure 3.14 shows the performance of SCT-treated samples with respect to reduction in *E. coli.* The SCT completely disinfected *E. coli* (100%) among 83% and 93% of the houses in weeks 1 and 2. During weeks 3, 4, and 5, SCT-households showed *E. coli* reductions of at least 90% in 53%, 56% and 64% of samples. For these weeks, there was 100% reduction in 47%, 50% and 57% of samples. For weeks 37 and 52, 40% of samples were completely free of *E. coli*, and there was at least 80% reduction was observed among 60% at week 52.

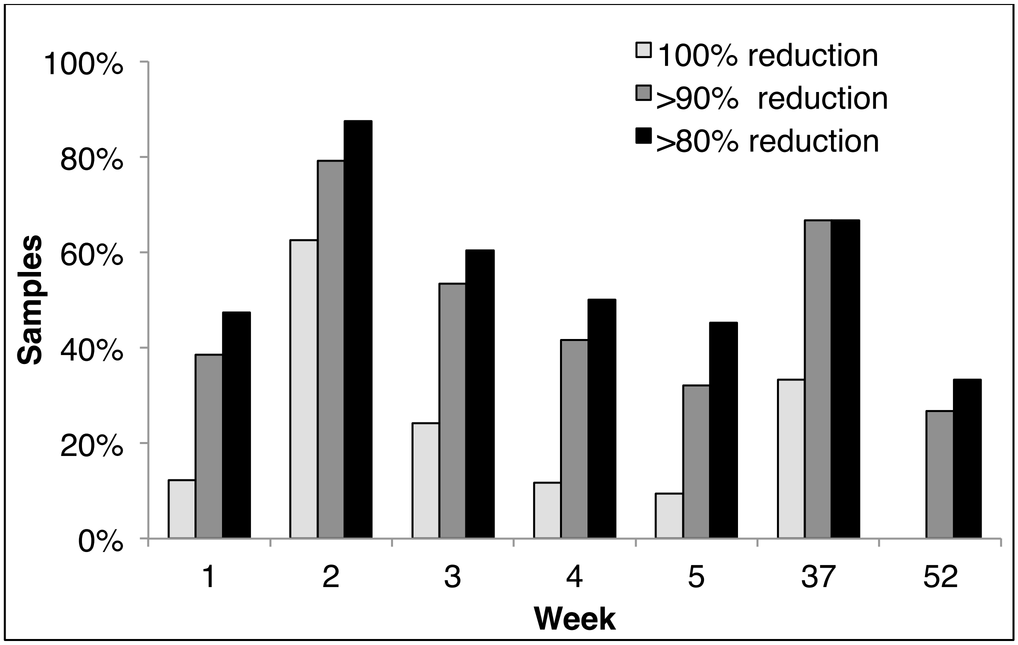

Figure 3.13. *Percent of ceramic tablet-treated samples with at least 80, 90 and 100% reduction in total coliform bacteria over 12 months.*

Table 3.4 summarizes baseline TC concentrations and overall water quality for households using SCTs as their primary POU method. Baseline bacterial concentrations were determined by quantifying TC levels in samples treated with the control tablet each week. This represents the water quality over time at the household level when using a storage container. Water quality determined by comparing samples treated with control tablet and SCT. The water quality was considered 'improved' if TC levels were lower among samples treated with the SCT compared to the control. The water quality declined if TC concentrations were higher in SCT-treated samples than in the control. Water quality improved among 82%, 84%, 86%, 68%, 69%, 80% and 60% of samples for weeks 1-5, 37 and 52. Table 3.5 shows the distribution of SCT-treated samples when categorized according to WHO risk categories for each week.

Figure 3.15 displays the average percent reduction in bacteria overtime for samples treated with SCT. Percent reduction for both TC and *E. coli* levels are shown for each week. Average percent reduction in *E. coli* was 90%, 93%, 68%, 44%, 69%, 44% and 57% for weeks 1-5, 37 and 52, respectively.

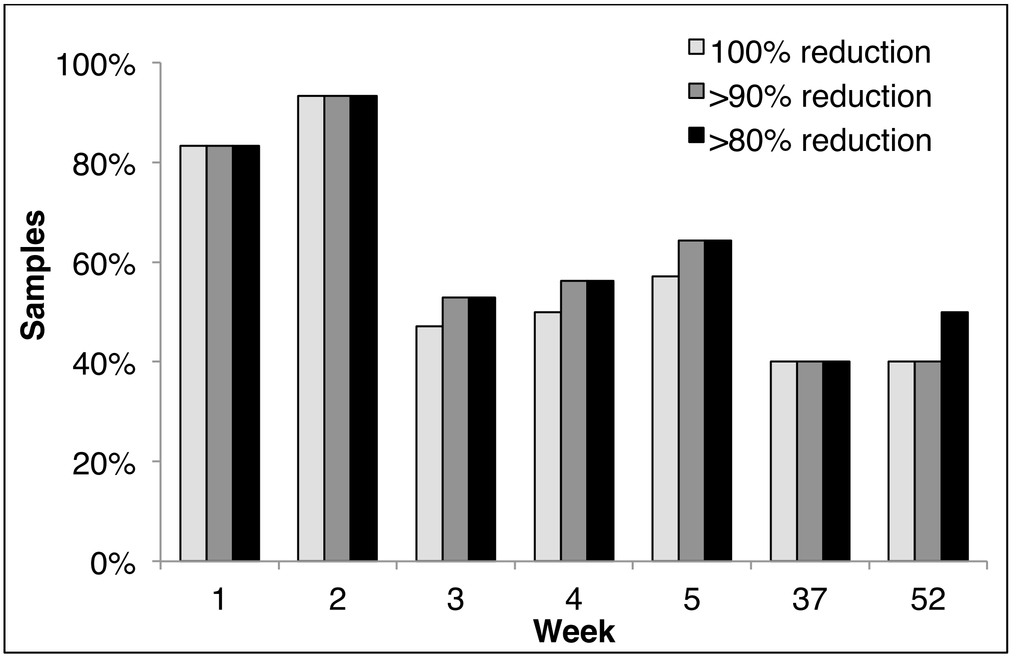

Figure 3.14. *Percent of ceramic tablet-treated samples with at least 80, 90 and 100% reduction in E. coli over 12 months.*

Total silver concentrations in water storage containers with the SCTs are shown in Figure 3.16. Average silver concentrations were higher among samples treated with the SCT compared to the control for all weeks except week 2 and 37 where no difference was seen. Silver concentrations were 2.67, 2.93, 1.39, 1.73, 2.61, 2.17 and 2.55 μg/L for samples treated with the SCT, and 1.45, 1.01, 0.39, 0.28, 0.44, 0.72 and 0.54 μg/L for samples treated with the control at weeks 1-5, 37 and 52, respectively.

Table 3.4. *Baseline total coliform (TC) bacteria levels and water quality of samples among SCT households*

	Week						
	1	2	3	4	5	37	52
Water Quality							
Number of Homes Showing Improvement in Water Quality	47 (82%)	41 (84%)	48 (86%)	41 (68%)	38 (69%)	8 (80%)	9 (60%)
Number of Homes Showing a Decline in Water Quality	9 (16%)	4 (8%)	8 (14%)	16 (27%)	14 (25%)	2 (20%)	6 (40%)
Number of Homes with Baseline TC levels:							
Less than 10 CFU/100mL	6 (11%)	10 (20%)	7 (13%)	6 (10%)	9 (16%)	1 (10%)	0 (0%)
From 10-49 CFU/100mL	6 (11%)	5 (10%)	9 (16%)	7 (12%)	9 (16%)	1 (10%)	7 (47%)
50-100 CFU/100mL	7 (12%)	8 (16%)	5 (9%)	8 (13%)	13 (24%)	4 (40%)	3 (20%)
More than 100 CFU/100mL	38 (67%)	26 (53%)	30 (54%)	39 (65%)	25 (45%)	4 (40%)	5 (33%)
Total number of samples	57	49	56	60	55	10	15

Table 3.5. *Percent of households in each WHO risk category of SCT-treated samples*

WHO risk category	*E. coli*	Week						
	(CFU/100mL)	**1**	**2**	**3**	**4**	**5**	**37**	**52**
No risk	< 1	36%	74%	36%	29%	57%	40%	40%
Low risk	1 to 10	64%	26%	59%	53%	14%	0%	40%
Medium risk	11 to 100	0%	0%	5%	18%	29%	60%	20%
High risk	>100	0%	0%	0%	0%	0%	10%	0%

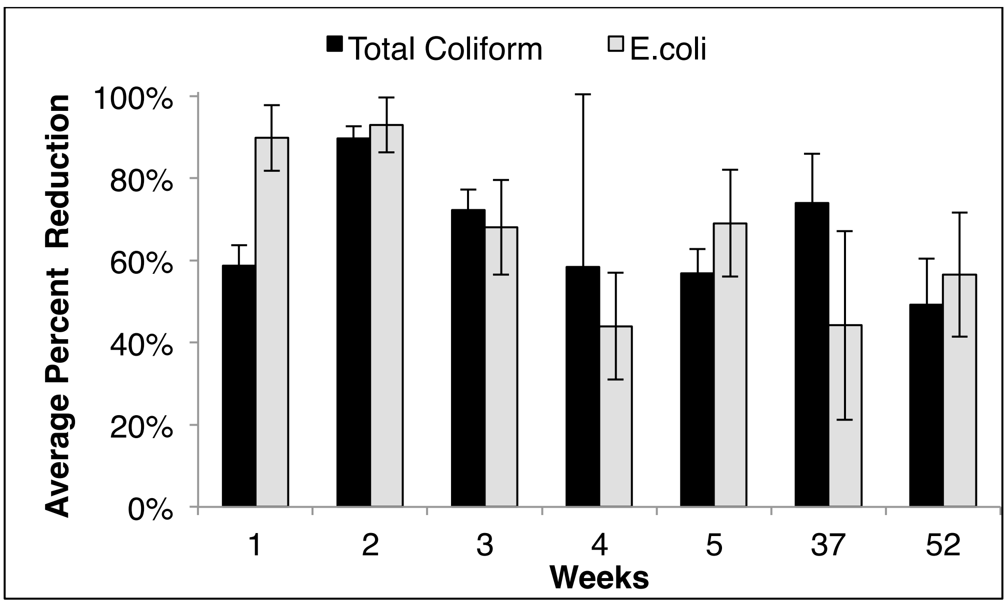

Figure 3.15. *Average percent reduction in bacteria among households using SCT as the primary POU method over-time. Data points represent average and error bars represent standard error.*

3.3.3 Comparing silver-embedded ceramic tablet field performance to laboratory

Ceramic tablets sampled at week 37 were removed from homes and brought back to the laboratory for further laboratory testing of silver release. Silver release levels from laboratory testing and field-testing are compared in Figure 3.17. Silver concentrations were normalized against the blind control by subtracting silver concentrations in the blind control from those in the SCT-treated sample. Silver concentrations among samples treated with the SCT were higher in laboratory samples compared to field samples among all households with the exception of tablets from two houses. The average residual silver concentration of water treated with the SCT was 8.97$\pm$3.85 μg/L in the laboratory and 1.45$\pm$0.611 μg/L in the field.

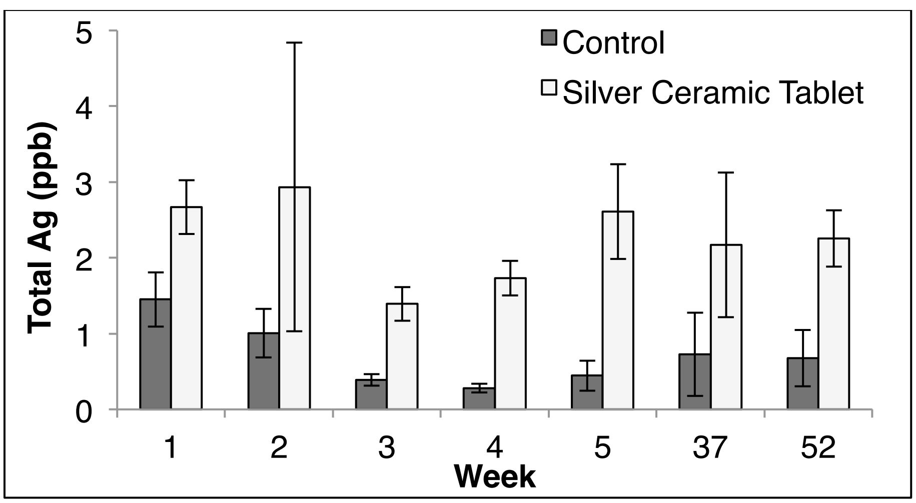

Figure 3.16 *Total silver concentrations among water storage containers with control and silver-embedded ceramic tablets. Data points represent average silver concentrations. Standard error was used to calculate error bars.*

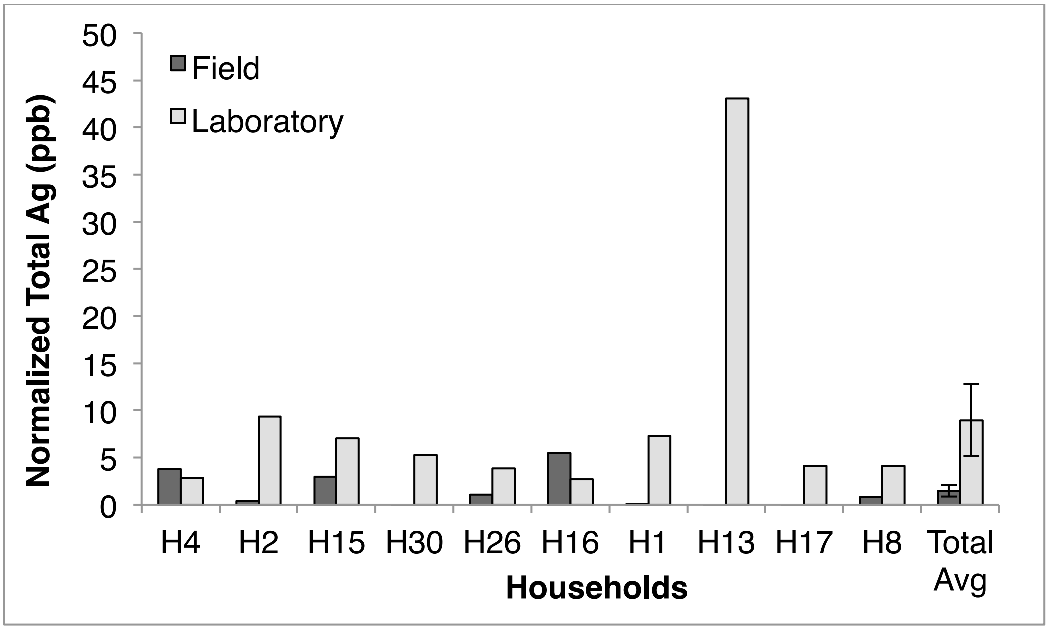

Figure 3.17. *Field and laboratory analysis of silver concentrations ceramic tablet-treated samples after 37 weeks. Control and silver embedded ceramic tablets were used to treat 10 L of water among households for 37 weeks. Samples were taken at 37 weeks from 10 households, and ceramic tablets were reanalyzed in laboratory settings. Silver concentrations were normalized by subtracting silver levels in the control from those in silver-embedded ceramic tablet-treated samples. Laboratory samples were collected after 24 h of treatment. Average silver concentrations were calculated for samples taken at 37 weeks both in the field and laboratory. Standard error was used to represent error bars.*

3.3.4 Effects of turbidity on ceramic water filters and silver-embedded ceramic tablet performance

Turbidity was measured among all the households during week 37 and 52. Figure 3.18 shows average turbidity levels among households using CWFs and CWF+SCTs. Turbidity was measured pre- and post-treatment. Average turbidity levels were higher among samples collected post-treatment (5.46$\pm$2.03, 3.58$\pm$0.857 NTU) compared to samples taken prior to any treatment (1.66$\pm$0.321, 2.28$\pm$0.58 7 NTU).

There was no difference in turbidity levels among samples taken from CWF households and CWF+SCT households both pre- and post-treatment. For households using the SCT as the primary POU method average turbidity was 0.888$\pm$0.176 NTU. In Figure 3.19 turbidity measurements were correlated to percent reduction in bacteria among households only using the SCT. Turbidity levels in samples treated with SCT, as the primary POU method, were plotted against corresponding percent reductions in TC and *E. coli*. No correlation was observed between turbidity and disinfection efficiency. Linear regression was performed and r-squared values were 0.102 and 0.028 for percent reduction of TC and *E. coli* compared to turbidity, respectively, demonstrating the performance of SCT was unaffected by turbidity levels.

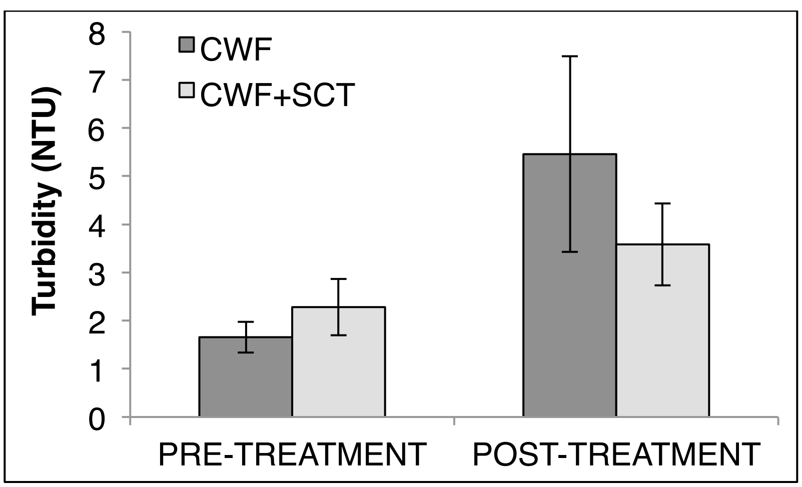

Figure 3.18. *Turbidity of ceramic-based technologies. Turbidity levels pre- and post-treatment among houses using ceramic water purification systems. Pre-treatment represented by influent samples and post-treatment samples represented by effluent samples. Data points represent average turbidity levels determined at weeks 37 and 52 combined. Standard error is used to calculate error bars.*

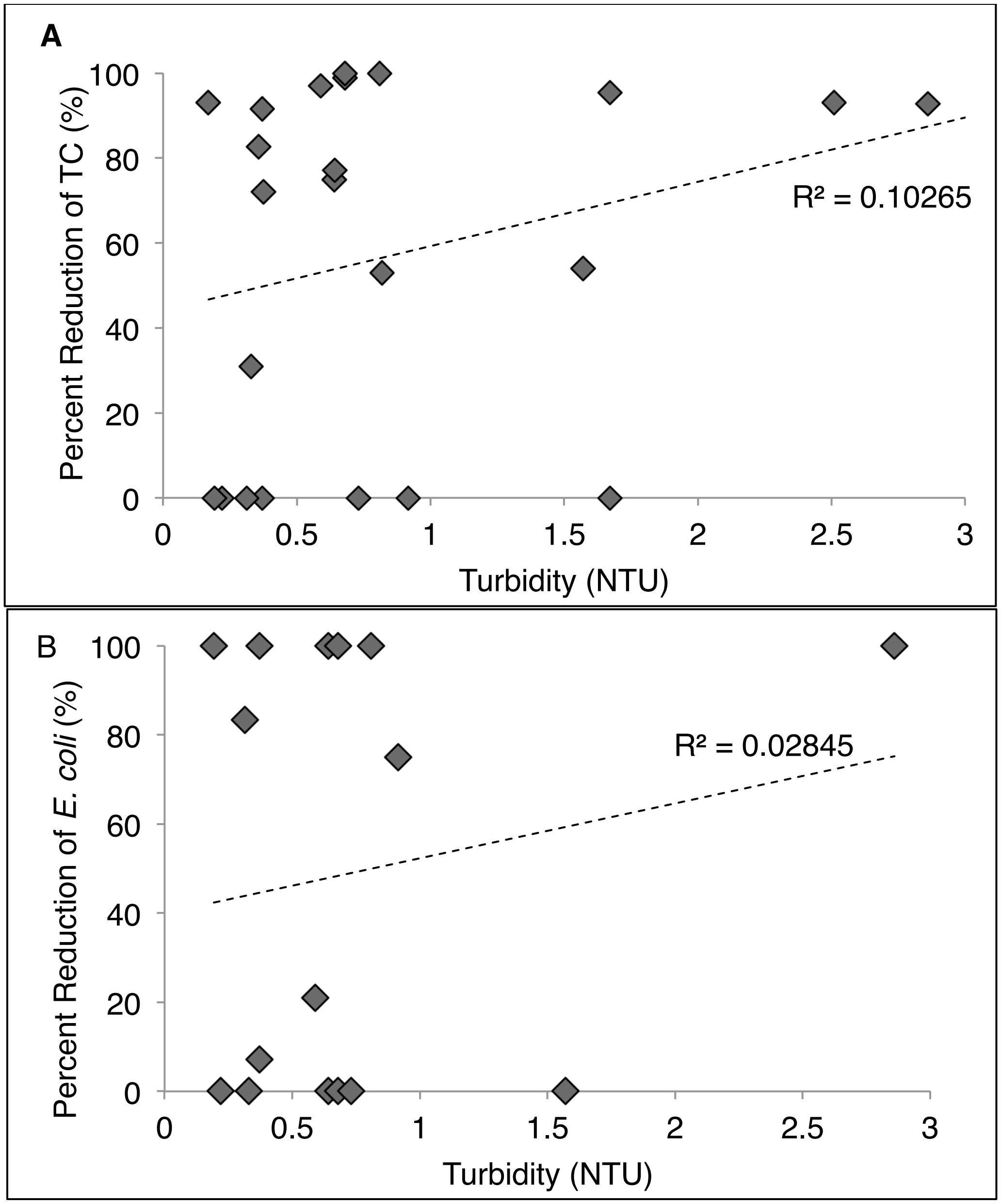

Figure 3.19. *Correlation of turbidity and percent reduction in bacteria among households using the silver-embedded ceramic tablet as primary POU method. Samples were treated with silver-embedded ceramic tablets and analyzed for reduction in total coliform bacteria (A) and E. coli (B) turbidity. Samples were taken at 37 and 52 weeks post-intervention.*

3.3.5 Social acceptability

All participants preferred using the POU methods to their current POU methods. The only improvements participants suggested for CWFs and SCTs was to have them treat larger volumes of water at a given time. All participants said that the ceramic-based POU methods improved the taste and odor of their water. Prior to these interventions, 56% of participants stored water in plastic buckets or drums. Storage containers were stored indoors among 95% of households and 57% cleaned containers with soap. 32% of participants claimed to never clean the storage containers. Water practices and demographic data of participants are described in Tables 3.6 and 3.7.

Table 3.6. *Demographic Data*

Head of household	
Median Age	44
Gender	
Male	8%
Female	92%
Average number of adults per household	2
Average number of children per household	3
Education	
Primary	22%
Secondary	62%
University	16%
Monthly Income	
Less than R250	7%
R250-1500	67%
Greater than R1500	26%

Table 3.7. *Water practices*

Primary Water Source	
Piped into yard	22%
Public tap/standpipe	55%
Borehole	18%
Surface water	5%
Water storage vessel	
Jerry can	35%
Plastic bucket (20-25 L)	34%
Water tank	1%
Plastic Drum (200 L)	22%
Plastic bottle	8%
Where is water stored in home	
Inside	95%
Outside	5%
Where inside?	
Kitchen	80%
Cleaning method for water storage vessel	
Boiled water	4%
Bleach	8%
Soap	57%
Nothing	32%

Willingness-to-pay (WTP) surveys were conducted among 79 households during the exit survey (Appendix B). Trends are shown in Figures 3.20 and 3.21. Binning methods were used to determine WTP [20]. WTP prices for the SCT, CWF and CWF+SCT began at R40 ($3.40 USD), R130 ($11 USD) and R200 ($17 USD) and increased by R10 ($1 USD) or decreased by R5 ($0.5 USD) depending on the response of the participant. Figure 3.20 shows the percent of participants willing to pay for the SCT, CWF or CWF+SCT at various price points. Approximately 50% of participants using the CWF and CWF+SCT were willing to pay between R100-R125 ($8-10 USD) and only R30 ($2.50 USD) for the SCT by itself. Median WTP for ceramic water filter units was R120 ($12 USD) and for ceramic water filters with the silver-embedded ceramic tablet R100 ($8 USD). Among households only using the SCT, 50% of households were willing to pay between R50 ($4.25 USD) and R55 ($4.70 USD) for SCTs (Figure 3.21). Median WTP for silver-embedded ceramic tablets was R50 ($4.25 USD) among households using the SCT as their primary POU method, and only R27.5 among households with the CWF+SCT.

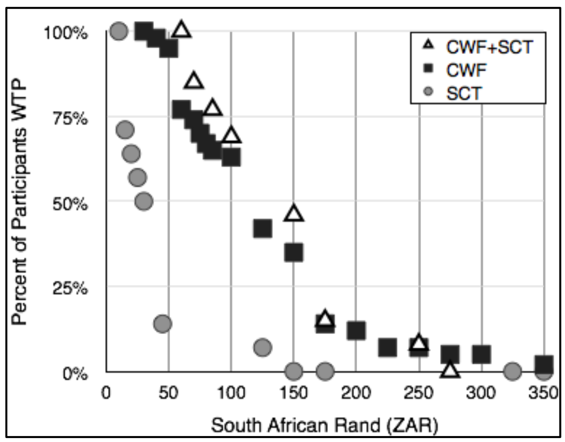

Figure 3.20. *Willingness-to-pay for each POU intervention (SCT, CWF and CWF+SCT) among 79 households in Limpopo Province, S. Africa. WTP was determined using binning method.*

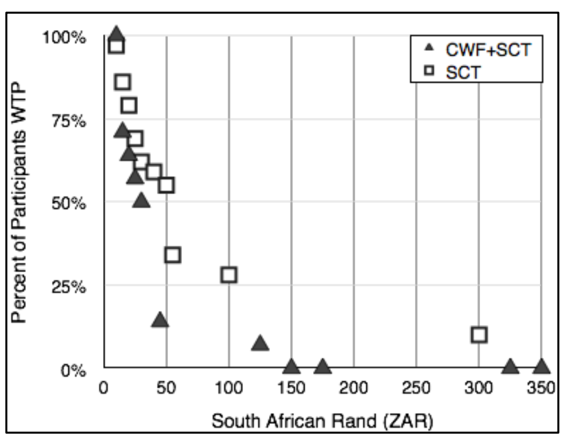

Figure 3.21. *Comparison of willingness-to-pay for SCT among households using SCT as primary POU method (SCT) and as secondary POU method (CWF+SCT).*

3.4 Discussion

This paper evaluates the short-term and long-term performance of three ceramic-based POU technologies: SCT, CWF and CWF+SCT (Figure 3.1 and 3.2). Short-term performance of SCTs was found to be comparable to current POU methods when used as the primary POU method [10,13,14,21-23]. SCTs can also be effective as a secondary POU method with CWFs to reduce recontamination and improve long-term performance. Furthermore, a blinded study was conducted to evaluate the SCT when used as the primary POU method. Until now, blinded trials for POU technologies have been limited to chlorine-based methods [10,16,17]. Given the nature of the SCT, a control ceramic tablet can be developed that has no silver however looks identical to the SCT. Therefore, the performance of the SCT was compared against a blind control in each household. Both tablets were used in parallel in each household reducing user bias and variability in water quality among control and intervention samples. Microbial water quality in water storage containers was measured and it was shown that total coliform levels among SCT water storage containers were lower than the control (Figure 3.9). *E. coli* disinfection efficiency was fairly high among all three POU methods and consistent with previous studies. Overall, the common trend was as expected, the POU method with the highest microbial disinfection efficiency was the CWF+SCT, followed by the CWF and then the SCT. Median percent reduction of TC and *E. coli* were high among all three interventions, ranging between 90-100% over 1 year.

For discussions in this paper, performances of the ceramic-based POU methods were compared to other studies in regards to *E. coli* and thermotolerant coliform (TTC) reduction. Many published POU intervention studies evaluate performance based on disinfection of *E. coli* and/or TTC [7,10,22]. TTC bacteria, which includes *E. coli*, refers to coliform bacteria that grow under cultures most representative of the mammalian gastrointestinal track [24]. Therefore, health risks associated with poor drinking water quality are often represented through quantification of TTC or *E. coli*.

3.4.1 Field performance of silver-embedded ceramic tablets

Short-term performance of SCT, CWFs and CWF+SCT POU methods were consistent with findings of previous studies [7,13,14]. CWF and CWF-SCT households had consistently high reductions in bacteria, demonstrating 86% and 99% average percent reduction in *E. coli* after 5 weeks (Figure 3.8). No difference was observed in microbial disinfection in CWFs and CWF+SCTs until weeks 37 and 52 (Figures 3.1, 3.3 and 3.8). Early performances of the SCT-only households showed average reductions in *E. coli* (93%) that are comparable to CWFs (79%, 97.5% [21]), CWFs+SCT (90%), chlorination (93.7% [7]) and flocculent/disinfectant powders (89.53% [7]). This suggests that the SCT as a primary POU method may be just as effective as other POU methods, such as chemical disinfection and filtration. However, SCT performance did decline over time, and this may be due to limitations in the study, which included low baseline *E. coli* levels and small sample size. Furthermore, silver release of the SCT was less than expected due to challenges that were faced during manufacturing. These challenges are discussed in more detail in the later half of this discussion. Even with these limitations though, the performance of the SCT is still comparable to other POU methods. Albert et al [7] evaluated CWFs, Waterguard (Chlorine-based liquid) and PUR (flocculent/disinfection powder) for two months and found 39%, 51%, and 33% of treated samples had <1 CFU /100mL of *E. coli*, respectively. Among households using the SCT a higher percentage of treated-samples (57%) had < 1 CFU/100mL of *E. coli* after 5 weeks.

Long-term performances of CWF and CWF+SCT POU methods were comparable to previous long-term CWF intervention studies [15,21,23,25]. Households using only the SCT method observed a decline in microbial disinfection compared to CWFs. However SCT long-term performance was consistent with other POU methods, such as chlorination. In a blinded, randomized control trial evaluating sodium dichloroisocyanurate (NaDCC) tablets, 37% of treated samples had < 1CFU/100mL of *E. coli*, [10] compared to the 40% of samples with < 1CFU/100mL of *E. coli* among SCT households seen in this study.

The CWFs and CWF+SCT households performed better in comparison to SCT households over one year. Furthermore, CWFs and CWF+SCT performances were consistent and at times better in comparison to other long-term CWF studies. Clasen and Boisson [22] observed that 54% of households with working ceramic candle filters were free of TTC after 16 mos. This is consistent with the findings in this paper, where 63% CWF-treated samples had < 1 CFU/100mL of *E. coli* after 1 year. Average percent reduction of *E. coli* among CWF households declined to 60% after 52 weeks, which is lower than what has previously been seen in long-term CWF studies. Kallman et al [21] and Mellor et al [23], observed 92% and 95.7% reduction in *E. coli* among households using locally made CWFs in Guatemala after a year.

Potential inconsistencies in these results may be due to different baseline *E. coli* levels in each study. Mean baseline levels were 163 CFU/100mL [21] and 269 CFU/100mL [23] in the Guatemala, while in S. Africa 17 CFU/100mL. Also, there may have been differences in the quality of filters. Filters were produced at two different factories that may have had slightly different manufacturing methods. Also, the different factories use different types of clay and raw materials, lending to potential differences in filter performance. It has been shown that the predominate clay mineral for Guatemalan CWFs was illite, and smectite for the S. African CWFs [26,27]. The differences in clay mineralogy may contribute to variations in the durability of CWFs. Over time, the structure of the S. African

CWF showed signs of deterioration. The ceramic media in S. African CWTs became more fragile and clay residue was observed in the effluent. As a result, turbidity was higher in effluent samples (Figure 3.18) and the shape of the CWF had slightly altered, loosening its fit in the lower reservoir and making the treated-water more prone to contamination. CWFs produced in Guatemala may have been sturdier, due to the properties of the clay, and thus maintaining high performances.

The CWF+SCT performed the best out of all the POU methods. All CWF+SCT-treated samples were free of *E. coli* after 1 year, and average percent reduction in *E. coli* was 100%. This is higher than what was observed among households using CWFs, suggesting that the secondary treatment by the SCT improved the microbiological performance of CWFs. The only other study to our knowledge that has evaluated a secondary POU method with CWFs is a study by Mellor et al [23] where a silver-impregnated ceramic torus was placed in the lower reservoirs of ceramic water filters in households in Guatemala. The ceramic torus was developed by PFP and produced exactly the same way as PFP CWFs. It was designed to release silver into solution to provide continual disinfection. After one year, no significant difference was observed in microbial disinfection or silver release between CWFs with (96.9%) or without the PFP ceramic torus (95.7%). In results presented in this paper, a difference in *E. coli* reduction was observed at week 52 between control and intervention groups. The difference in performance could be because only a small fraction (~10%) of the silver embedded in the SCT was embedded in the torus ceramic, therefore the torus ceramic POU was not an effective POU method compared to the SCT. The SCT was evaluated as a primary POU method in addition to a secondary POU method in this study, and it was shown that the SCT does disinfect waterborne pathogens through the release of silver (Figure 3.11) among water storage containers and reduce recontamination of stored water (Figure 3.10). To our knowledge, studies to this extent have not been conducted on the PFP ceramic torus.

Neither study observed differences in average residual silver concentrations after 52 weeks. However, this may not have been reflective of microbial disinfection efficiency. For the PFP ceramic torus, it is not evident if silver release was in sufficient quantities or in the right form of silver to provide microbial disinfection [23]. For CWT+SCT households, silver release among the control and intervention group were a combination of silver washing of the CWF and silver being released by the SCT. One potential explanation for this discrepancy in microbial disinfection and silver release data in this study may be that differences in silver concentrations are more representative of silver washing off the filters than silver being released by the SCT. Figure 3.9 demonstrates that average residual silver concentrations in CWF-treated samples ranged from 46.4 μg/L to 6.94 μg/L, while for SCT-treated samples total silver concentrations ranged from 2.93 μg/L to 1.39 μg/L (Figure 3.16). The variation in silver washing-off the CWF was greater than the variation in the silver being released from SCTs. Thus the variation in total residual silver concentrations may be more representative of different amounts of silver leaching off the filters than representative of additional silver being released into solution due to the presence of SCTs.

Also it is important to note that silver released from the CWFs and PFP ceramic torus is most likely in the metallic form, since colloidal silver was used in their production. Majority of the silver released from SCT has been shown to be in the ionic form [27]. Furthermore, previous studies have demonstrated that ionic silver is a stronger disinfecting agent than colloidal silver [28]. Therefore the CWF+SCT and CWF-treated samples may have had different ratios of ionic to metallic silver in solution, which may impact microbial disinfection efficiency. If so, then differences would not been observed in total silver concentration, but reflected in microbial disinfection. This provides another explanation as to why the PFP ceramic torus may not have been effective. If any silver is being released from the ceramic torus, it is most likely in the metallic form and therefore less effective as a microbial disinfectant compared to the ionic silver released from the SCT. Of course, silver levels among SCT-treated samples are very low therefore further testing needs to be done to validate this hypothesis, but observations from this study suggest the SCT provided continual disinfection through the release of ionic silver, which was effective in improving CWF performance at week 52.

Overall, this study provides support for both the short-term and long-term effectiveness of three ceramic-based POU methods. It provides a non-biased evaluation of a novel POU method, SCT. Results suggest this novel POU method is effective in improving water quality. Performance of the SCT among households using it as their primary POU method demonstrates that the SCT is just as effective in improving water quality compared to other low-cost, portable methods such as chlorine and flocculent/disinfecting powders. Survey data suggestions that the SCT is also socially acceptable in comparison to other low-cost, single-use methods due to their reusability, ease of use and ability retain the natural taste and odor of water. At high enough silver release rates, the SCT is comparable to CWF systems, as seen at week 2 in Figures 3.15 and 3.16. Long-term performance is best achieved with CWF systems, and the SCT is effective in reducing recontamination of CWF-treated water when used as a secondary POU method. This is in particularly important, as the SCT can potentially provide continual disinfection for any primary POU method when used as a secondary POU method.

3.4.2 Challenges with mass production and silver-nanopatch formation

During this field study, there were a few limitations. One major limitation was the silver release rates of ceramic tablets at lower than expected levels. In laboratory experiments, the SCT was shown to release 26 μg/L after 24 hours in 10 L of PB solution (Figure 2.27). The same silver concentrations were expected among

SCT-treated field samples, however silver concentrations were much lower, ranging from 2.93 μg/L to 1.39 μg/L. To determine if the low silver levels were due to the performance of the SCT or due to user compliance, SCTs were collected from homes visited at week 37 and tested for silver release in a controlled laboratory setting. Silver levels were higher in samples collected in the laboratory compared to the field, however overall mean silver levels were lower than what was previously observed in the lab. One potential explanation of the different silver levels between field and lab samples may be due to treatment times of SCTs in households prior to collection. In the laboratory, water was treated for exactly 24 h with the SCT. In the field, participants were instructed to always keep the ceramic tablet in their storage containers and allow at least 8 h for treatment of fresh water. These treatment times were not monitored directly in the field therefore lower silver concentrations in the field may be reflective of different exposure times of the SCT.

The overall average silver concentrations among laboratory samples were lower than what had previously been observed. Explanation of these results may be correlated to challenges faced when transitioning from small-scale to large-scale mass production of ceramic tablets. Prior to the field study, ceramic tablets had been made in batches of 2-3 at a time. Manufacturing settings were optimal for low production volumes and had never been tested for large-scale production. Production volumes for SCTs increased, in preparation for the field study without optimization of manufacturing processes. During fall of 2013, numerous evaluations of manufacturing processes were conducted to troubleshoot for the low silver release of the ceramic tablets. It is believed the low silver release observed among SCTs is due to a combination of factors, but ultimately the consequence of these factors altered the process of silver-nanopatch formation.

Potential factors that may have caused this change include, changes in the chemical composition of clay or sawdust. For larger-scale production, new supplies were ordered in bulk. There may have been unaccountable variation between supply orders. Clay was from Resco Products, Inc., which mines the clay from a natural clay deposit. The company performs quality assurance testing every two years, for particle-size distributions and particular mineral content to ensure consistency between batches. However, since the reducing agent of the silver nanopatch formation is unknown, slight changes in clay mineralogy may have impacted silver formation. As shown in Chapter 2, different clay mineralogies do impact silver release.

The type, pre-treatment and particle size distribution of sawdust may have also changed and impacted silver formation. Sawdust was collected from a lumber mill in Virginia. The supplier does not document the type of sawdust. Thus, if the chemical reactions governing silver nanopatch formation are related to properties of the sawdust, then this may have changed and impacted silver nanoptach formation.

Additionally, the sawdust was processed alongside other types of sawdust at the lumber mill. Sawdust particle size distribution varies from batch to batch. For SCT manufacturing, any sawdust that passed through a 20-mesh sieve (0.841 mm) is used. However, there has been limited research on what the specific particle size distribution of sawdust passed through the 20-mesh sieve needs to be for optimal silver release. Until now, laboratory data has only demonstrated that SCTs made with sawdust particles finer than 0.595 mm in diameter do not release silver. Therefore, it is possible that the sawdust that has passed through the 20-mesh sieve has changed in particle size distribution and the ratio of finer to coarser sawdust particles has increased. This would impact the interconnectivity of pores, pore diameters and total available porous space of the ceramic media, impacting ion diffusion paths.

Finally, there are manufacturing processes such as heterogeneous mixing and firing batch-size that could have impacted silver-nanopatch formation. Non-homogenous mixing of the clay, sawdust and silver solution could have impacted distribution of silver throughout the media. Uneven distribution of silver would concentrate silver ions at specific regions in the ceramic media and thus increase nanopatch diameters, reducing available surface area for silver release. Also, the geographic locations of the silver nanopatches may be altered as well. It is expected that silver nanopatches closest to the surface are releasing majority of the silver from the media. Thus, non-homogenous mixing may cause majority of silver nanopatches to form towards the center rather than exterior surface or edge, increasing diffusion length and tortuosity of the silver ion's diffusion path.

Firing batch-size also may impact silver release because it would impact the distribution of heat throughout the ceramic media. Among large batch firings (50-100 tablets) it was found that regions of the ceramic media had not been fired completely, demonstrated by discoloration. High temperatures are required for the formation of silver nanopatches and combustion of sawdust. Thus if the heat is not evenly distributed then the silver nanopatches, pores and pore channels are not forming properly, which would hinder the diffusion of silver ions through the ceramic media.

Further research needs to be done to better understand the fundamental chemical processes that are regulating the organic formation of the silver nanopatches. Additionally, material composition and manufacturing processes need to be developed to attain the optimal conditions for organic formation of silver nanopatches and creating a porous structure for diffusion of silver ions into solution at levels effective for improving drinking water quality.

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Chapter 4

Investigation of Disinfection Efficiency Against Various High-risk Waterborne Pathogens

This chapter is being prepared for publication.

Ehdaie B, Su Y-H, Swami NS, Smith JA. Disinfection of protozoa and viruses by novel porous ceramic tablets embedded with silver and copper nanopatches for point-of-use water purification. 2015, In preparation.

4.1 Introduction

Each year 3.4 million deaths are due to preventable waterborne illnesses, and thus access to safe drinking water is a critical component in reducing the prevalence of these illnesses[1,2]. Point-of-use water treatment (POU) interventions have shown promise in improving drinking water quality through their ability to eradicate coliform bacteria and *E. coli*[2,3]. However, their impact on human health is limited by the prevalence of other harmful waterborne pathogens, such as protozoa and viruses. These waterborne pathogens are often times unaffected by common POU methods, such as filtration and chlorination[4-7]. Previous studies have shown silver to be a promising disinfecting agent in this regard, however research has been very limited, especially in the context of POU applications[5,8]. In this chapter, silver disinfection against protozoa and viruses is investigated in the context of POU applications by directly testing the disinfection efficiency of the silver-embedded ceramic tablet against such waterborne pathogens.

Protozoa are single-celled microorganisms that infect the mammalian gastrointestinal system through sporozoites[9,10] and cause illnesses such as Cryptosporidiosis[10,11]. Cryptosporidiosis is one of the most problematic waterborne illnesses worldwide, as it is estimated to account for 50% of parasite attributed waterborne diseases[12]. When dormant, protozoa are in the form of oocysts, which are 4-7 μm in diameter and encapsulate four sporozoites[4,9,13]. The oocyst has a very thick wall and releases sporozoites under conditions favorable for sporozoite infectivity[10,14], such as in mammalian gastrointestinal systems. Otherwise the sporozoites will remain in the oocyst, being protected from harsh environmental conditions[10,13-15]. As a result, oocysts such as those of *Cryptosporidium parvum (C. parvum)* can evade disinfection by chlorination[4,10,14,16]. *C. parvum*, one of the infecting agents causing Cryptosporidiosis, is problematic because it requires a low infectious dose (<10 oocysts) and is commonly found in surface water, a common source for drinking water for those living in developing communities[6,13,15,17]. Some of the most effective POU methods for disinfection of oocysts are UV-disinfection[18,19] and microfiltration systems[20-22], however these methods are fairly expensive for those in developing communities[23-26].

Viruses are another class of waterborne pathogens that cause many waterborne illnesses[8,27]. They range in size from 20 to 100 nm, making them too small for most filtration systems[28]. Chlorine disinfection can be effective, but requires high free chlorine concentrations with long contact times[8]. These treatment conditions are often times not suitable for POU technologies or safe for human consumption. As a result, current POU methods, such as filtration and chemical disinfection, are not as effective against viruses as they are against bacteria.

A promising alternative could be silver-based POU methods, however there is both limited research and methods to demonstrate its efficacy on both protozoa and viruses[5,27]. Effect of silver disinfection on *C. parvum* oocysts is very challenging to study because sporozoite release is only possible in a mammalian gastrointestinal system or closely simulated systems. Only recently has it been shown that silver-treated water reduces infectivity of protozoa, *C. parvum* oocysts[5]. Su et al[5] recently collected data to this effect using a murine (mouse) model and found almost a two-order of magnitude reduction in oocyst shedding for the silver-nanoparticle-treated oocysts relative to the untreated oocysts. In this study, excystation also decreased in response to silver nanoparticle treatment, but they used silver concentrations a hundred times greater than the recommended drinking water standard. Prior to this no published studies have attempted to quantify the antimicrobial effects of silver nanoparticles or ionic silver for *C. parvum*. Although, no data currently exists for the ceramic tablet's disinfection of *C. parvum*, these recently published findings suggest that silver can reduce *C. parvum* infectivity. Therefore, the question remains whether lower silver concentrations that are safe for human consumption would be effective in the disinfection of *C. parvum* oocysts.

In the context of virus disinfection, silver has been shown to disinfect viruses in the forms of silver nanoparticles[27,29-31] and biogenic silver (bio-Ag^0) [32,33]. Studies have shown that silver nanoparticles are effective however disinfection efficiency varies depending on capping agent and nanoparticle size[29,34]. Silver nanoparticles are shown to be most effective in the range of 1-10 nm diameter[29], but this is difficult to achieve since silver nanoparticles have a tendency to agglomerate within this range[35]. Also silver nanoparticles are fairly expensive and not locally accessible, thus not very sustainable for POU applications.

The other alternative is bio-Ag^0, which is the organic reduction of Ag^+ to Ag^0 through natural chemical reactions that occur on the surface of *Lactobacillus fermentum*[33,36]. This method is advantageous, because very small sizes of Ag^0 can be produced and distributed on the bacterial carrier matrix without any agglomeration[32]. However, highly concentrated bio-Ag^0 matrixes are required for virus disinfection, resulting in residual silver concentrations that surpass the drinking water standard. Also, there are challenges of sustainability and reusability with current applications of bio-Ag^0. Studies have shown that a significant portion of the silver is washed out of the matrix within the first 100 L of treated water[32,33].

In this paper we evaluate the ability of a low-cost silver-embedded ceramic POU water purification tablet to disinfect protozoan (*C. parvum)* and a virus (MS2 bacteriophage). As previous studies have shown, it is effective against bacteria and safe for consumption[37]. However, to be truly effective in improving human health, its disinfection capabilities against various pathogens must also be investigated. The data presented in this chapter also contributes to further understanding of silver disinfection kinetics and mechanisms against protozoa and viruses, which until now has been limited.

4.2 Experimental Methods

4.2.1 Ceramic tablet fabrication

Redart clay (56.25 g) and sawdust (6.25 g), sieved through a 0.841 mm-screen (20 mesh), were mixed together with 19.2 mL of a silver nitrate solution (81.8 g/L). The mixture was molded into a cylindrical shape (65 mm diameter x 15 mm width), and pressed for 1 minute at 6,895 kPa using a hydraulic manual press. The ceramic was portioned into eight equally sized pieces using a cutting knife to form eight miniature ceramic tablets. After air-drying for 72 h, tablets were fired in an electric kiln (Evenflow) at 150˚C /h until 600˚C and then at 300˚C /h until 900˚C and held for 3 h. Miniature ceramic tablets were used for these experiments to correspond to the smaller volume used in the batch reactions. Control ceramic tablets were prepared using the exact same methods, however the silver nitrate solution was replaced with19.2 mL of deionized water.

4.2.2 Preparation of C. parvum

Infectious *C. parvum* oocysts were obtained from Waterborne, Inc. and stored at 4 ˚C in phosphate-buffered saline water. All *C. parvum* experiments were conducted within one month to avoid significant de-activation over time.

4.2.3 Protozoa batch reaction experiment

In a 50-mL conical tube, *C. parvum* oocysts from stock solution were vortexed and added to 25 mL of distilled water for a final concentration of 2×10^6 oocysts / mL. A ceramic tablet was placed in each tube and samples were taken after 24 h. Samples were analyzed for excystation and total residual silver concentration. Silver concentrations were measured using the GFAA, as described in section 2.2.6. Each experiment was performed in duplicate. The negative control consisted of 25 mL of deionized water with a known amount of oocysts, and a ceramic tablet without any silver. A control consisting of 25 mL of distilled water with a known amount of *C. parvum* oocysts, without a ceramic tablet, was also used to account for any effects the porous ceramic media may have on oocyst viability. The positive control consisted of 25 mL of deionized water with a known amount of oocysts that were heat-treated. Heat-treated samples were incubated in a hot water bath (100˚C) for 15 min.

4.2.4 Excystation of C. parvum oocysts

After 24-h incubation, each sample was centrifuged at 1,100 g for 5 min. The supernatant was discarded, and the pellet was resuspended in distilled water and stored at 4˚C. In a 1-mL eppendorf tube, 16 μL of the sample was mixed with 4 μL of 0.525% NaOCl stock for a final NaOCl concentration of 0.052%. The NaOCl-treated samples were incubated for 30 min at room temperature, during which samples were vortexed every 10 min. Samples were transferred to a cover slide and covered with a second cover slide. Cover slides were kept at room temperature for 1 h. Two cover slides were prepared for each sample. Cover slides were examined using an inverted microscope with 40x and 10x objective lens. Phase contrast images were taken with a Hammatsu Orca Flash4 camera to visually quantify excysting and non-excysting oocysts.

4.2.5 DAPI and PI labeling

Stock solutions of propidium iodide (PI) and 6-diamidino-2-phenylindole (DAPI) dye were purchased from Sigma Aldrich and stored and at -20˚C. Fresh DAPI and PI working stocks were prepared with distilled water for final concentrations of 10 μg/mL and 2 μg/mL, respectively. DAPI working stock was added to oocyst samples for a final DAPI concentration of 1μg/mL. The sample was stored at room temperature for 45 min with minimal exposure to light and vortexed every 15 min. PI working stock was added to the DAPI-oocyst sample for a final PI concentration of 0.2 μg/mL. The sample was stored at room temperature for 5 min in the dark. Samples were transferred to a coverslip and covered with another coverslip. The samples were imaged using a Zeiss Observer Z1 microscope with 40x and 10x objective lens and a Hammatsu Orca Flash4 camera. Four images were taken of each observed area: a phase contrast image, Differential Interference Contrast (DIC) image, a fluorescence image using a 358/470nm filter for DAPI and another fluorescence image using a 536/617 nm filter for PI. Transmitted light was used to take the phase contrast and DIC images. Reflected light was used to take the fluorescence images. The experiment was run in duplicate for each condition, and two coverslips were prepared per sample with 10 to 20 areas observed per coverslip. Images were analyzed using Image J software.

4.2.6 Materials for virus disinfection experiments

Tryptic soy broth (TSB) was purchased from BD scientific and prepared by dissolving 30 mg of TSB with 1 L of distilled water. The solution was heated until the TSB was completely dissolved. The dissolved solution was autoclaved for 25 min at 121˚C. Tryptic soy agar 1.5% (TSA) was purchased from BD scientific and prepared by dissolving 40 mg of TSA with 1 L of distilled water. The solution was brought to boil to ensure the TSA was completely dissolved and then autoclaved for 25 min at 121˚C.

TSA solutions were cooled to 50-60˚C then poured into agar plates. Agar plates were allowed to cool and solidify at room temperature (25˚C). Top agar 0.5% was prepared by diluting TSA working stock with TSB in a 50-mL conical tube. Phosphate buffer was prepared as described in 2.2.1 and used in batch reactions to preserve viability of MS2 bacteriophage prior to any treatment.

4.2.7 Culturing E. coli and MS2 bacteriophage

E. coli C300 was purchased from ATCC and used in propagation and plaque counting of MS2 bacteriophage. *E. coli* stock was cultured by resuspending dehydrated pellet in 1mL of TSB. In a 250-mL flask, 100 μL of *E. coli* stock was transferred to 25 mL of TSB and kept in a shaking incubator at 37˚C overnight. Solid bacteria culture was prepared in addition to liquid culture by inoculating a TSA plate with 10 μL of *E. coli* liquid culture and incubating the plate at 37˚C overnight. The overnight solid culture was stored at 4˚C and used within 5 d, after which fresh bacteria cultures were prepared. Solid cultures were used to prepare log-phase *E. coli*. Log-phase *E. coli* was prepared by inoculating 10mL of TSB with *E. coli* C300 from solid culture and incubating in a shaking incubator for a few hours at 37 ˚C until an OD_{600} reading between 0.4-0.8 was achieved.

MS2 bacteriophage was used as the surrogate to waterborne viruses in these experiments. It was purchased from ATCC and resuspended in 1 mL of TSB and stored at 4˚C. MS2 bacteriophage is similar in size (25 nm), shape (round), and type of nucleic acids (RNA) to waterborne viral pathogens such as rotavirus, enterovirus, and norovirus, and often times used as surrogate in laboratory research[38].

4.2.8 Virus batch reaction experiment

In a 50-mL conical tube, 25 mL of 10mM PB solution was inoculated with MS2 bacteriophage for a final concentration of 10^6 pfu/mL. A ceramic tablet was placed in each tube and kept at room temperature. Samples were taken at 8 h and 24 h, and analyzed for silver levels and virus disinfection. Silver concentrations were measured using the GFAA, as described in section 2.2.6. Each experiment was performed in duplicate. The control consisted of 25 mL of 10mM PB with 10^6 pfu/mL MS2 bacteriophage. The negative control consisted of a ceramic tablet without any silver placed in 25 mL of 10mM PB with 10^6 pfu/mL MS2 bacteriophage.

4.2.9 Virus quantification

Quantification of MS2 bacteriophage was performed by standard plaque counting methods. Samples for each time point were treated with 60 g/L sodium thiosulfate (26.4 μL per 1 mL of sample) for 2 min at room temperature to inhibit continual disinfection. Preliminary experiments were run to ensure sodium thiosulfate treatment of phage did not impact virus viability, see Figure 4.1. Samples were then incubated with log-phase *E. coli* (200 μL of *E. coli* per 10 μL of phage sample) for 4 min at room temperature. The phage-bacteria culture was added to 3 mL of melted 0.5% TSA top agar and immediately poured onto 1.5% TSA agar plate. The top agar was allowed to solidify at room temperature. Plates were incubated inverted at 37 ˚C overnight. During the overnight incubation, viable viruses infected *E. coli* and lysed forming visible clear plaques over the bacteria lawn. Next day, clear plaques were counted to determine the number of viable viruses in solution [39-41].

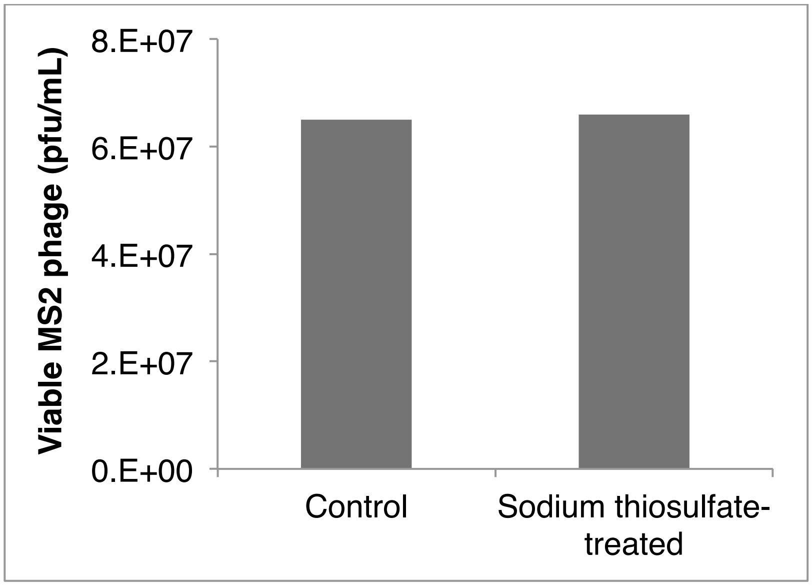

Figure 4.1. *Preliminary experiment testing effects of sodium thiosulfate on MS2 phage viability. Samples were prepared with 10mM PB and 10^6 pfu/mL. The thiosulfate sample was incubated with 60g/L of $Na_2S_2O_3$ neutralizer (26.4 uL/mL of sample) for 2 minutes at room temperature.*

4.3 Results

4.3.1 Protozoa disinfection by silver embedded ceramic tablet

Figure 4.2 shows phase contrast images of excysting and non-excysting oocysts from samples treated with three types of ceramic tablets: a control without any silver (Figure 4.2A), a 50 mg (Figure 4.2B) and a 500 mg silver-embedded ceramic tablet (Figure 4.2C). Excystation was quantified in each sample by visually counting the number of non-excysting and excysting oocysts.

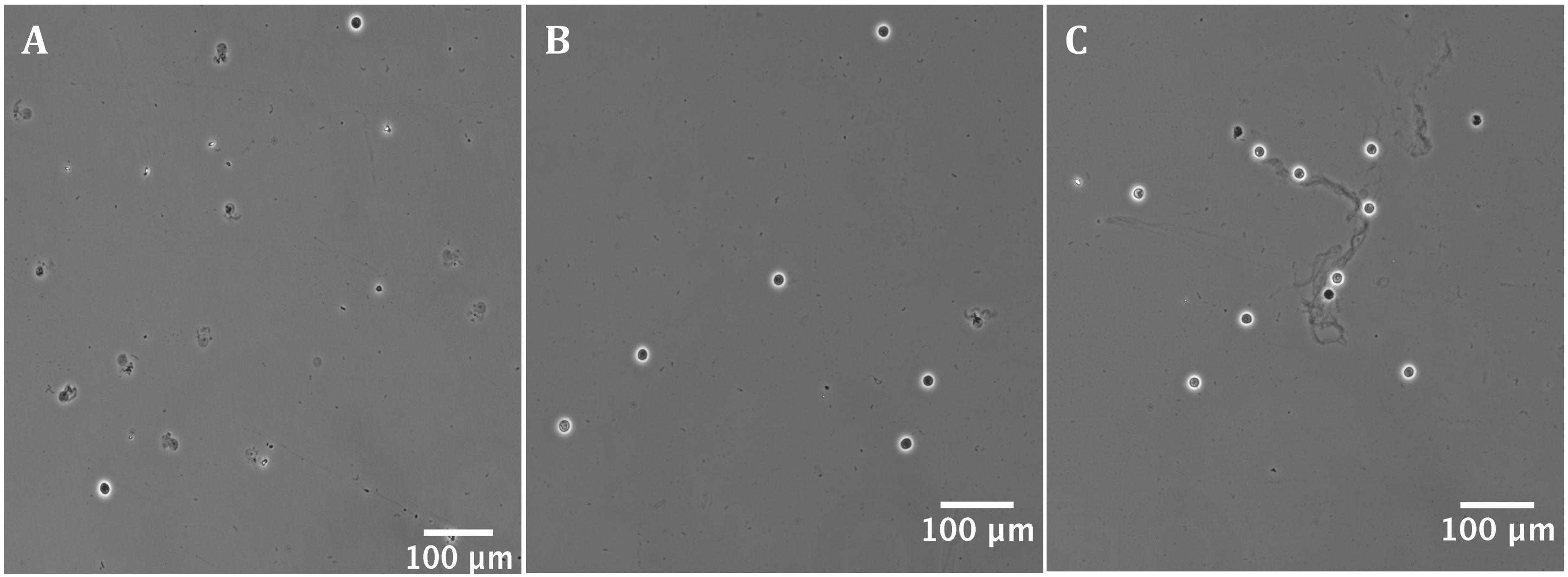

Figure 4.2. *Phase contrast images of ceramic tablet-treated C. parvum oocysts undergoing in vitro excystation. Samples had been treated for 24 h with (A) a control ceramic tablet, (B) 50 mg silver-embedded ceramic tablet or (C) 500 mg silver-embedded ceramic tablet.*

Percent excystation was calculated by dividing the total number of excysting oocysts by the total number of oocysts (sum of excysting and non-excysting) in each sample. Figure 4.3 displays average percent excystation of *C. parvum* oocysts for each condition. Control tablets had an average oocyst excystation of 74%. Ceramic tablets embedded with 50 and 500 mg of silver had average excystations of 35% and 14%, respectively. Total residual silver concentrations were 0, 21.3 and 85.7 μg/L for samples treated with ceramic tablets made with 0, 50 and 500 mg of silver, respectively (Figure 4.4). Heat-treated oocysts did not excyst at all.

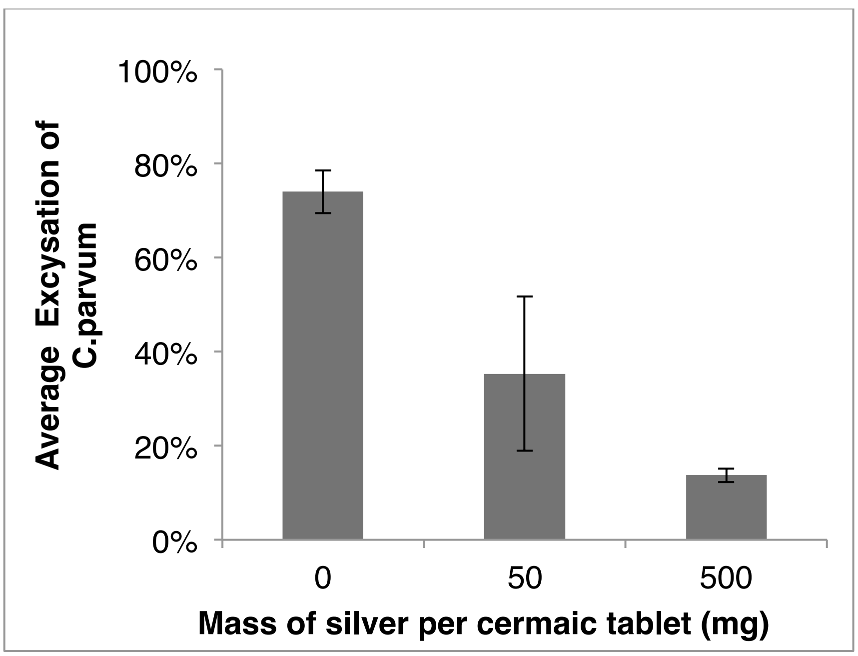

Figure 4.3. *Average percent excystation of C. parvum oocysts after 24h treatment with ceramic tablets embedded with 0, 50 and 500 mg of silver. Sampled were taken after 24 h and run in duplicate. Data points represent the average per condition and standard error was used to calculate error bars.*

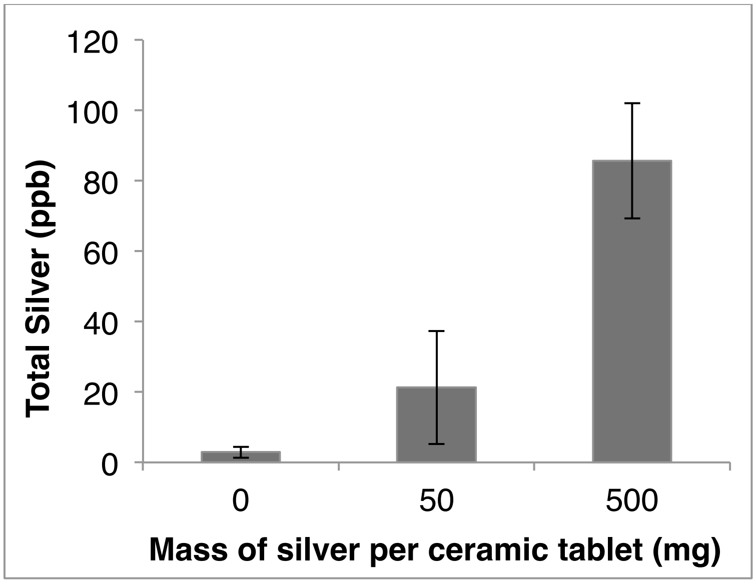

Figure 4.4. *Total silver concentrations of C. parvum oocyst-samples that were treated with ceramic tablets embedded with 0, 50 and 500 mg of silver. Samples were taken after 24 h of treatment. Each data point represents the average of duplicate samples and standard error was used to calculate error bars.*

4.3.2 DAPI and PI Labeling

Oocyst samples were stained for DAPI and PI to investigate mechanisms of disinfection. Table 4.1 shows the percent of oocysts per condition where DAPI and PI labeling were present. DAPI and PI labeling were present among all of heat-treated oocysts. Only 63% and 22% of oocysts treated with control ceramic tablets showed presence of DAPI and PI labeling, respectively. Samples treated with silver-embedded ceramic tablets had DAPI and PI labeling present among 52% of oocysts.

Table 4.1. Percent of C. parvum oocysts labeled positive for DAPI and PI

Treatment	Median %	
	DAPI +	PI +
Heat Treated	100%	100%
Control Ceramic Tablet	63%	17%
500 mg Ag Ceramic Tablet	52%	52%

Figure 4.5 shows phase contrast, DIC, DAPI and PI images of heat-treated oocysts demonstrating oocyst wall has been damaged. Figure 4.6 shows images of oocysts treated with control ceramic tablets. Phase contrast (Figure 4.6A) and DIC (Figure 4.6B) images suggest oocyst walls and sporozoites remain intact after treatment. DAPI labeling was present among these oocysts (Figure 4.6C), while PI labeling was absent (Figure 4.6D).

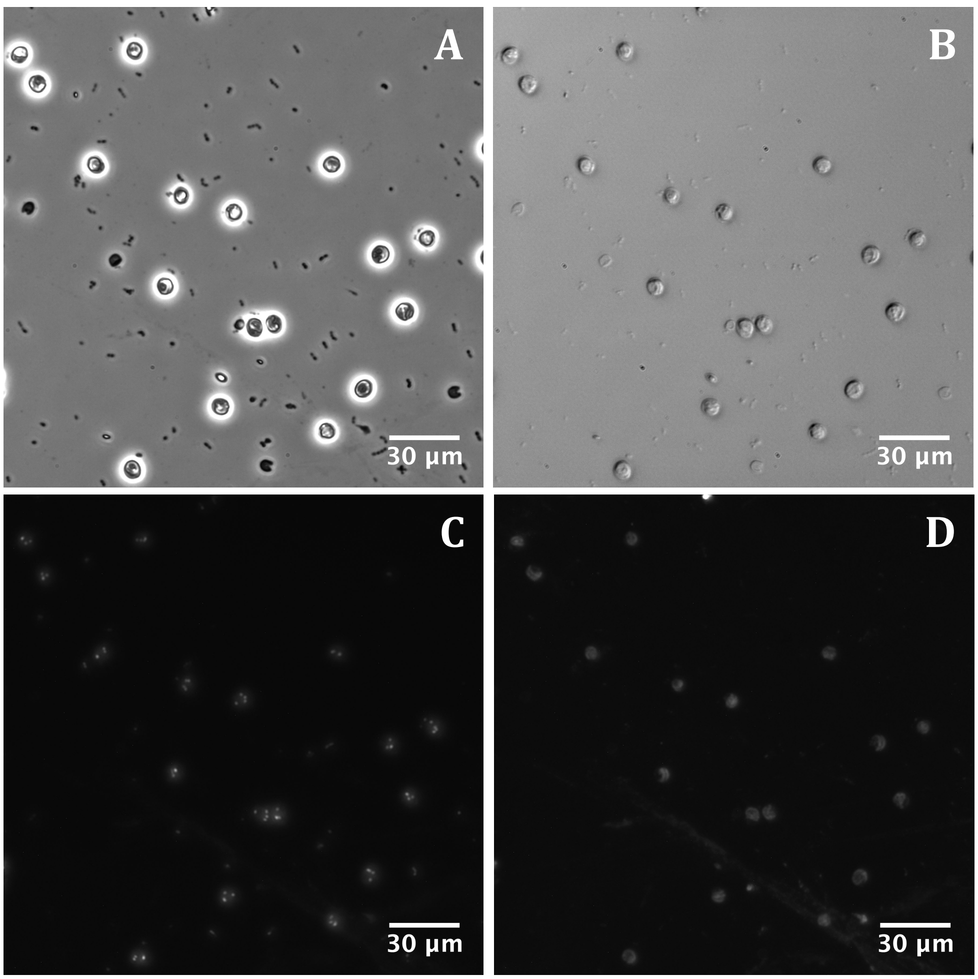

Figure 4.5. *Images of heat-treated C. parvum oocysts. Oocysts were treated for 15 min in hot water bath and labeled for DAPI and PI. Phase contrast (A), DIC (B), DAPI (C) and PI (D) images were taken of the same field of view.*

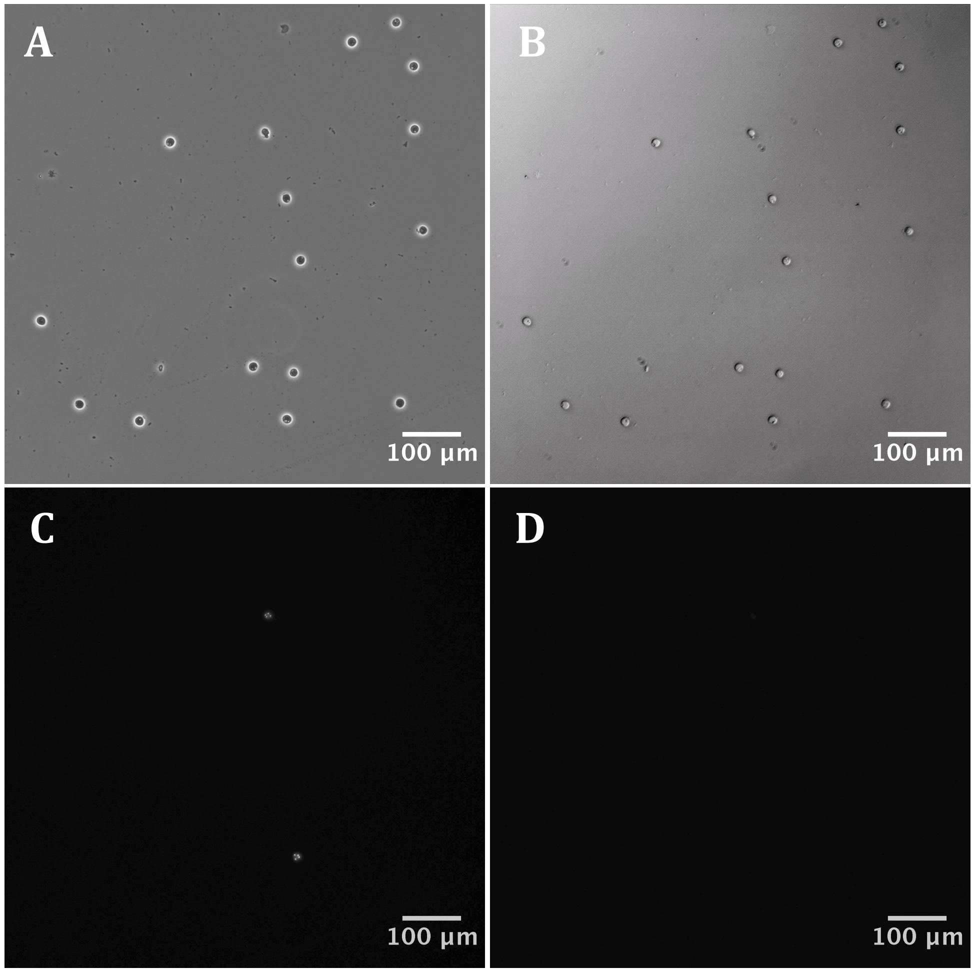

Figure 4.6. *Images of C. parvum oocysts treated with control ceramic tablets. Oocysts were labeled with DAPI and PI dye. Four images were taken of the same field of view, phase contrast (A), DIC (B), DAPI (C) and PI (D).*

Oocysts treated with silver-embedded ceramic tablets were heterogeneous for DAPI and PI labeling as seen in Figures 4.7 and 4.8. Figure 4.7 shows phase contrast, DIC, DAPI and PI images of silver-embedded ceramic tablet-treated oocysts from two samples. DAPI and PI labeling are present in one sample (Figures. 4.7C and 4.7D), while absent in the other sample (Figures. 4.7G and 4.7H). DIC and phase contrast images were taken as well, where in one sample, sporozoites are intact, labeled as SpV, (Figures. 4.7A and 4.7B) and in another sporozoites seem altered, labeled as SpX

(Figures. 4.7E and 4.7F). Figure 4.8 shows the heterogeneous morphology (Figures. 4.8A and 4.8B) and staining (Figures. 4.8C and 4.8D) within one sample and one field of view for oocysts treated with 500 mg silver-embedded ceramic tablets.

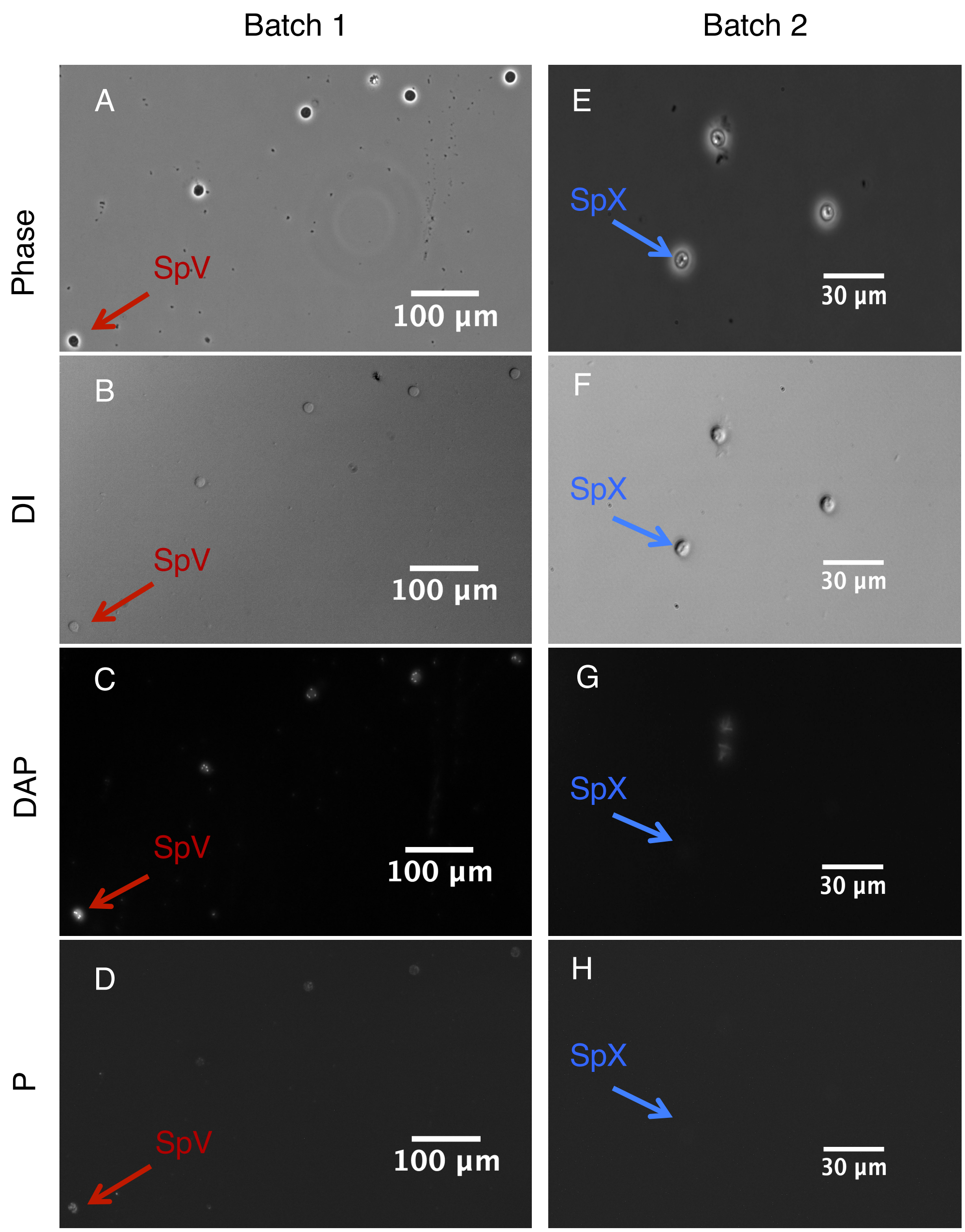

Figure 4.7. *DAPI and PI labeling of C. paruvm oocysts treated with 500mg silver-embedded ceramic tablets. Two samples were imaged for phase contrast (A and E), DIC (B and F), DAPI (C and G) and PI (D and H). Intact sporozoites are labeled SpV and sporozoites with altered morophology are labeled SpX.*

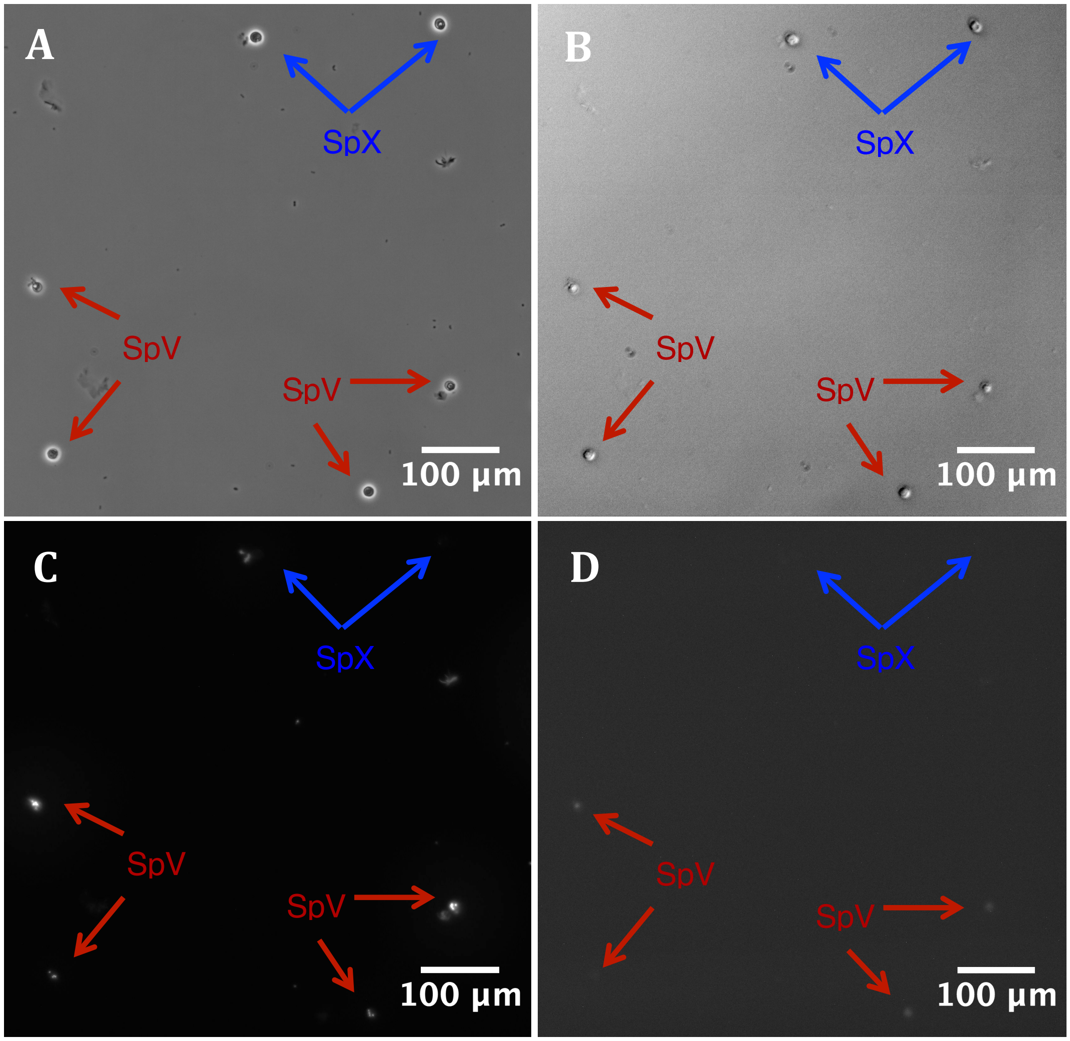

Figure 4.8. *DAPI and PI labeling of C. paruvm oocysts treated with 500mg silver-embedded ceramic tablets. Heterogenous labeling and morphology are shown in a single field of view of treated oocysts. Phase contrast (A), DIC (B), DAPI (C) and PI (D) images were taken. Sporozoites with intact structures were labeled SpV and sporozoites with altered structures were labeled SpX.*

4.3.3 Virus disinfection by silver embedded ceramic tablet

Figure 4.9 shows the disinfection efficiency of silver-embedded ceramic tablets for MS2 bacteriophage. Three types of ceramic tablets were tested, a ceramic tablet without any silver, a ceramic tablet embedded with 50 mg of silver and another embedded with 500 mg of silver. At each time point, the difference between number of viable viruses in the treated and control samples was calculated and divided by the number of viable viruses in the control to determine percent reduction. MS2 bacteriophage viability declined by 89% and 97% among samples treated with 500 mg silver-embedded ceramic tablets for 8 h and 24 h, respectively.

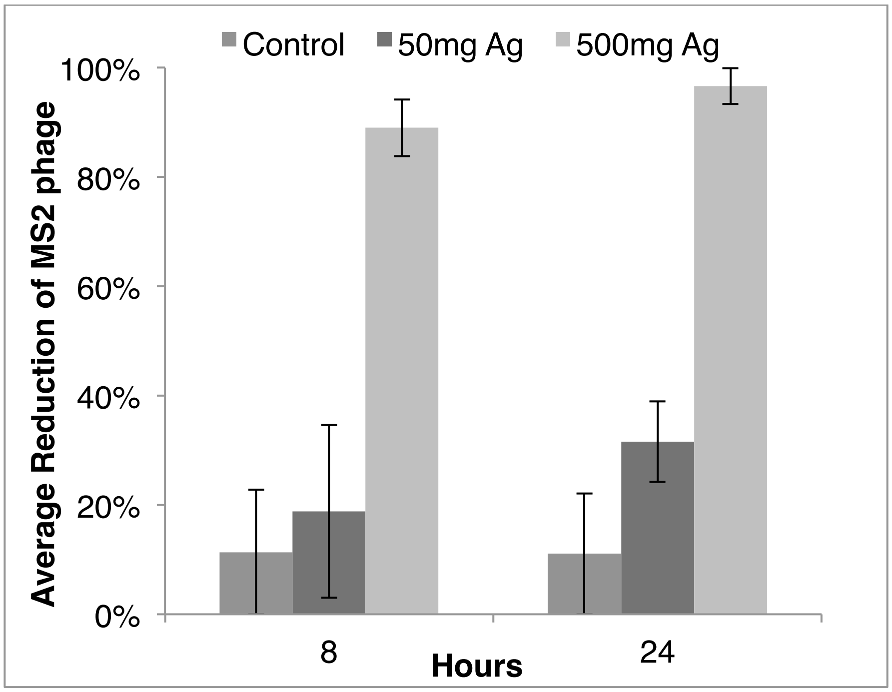

Figure 4.9. *Disinfection of MS2 bacteriophage by silver-embedded ceramic tablets. MS2 bacteriophage was treated with ceramic tablets embedded with 0, 50 and 500 mg of silver. Samples were taken at 8 h and 24 h. Data points represent average of duplicate samples. Error bars represent standard error.*

Samples treated with 50 mg silver-embedded ceramic tablets had a percent reduction of 19% and 32% after treatment for 8 h and 24 h, respectively. The negative control had a percent reduction of 11% at 8 h and 24 h. Figure 4.10 shows total silver concentrations of all samples after 24 h of treatment. Control, 50 mg and 500 mg silver-embedded ceramic tablets had silver concentrations of 0, 32.7 and 211.2 μg/L, respectively. Silver levels were also measured at 8 h for samples treated with 500 mg silver-embedded ceramic tablets and found to be 172.9±10.9 μg/L.

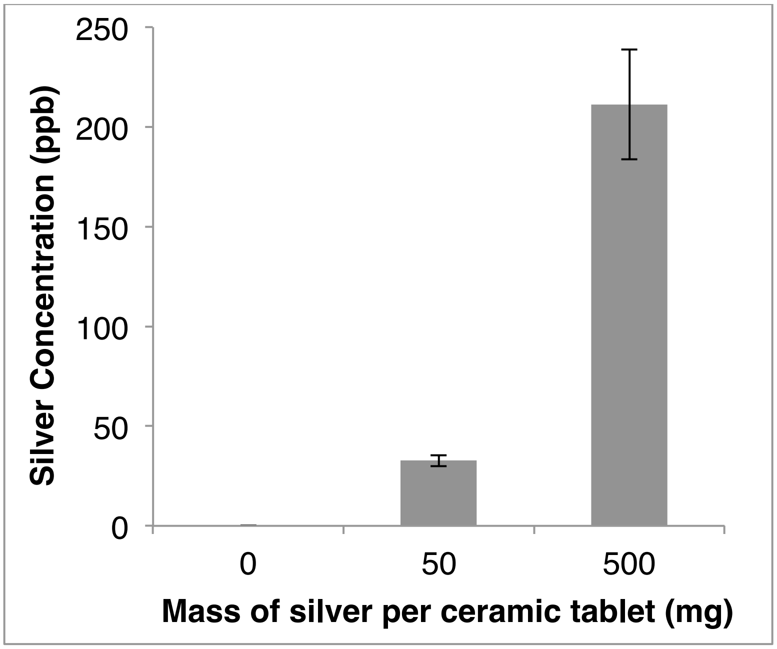

Figure 4.10. *Total silver concentrations of MS2 phage samples that were treated with ceramic tablets. Samples were treated with ceramic tablets embedded with 0, 50 and 500 mg of silver for 24 h. Samples were run in duplicate. Data points represent the average silver concentrations for each condition and error bars represent standard error.*

4.4 Discussion

In this paper we demonstrate that silver is an effective disinfecting agent against protozoa and viruses. This chapter provides further understanding of the silver disinfection mechanisms and kinetics against protozoa and viruses, and also demonstrates the ability of a low-cost POU tablet to treat harmful waterborne pathogens. Pathogens were treated with silver through a novel POU water treatment technology. This novel POU is a cylindrical-shaped porous ceramic media embedded with silver ions. Once placed in water, silver ions are released from the tablet into solution, disinfecting waterborne pathogens while maintaining silver levels below the drinking water standard.

As demonstrated through in vitro excystation experiments, silver-embedded ceramic tablets disinfected *C. parvum* oocysts by damaging the oocyst wall and inhibiting sporozoite metabolic ability (Figures. 4.3 and 4.7D). In vitro excystation experiments were conducted to recreate the high acidic environment found in the mammalian gastrointestinal system, under which oocysts release sporozoites for infection. Previous studies have demonstrated there is a strong correlation between excystation and oocyst viability and infectivity[16,42,43]. If the oocyst wall and sporozoites are intact then the oocyst is viable and sporozoites will excyst to infect the host. However, if the oocyst wall is damaged or the sporozoites are not intact, sporozoites will not excyst no longer being infective[16].

Upon treatment with the silver-embedded ceramic tablet, percent of excysting oocysts declined suggesting sporozoite metabolic ability was lost. As expected, majority of oocysts treated with the control ceramic tablets excysted (Figures 4.2 and 4.3), suggesting majority of oocysts were viable. Heat-treated oocysts did no excyst, indicating they were not viable (Figure 4.3). This data is consistent with the findings of Su et al[5], where oocysts treated with silver nanoparticles demonstrated a partial decline in excystation and infectivity. Su et al[5] evaluated infectivity through a mouse model, where mice were exposed to *C. parvum* oocyst and infectivity was measured by quantifying oocyst shedding in stool samples using RT-PCR. Su et al[5] observed a 2-log reduction in oocyst shedding and 40% excystation among oocysts treated with silver nanoparticles. In comparison, the silver-embedded ceramic tablet shows greater loss of excystability in vitro, thus suggesting it may be more effective in reducing infectivity by multiple log factors in vivo.

Figure 4.3 suggests that silver disinfection of protozoa is concentration and contact-time dependent. As shown in Figure 4.4 and studies by Ehdaie et al[37], increasing the initial mass of silver embedded in the ceramic tablet increases the release of silver into solution. With higher residual silver concentrations oocyst disinfection also increased, as observed by the decrease in excystability (Figure 4.3). In all samples, silver concentrations remained below the drinking water standard of 100 μg /L. Results suggest oocyst disinfection is feasible at lower silver concentrations (<100 μg/L), in addition to being more effective if treated with longer contact times. Su et al[5] observed a decline in excystability from 89% to 42.7% when oocysts were treated for 4 h with silver nanoparticles, while Figure 4.3 demonstrates excystability declining from 74% to 14% when oocysts are treated for 24 h with silver-embedded ceramic tablets. Residual silver concentrations were hundred times higher in studies conducted by Su et al[5] compared to those in Figure 4.3. This suggests that the concentration of disinfectant is a factor in disinfection kinetics, however contact-time may play a more significant role. Further studies need to be done to confirm this hypothesizes. However studies thus far suggest both concentration and contact time play critical roles in disinfection, and disinfection is feasible at silver concentrations safe for human consumption.

Mechanisms of silver disinfection on protozoa were also investigated through DAPI and PI labeling. DAPI is a permeable fluorescent stain that binds to nucleic acids, labeling intact sporozoites[16,43-45]. PI is an impermeable fluorescent dye that stains the cytoplasm and DNA when the cell wall is permeable or damaged[16,42,43]. As demonstrated in Figures 4.7 and 4.8, we believe there are two mechanisms by which silver disinfects protozoa. First, silver ions interfere with the oocyst wall disrupting the structure making it permeable and making oocysts non-viable. This is demonstrated in Table 4.1 and Figure 4.7. Presence of DAPI and PI labeling among 52% of the silver-treated oocysts indicate the oocyst wall has been damaged, allowing the dye to stain the cystoplasm and demonstrating oocysts are non-viable.

The second mechanism by which silver may be disinfecting protozoa is through altering the sporozoite structure. In 48% of oocysts treated with silver-embedded ceramic tablets DAPI and PI labeling were completely absent. This suggests that the oocysts wall is intact, however excystation demonstrated only 14% of oocysts treated with silver-embedded ceramic tablets were viable and infective. DAPI/PI results are inconsistent with the excystation data. One possible explanation for this may be that silver altered the sporozoite structure without damaging the oocyst wall. As a result oocyst excystability is lost, while DAPI and PI labeling are absent. Su et al[5] were first to observe this phenomenon. They observed DAPI and PI labeling (DAPI+/PI+) in some silver nanoparticle-treated oocysts, while among others DAPI and PI labeling was absent (DAPI-/PI-). Phase contrast and DIC images suggested that sporozoite structures had been altered among DAPI-/P- oocysts, while they were intact among DAPI+/PI+ oocysts and oocysts from control samples. Therefore, silver may be altering sporozite structures causing inhibition of sporozoite metabolic ability to excyst.

We found similar results when examining the phase contrast and DIC images of oocysts treated with silver-embedded ceramic tablets. In Figures 4.7 and 4.8, altered sporozoite structures (SpX) seem to be associated with DAPI-/PI- labeling and intact sporozoite structures (SpV) were associated with DAPI+/PI+ labeling. The changes in morphology are subtle, thus further research is required with higher resolution microscopy techniques to confirm the consistency of these findings.

These results lend support to silver as an effective disinfecting agent for protozoa. This is extremely valuable because protozoa are resistant to common disinfectant agents[14,16], including chlorination. Silver may be one of the few chemical disinfectants that are effective, thus making it an important disinfectant to consider in future POU designs. It also suggests there are multiple mechanisms that silver is deactivating oocysts: (1) through traditional means of damaging the oocyst wall and (2) by altering the sporozoite structure inhibiting sporozoite metabolic activity.

Figure 4.9 demonstrates that the silver-embedded ceramic tablet is also effective against disinfection of viruses, specifically MS2 bacteriophage. The disinfection seems to be concentration dependent as seen in Figures 4.9 and 4.10. Contact-time does not seem to be an influential factor, because percent viability of viruses does not change between 8 h and 24 h time points. Previous studies have demonstrated that silver ions bind with thiol groups and disrupt surface proteins of viruses, and thus inhibiting their ability to infect their host[34,46,47]. Disinfection efficiency of silver on viruses has been shown to relate to the particle size of silver nanoparticles, where larger particle silver particles do not bind as well to proteins and thus not as effective[29]. Even though some POU methods have used silver in the form of silver nanoparticles for virus disinfection, overall application of silver nanoparticles is challenging due to agglomeration, size dependence and cost. The other alternative is biogenic Ag^0, which has been shown to be effective in disinfection. However, it faces challenges of high residual silver concentrations and significant wash-out within the couple of uses, which does not make it sustainable for POU applications.

The silver-embedded ceramic tablet described in this chapter is effective in reducing virus viability by 89%. Even though, these disinfection results are not as effective as bio-Ag^0 approaches, this mechanism of silver delivery is reusable for up to 6 months and silver levels are only slightly above the drinking water standard[37]. With additional optimization to maintain silver levels below the drinking water standard, this novel POU method could be applied with other existing methods to improve virus disinfection and promote continual disinfection. Previous studies have used silver in conjunction with existing POU methods, such as UV- disinfection[48], nanoparticle embedded fiberglass[49] and filtration[20,21], to further enhance disinfection capabilities. This novel silver-embedded ceramic tablet would be a better alternative secondary POU technology for virus disinfection, because it is less expensive than silver nanoparticle POU technologies and more sustainable compared to bio-Ag^0 methods. However, additional experiments need to be conducted to measure disinfection efficiency at levels safe for human consumption.

Overall, the data presented in this chapter demonstrates that silver is an effective disinfecting agent against some of the most harmful waterborne pathogens. It is shown that silver disinfection kinetics vary among different pathogens. It is contact-time dependent for protozoa, while concentration-dependent for both viruses and protozoa. Finally the data presented here lends support to the silver-embedded ceramic tablet as an effective POU technology. The ceramic tablet provides a sufficient method to deliver silver ions into solution to not only improve water quality but also potentially improve human health through the purification of drinking water. Further research needs to be conducted to confirm and quantify the human health impact, however data from this chapter suggest the POU shows great potential in disinfecting waterborne bacteria, viruses and protozoa.

4.5 Acknowledgements

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Chapter 5

Market Evaluation of Silver-embedded Ceramic Tablet

5.1 Market Drivers

The main driver behind the market growth and opportunity in the global water treatment market is the lack of access to safe drinking water. Safe drinking water is defined as water that is safe for human consumption in reference to microbiological and chemical contaminants. The silver-embedded ceramic tablet will be of value to anyone who requires disinfection of pathogenic microorganisms in their drinking water at the household level. Therefore, the available market includes anyone without continuous access to safe drinking water. This includes about 1 billion people in developing world settings who lack access to an improved water supply as defined by WHO guidelines[1,2] . Furthermore, an additional 1-2 billion people use untreated water that is received from a well, protected spring, or impaired municipal water system[1] .

Access to safe drinking water is also an immediate concern in many emergency situations, including natural disasters and humanitarian crises[3] . In 2012, 144 million people were displaced by conflicts and aid organizations targeted 65 million for humanitarian assistance[4] . Emergency settings may cause water supply to be interrupted and as a result causing water quality to decline. Additional treatment of drinking water for the affected populations is necessary. Responders to emergency scenarios often look for products that are simple and easy to use, require minimal education, provide effective treatment, are easy to transport, and cost-effective.

Demographics, social and political factors are supporting drivers that also contribute the water purification market. Estimates show that 90% of the world's population growth will be in developing countries, where water quality is are already pervasive[5] . Therefore, a conservative estimate of the available market is 2-3 billion people total in need of access to safe drinking water globally[2] .

According to recent reports, the global water treatment market size was estimated to be $500 billion in 2014. In South Africa alone, where our work originates from, the estimated water treatment market is $6.1 billion [6] . With already impaired municipal water treatment infrastructure and a growing population, the market is looking at more innovative solutions, compared to traditional centralized water treatment approaches. Although important for long-term solutions, centralized water systems have not been able to address these challenges due to recontamination resulting from poor sanitation and hygiene conditions. Therefore decentralized water treatment methods are essential and shown to be more effective in improving access to safe drinking water and human health. The market is looking for solutions that allow water quality to be controlled by the consumer at the point-of-consumption or -use (POU). Of that global water treatment market, the POU water market is estimated to be $25 billion and expected to increase at a rate of 16.5% per year according to 2008 PATH reports[7] .

The largest foreseen challenge for new ventures in the global water market is entering an existing and somewhat saturated market. There are a few major corporations that control the market as a result of brand recognition and consumer acceptance. However, many potential end-users have not been reached due to affordability and challenges in distribution. This untapped group is thought to consist of 1 billion people who are considered to be at the bottom of the pyramid [6,8] . For these reasons the silver-embedded ceramic tablet has potential to be a disruptive product because it is very inexpensive compared to current competitors and is easy to distribute especially through partnerships with NGOs. In this chapter we evaluated the market demand and opportunity to launch a start-up venture based off of this novel silver-embedded ceramic tablet POU method.

5.2 Methods

5.2.1 Market evaluation

Economic sustainability of the silver-embedded ceramic tablet was evaluated based off of three factors: (1) end-user demand, (2) market demand, and (3) production costs. End-user demand was evaluated through willingness-to-pay (WTP) surveys conducted among 79 households in Chapter 3, where a binning method was used [9] . Market demand and opportunity were investigated through the National Science Foundation Innovations Corp program. During a 6-week program, over 100 interviews were conducted with stakeholders in the water purification market. Interviewees ranged from end-users of the technology (middle- and low-income end users in Limpopo Province, South Africa) to economic buyers (Oxfam, Red Cross, the International Rescue Committee, and Global Water Brigades) and key partners (Center for Disease Control and Prevention and the Small Enterprise Development Agency in South Africa, USAID, Unilever and the US Embassy's Cultural Affairs Office in South Africa). Each interview provided information about consumer needs, distribution strategies, production costs and key partners. A portion of the interviews were conducted in Limpopo Province to reflect the specific characteristics of the community, such as key partnerships with specific federal and state government agencies. Summaries of each interview are provided in Appendix C. Data collected from the interviews was applied to a business model, which was evaluated by the business teaching team on a weekly basis. The teaching team consisted of five instructors from the Georgia Tech VentureLab with expertise in start-up enterprises.

5.2.2 Evaluation financial projections

Revenue models and financial projections were developed in order to evaluate economic sustainability of the technology in a start-up business enterprise. To develop realistic projections, production and manufacturing costs of the silver-embedded ceramic tablet were evaluated through a pilot production facility in Charlottesville, Virginia with the help of Billy Duval, Matthew Smith and Anna

Smith. Unit cost of silver-embedded ceramic tablets was determined by creating large-scale production protocols (500 units per day). This information was then applied to the business model in combination with end-user and market demand data to provide insight on the economic sustainability of the ceramic tablet.

5.3 Results

Figure 5.1 displays the initial business model canvas for the silver-embedded ceramic porous media technology, where early predictions of business model strategies and target markets are shown. Business models were modified weekly based off of interview data. Figure 5.2 represents the level of interest and demand for the silver-embedded ceramic tablet between two consumer segments: persons in recreational market and persons with impaired municipal water treatment systems (IMWTS) market. Interviews were conducted among stakeholders in each consumer segment and responses were ranked with respect to the following categories: POU product specifications (lifespan, operation time, ease of use, cost), excitement for the technology and the need for it. Each interview was ranked from 1 to 3. Score of 3 represented 'high importance' and 1 representing 'little to no importance' to the stakeholder. The average ranking was calculated in each category for each consumer segment. Excitement and need for the technology were higher among the IMWTS consumer segment compared to the recreational segment.

Key Partners

Gov't Agencies

NGOs

Filter factories

Ceramists

Distribution

Key Activities

Branding

Marketing/sales

Field-testing

Identifying suppliers

EPA regulation

Key Resources

Patent/licensing rights

Production site

Materials

Research

Value Propositions

Disinfects water

Locally available

Minimal maintenance required

Reusable

High profit margin

Portable

Keeps natural taste of water

Customer Relationships

CDC/USAID support

Customer review

Channels

PureMadi.org

Gov't contracts

Retail Store

NGOs

Consumer Segments

Dept. of Defense

Disaster relief NGOs

Water & Sanitation NGOs

Rural residential well-water users

Persons living in impaired municipal water systems

Cost Structure

Employees

Licensing/branding

Marketing

Production (materials, tools,

Revenue Streams

Sub-licensing to current filter factories

Asset sales

Pricing strategy: customer segment dependent, volume dependent, negotiation

Figure 5.1. *Business model canvas prior to customer discovery*

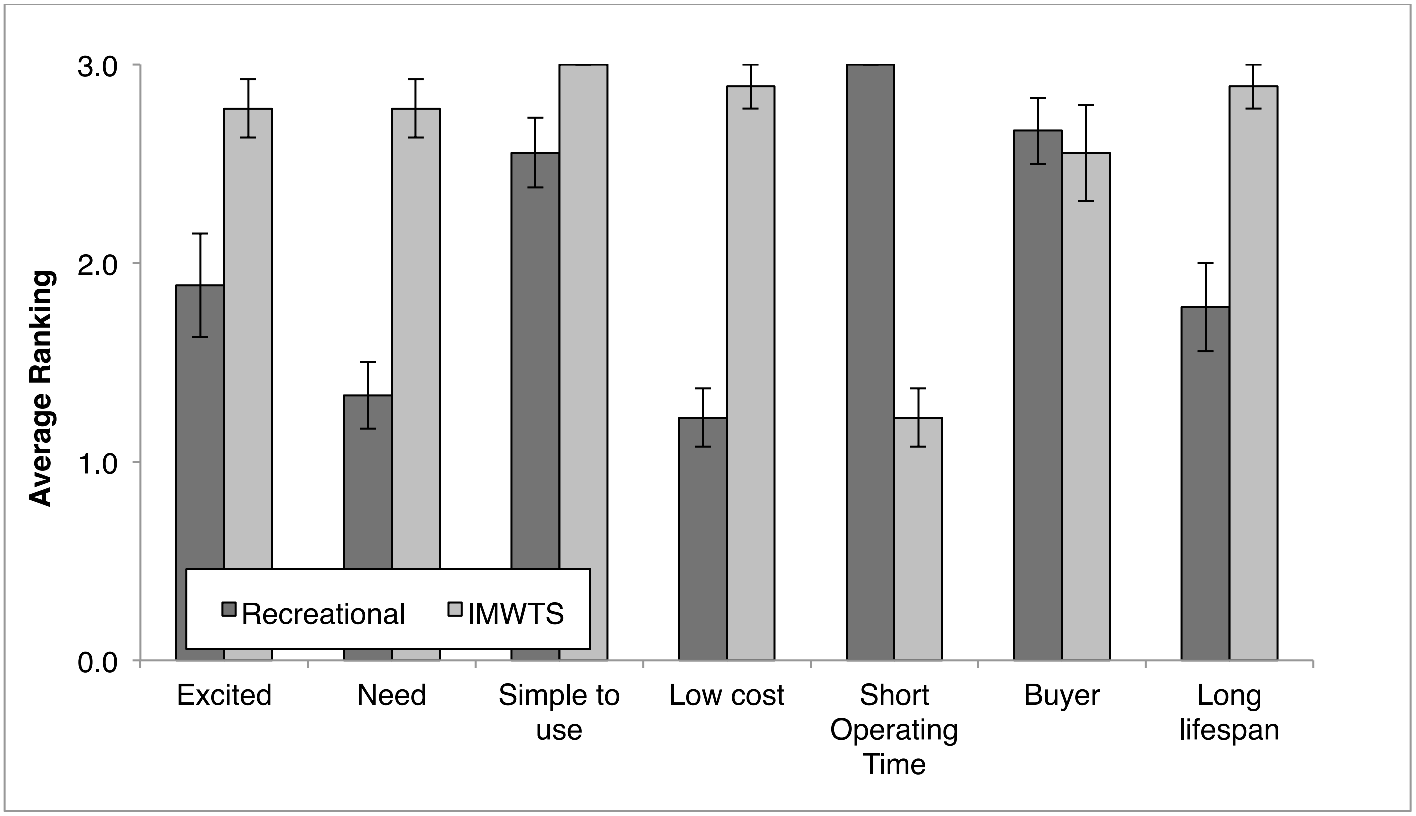

Figure 5.2. *Consumer demand for silver-embedded ceramic tablet for different consumer segments. Eighteen interviews were conducted among stakeholders that were either in the recreational/outdoor consumer segment (Recreational) or persons with impaired municipal tap water systems (IMWTS). Each interview was ranked (1 to 3) for levels of importance among six categories. Score of 1 represents no importance and 3 represents very important. Averages were taken for each category and standard error was used to calculate error bars.*

Figure 5.3 is a flow chart of the decision-making process for purchasing and distributing POU technologies specifically for the IMWTS consumer segment. The diagram includes value propositions specific to each component of the decision-making process that are also applicable to the silver-embedded ceramic tablet.

Table 5.1 and 5.2 provide profiles of various economic buyers and end-users in the IMWTS consumer segment. Table 5.1 describes consumer profiles of five economic buyers. These profiles represent general categories of potential economic buyers for the silver-embedded ceramic tablet in the IMWTS segment: small to medium sized NGO (Global Water Brigades), large NGO (IRC), aid agencies (USAID), local retailer (Shoprite) and multinational corporations (Tupperware). End-users of the technology are described in Table 5.2, outlining the demands and needs within each socio-economic class. Some end-users were also economic buyers, but none of the described economic buyers were also end-users of POU technologies. All consumer profiles in Table 5.2 were a compilation of interviews conducted in Limpopo Province, S. Africa. Table 5.3 compares the silver-embedded ceramic tablet against current competitor POU technologies. Competitor products were selected based off of data collected from stakeholder interviews. Product specifications and value propositions of the

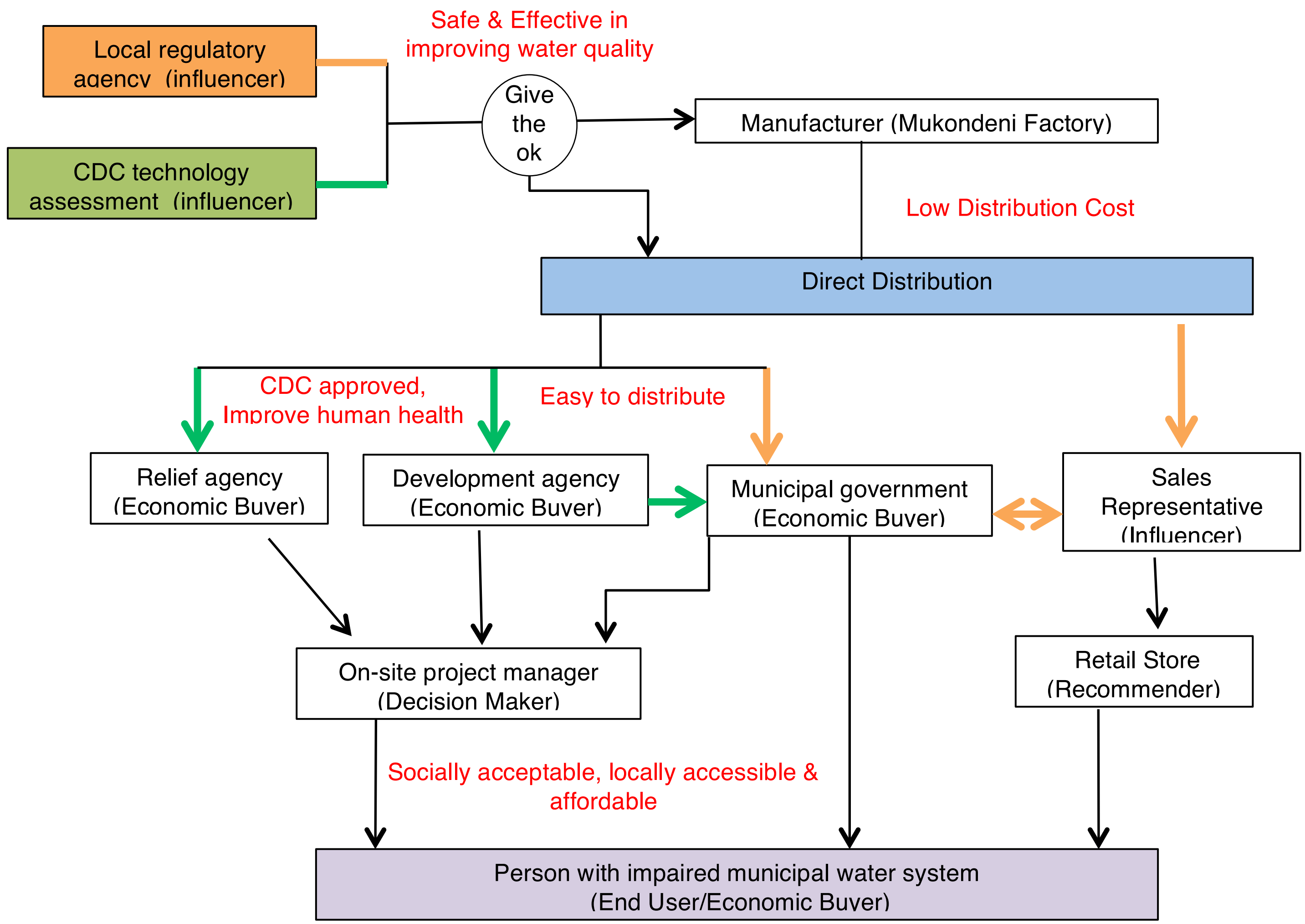

Figure 5.3. *Decision-making process and value propositions for distribution of point-of-use water purification technologies for IMWTS consumer segment.*

product are compared to the silver-embedded ceramic tablet in Table 5.3. Market strategies for competitor products are described in Table 5.4, and compared to market strategies proposed for the silver-embedded ceramic tablet. Four components of market strategy were considered for this study: target consumer segments, key partnerships, customer relationship strategies and distribution channels.

Financial projections were created for a start-up enterprise based off of the silver-embedded ceramic tablet. Financial projections are based off of primary data collected through the pilot production facility and stakeholder interviews. 5-year projection of revenue and profits are described in Table 5.5. Gross profit is expected to be (-$301,438), $142,753, $475,350, $1,063,113 and $2,099,790 USD for the first five years. Required start-up funds are estimated to be $188.127 USD (Table 5.6) with total expenditure cost of $308,299 USD (Table 5.7) for year 1 of the venture. Breakdown of revenue and costs are shown in the cash flow diagram in Table 5.8. Many assumptions had to be made to develop these financial projections, which can be found in Table 5.9.

5.4 Customer discovery

Through the NSF Innovation Corps (I-Corps) program, 100 customer discovery interviews were conducted to evaluate market opportunity. Initial interviews suggested that there exist two major target consumer segments within the global water treatment market: (1) developed world commercial retail market targeting recreational and outdoor consumers and (2) persons living with impaired municipal water treatment systems (IMWTS). Comparison of the two suggested that the product offerings of the silver-embedded ceramic tablet best suits the needs of the IMWTS consumer segment (Figure 5.2). The remainder of the interviews and data collection was focused on investigating the target market channels and consumer segments within the IMWTS consumer segment.

5.4.1 Target markets

All the data from the customer discovery was compiled into a decision-making flow chart (Figure 5.3), from which two major channels were identified. The main channels to reach consumers in the IMWTS market were determined to be through the emerging retail market and the aid/relief market.

The developing retail consumer market is very large and complex. It presents challenges that range from building consumer awareness to navigating international distribution channels. The development of the retail market requires strategic partnerships. Nevertheless, long-term, the retail market will provide a more consistent and stable source of revenue for a wide range of customers throughout the world. It makes the silver-embedded ceramic tablet a desirable product for individuals in a submerging consumer segment, who aspire to purchase the product one day.

The second target market is the global development and relief market, which is serviced by a variety of NGOs. Customer discovery data suggests that cultivating relationships with organizations that support global access to safe drinking water (e.g. the World Health Organization, USAID, the Clinton Foundation) will offer the high initial volume of sales. Working with NGOs will also help build product awareness, which will support the development and growth of retail markets. NGOs also provide resources and methods to help with end-user adoption, education and distribution.

5.4.2 Consumer segment

From the decision making chart it is evident that there are two types of consumers: economic buyers and financially independent end-users. The economic buyers and end-user are not necessarily the same person, as is the case in other markets. Within the IMWTS segment and global water treatment market, they are often times two very different customers with different needs.

Sole economic buyers include organizations in the international aid and relief market. This would include non-profit organizations, governmental aid agencies and relief agencies. Economic buyers acquire the role of economic buyer because the end-user cannot afford the product but is in need of it. End-users are defined as individuals who would actually be using the product. Some end-users cannot afford the technology, thus must rely on economic buyers. Other end-users are individuals that can afford the product, and therefore are both the end-users and economic buyers, thus financially independent. This later group of end-users directly purchases POU products through local retail stores.

5.4.3 Customer archetypes

Economic buyers and end-users were categorized into various consumer archetypes to understand the needs of each. This provided insight to the distribution channels required to reach them. Examples of customer archetypes for economic buyers and end-user are provided below and in Tables 5.1 and 5.2.

From customer discovery interviews, examples of economic buyers were found to be local and federal government aid agencies, NGOs and relief organizations. These consumers work to assist persons living on less than $2 per day, with focus on those in emergency situations and under-resourced communities. In the realm of NGOs, the needs of these organizations change based on their size and specialization (water, sanitation, global health). Generally though, the ideal water purification method to them would be low-cost, effective, transportable, and socially acceptable. This group of economic buyers can be further segmented into five archetypes as shown in Table 5.1.

Table 5.1. *Economic buyer archetype for POUWTs in Limpopo Province, S. Africa.*

Global Water Brigades (University-based NGO)	**Shoprite (S. African Retailer)**
Location: Seattle, WA (USA)	Location: Western Cape province, SA
Size: 200 employees	Size: 10,000+ employees
Industry: NGO	Industry: Retail
Target Market: Philanthropists, and developing communities	Target Market: African households
Key interests: Empower local communities members to overcome global health and economic disparities; education; sustainability; safe drinking water; sanitation.	Key interests: Africa's largest food retailer, **Provide African communities** with **food and household items**; **Well-known retailer**; Provides water purification household products.
International Rescue Committee (on-ground NGO)	**USAID (Aid Agency)**
Location: New York, NY 	Location: Washington, DC
Size: 10,000 employees	Size: 10,000+ employees
Industry: NGO	Industry: Government
Target Market: Refugees	Target Market: Government, Aid Organization
Key interests: **Aid**, education; health care; **disaster response** & preparedness, **water & sanitation;** refugee resettlement; **provide life saving care and assistance to refugees**; **Low-cost**	Key interests: International development; Disaster response; Global health; Government; Alleviate poverty; Foreign relations; US humanitarian efforts

Tupperware (Multinational Corporation)	
Location: Orlando, FL (USA)	
Size: 10,000+ employees (100+ countries)	
Industry: Consumer goods	
Target Market: Households	
Key interests: Provide **design-centric products** for everyday household use; **Wide market of consumers**; Has **interest in developing world** and non-profit initiatives; **Global team**; empower independent sales forces; Focuses on **storage containers**; Looking for creative **water purification solutions**.	

Consumer archetypes for economic buyers include large NGOs and major aid agencies. These consumers require long-term investment due to various required validation steps. Customer discovery data suggested that these larger organizations require technical validation through peer-reviewed publications, which demonstrate efficacy of the product both in the laboratory and field. This process could take months to years. Then there are small NGOs, such as Global Water Brigades or church groups. This consumer archetype is less likely to require detailed technical reports and is willing to test the product in the field for themselves, making the procurement process faster.

The final archetype for economic buyers would be the commercial and retail market, such as major grocery or household appliance stores. These stores are looking to sell directly to end-users for a profit and have established consumer relations. All of these economic buyers would be purchasing in bulk (100-10,000 units), which the pilot production facility developed in this study can manage during early stage of sales (1-2 years).

Among the end-users further categorization was done based off of socio-economic status: (1) persons with IMWTS living above the poverty line, (2) displaced persons, (3) persons living on $1-2/day with IMWTS and (4) persons with IMWTS living on $2-5 per day. Access to these consumers would be two fold: through a third-party organization such as NGOs or through retail sales.

Lower income classes and those living on less than $1/day would most likely attain silver-embedded ceramic tablets through economic buyers described above. The independent end-user would consist of persons living above the poverty line or in the submerging market ($2-5/day) with IMWTS. These consumers make enough money to be able to afford POU technologies. However, they need to be educated on the importance of safe drinking water and the advantages of any new POU method. Branding is important to these consumers, so strong marketing strategies need to be implemented to target them in order to be competitive against already existing brand names.

5.5 POU water treatment methods

5.5.1 Current POU methods

From a business perspective, current POU methods and products can be grouped into three categories: traditional, commercial single-use, and commercial long-term-use. Examples of each type of POU method and product features are summarized in Table 5.3. Studies have demonstrated that these technologies perform very well in the laboratory, however their field performance is limited due to recontamination, social acceptance and economic sustainability [2] .

Traditional methods are non-commercial techniques that are common in developing-world communities. Traditional methods include boiling, fabric filtration, solar disinfection, and natural plant coagulants.

Table 5.2. *Customer profiles archetype for POUWTs in Limpopo Province, S. Africa*.

Cornelius	
Age: 42	Location: Thohoyandou, Limpopo Province, SA (urban)
Gender: Male	Occupation: Professor
Martial Status: Married	Size of household: 4
Education: Juris Doctorate	Monthly Income: $1200 USD
Key tasks: **Sole breadwinner** in family: **Loves high-tech gadgets**; has **two children under 13 years of age**; Municipal tap is main water source but only works 20-30 hrs per week. He has to **store water in home**.	
Anna	
Age: 30	Location: Mashamba, Limpopo Province, SA (rural)
Gender: Female	Occupation: Potter
Martial Status: Married	Size of household: 3
Education: None	Monthly Income: $50 USD
Key tasks: Looks after the children and house. **Sole breadwinner** but some of her children do not live with her. Her **children collect water from local tap** or neighbor's **borehole**. She works at the pottery cooperative **to pay for her children's education and provide for her family**. She relies on the **government welfare funds.**	
Grace	
Age: 44	Location: Mukondeni, Limpopo Province, SA (rural)
Gender: Female	Occupation: unemployed
Martial Status: Married	Size of household: 4
Education: none	Monthly Income: $5 USD
Key tasks: Responsible for taking care of children and household duties (cleaning, **preparing food and collecting water**). She **collects water from local tap.** Takes her **30 min to collect water**. Collects water in **20-L plastic bucket**. Water quality is important to her. She takes care of her **grandchildren**. Relies on **welfare funding**.	
Elisa	
Age: 50	Location: refugee camp
Gender: Female	Occupation: unemployed
Martial Status: Married	Size of household: 5
Education: none	Monthly Income: none
Key tasks: Has little to no money. Completely **dependent on NGOs and aid agencies**. She has two children to provide for. **Access to food and water are limited**. Safe drinking water and sanitation is important to her, because she **can't afford medical attention**. Collects water from a **local tap and wells**. Supply of water is limited due to the **over-populated area**. Currently uses **chlorine tablets or flocculent/disinfectant powders**, **commercial single-use products**. Collects and stores water in **20-L plastic container**.	

Commercial single-use technologies include chlorine and metal-based solutions in liquid, tablet, and powder forms. These technologies have a low capital cost per unit, but only work once on relatively small volumes of water being expensive and impractical long-term solutions. From the customer discovery research, traditional and commercial single-use technologies are common and often preferred in emergency settings or high-volume interventions. This would make them preferred POU methods for end users who are financially dependent on economic buyers, such as relief organizations and aid agencies. Their small size, simple to use methodologies, and low cost make them easy to distribute and integrate into a community. However lack of user compliance and sustainability limits the effectiveness of traditional and commercial single-use POU methods in the community and in improving water quality and human health.

Commercial long-term technologies are reusable but have high initial capital costs. Also, these technologies may require routine maintenance or replacement filter cartridges, which may not be available locally. As a result these POU products are preferred among more financially independent end users and those in the submerging market as aspirational products. These methods are also purchased among economic buyers, such as large NGOs and aid agencies, however sales to NGOs are limited due to cost and maintenance requirements to use the product effectively. Furthermore, some of these technologies are also difficult to distribute, such as ceramic water filters. Therefore, these technologies although more effective in improving water quality at a technical level may perform worse than traditional and commercial single-use POU methods in a household setting due to low user compliance.

5.5.2 Product features

The silver-embedded ceramic tablet is unique in that it bridges the categories listed in Table 5.3. It encompasses many of the key strengths of current POU methods, while excluding significant limitations that make many current methods and products infeasible. Some of these key strengths include, ease of transport, ease of use, reusability, maintaining natural taste of water and energy-independence. As a result, the simplicity, efficiency and local availability of the silver-embedded ceramic tablet meet the needs of the consumer and make it a strong competitor against current solutions.

5.5.3 Competition

The most common POU methods within the categories of traditional, commercial single-use and commercial long-term POU methods include boiling, chlorine-based tablets or liquids, flocculent/disinfecting powders (PUR) and filtration. In the following paragraphs three major competitive technologies are presented and Table 5.4 summarizes target markets, company partners and distribution channels for these common POU methods.

Table 5.3. *Value proposition comparison of silver-embedded ceramic tablet to competing products*

FACTOR	Traditional	Commercial single-use		Commercial long-term use	Silver-embedded ceramic tablet
	Boiling	Liquid Chloride	Disinfectant powder	Ceramic filter	
Socially Acceptable	×	×	×	✓	✓
Price (USD)	$0.01/L	$0.031/L	$0.011/L	$0.007/L	$0.002/L
Keeps natural taste & odor	×	×	✓	✓	✓
Service	×	✓	✓	×	✓
Maintenance	×	✓	×	×	✓
Lifespan	Varies	10 L	10L	3-4 yrs	6 months
Ease of use	Multi-step	Single step	Multi step	Single step	Single step
Energy independent	×	✓	✓	✓	✓
Branding	N/A	✓	✓	✓	×
Locally available	N/A	×	×	×	✓
Volume Treated	Varies	10 L	10 L	1-3 L	15 L
Transportable	×	✓	✓	×	✓

Filtration POU methods, such as ceramic water filters, Aquasure, PureIt, and Rama (3-candle ceramic purifier) are very effective in removing harmful pathogens in addition to turbidity in the water. However, they have high capital costs ranging from $20-$60 USD. This does not include the maintenance cost for replacement filters and cartridges, approximately $4 USD[7,10]. Often times, they are not affordable for end users in the submerging market. As a result the target market for filtration methods are limited to high-income end users or economic buyers who must distribute the product for free or at a subsidized price point. However, they are easily accessible because they are sold through grocery retail stores.

Low capital cost technologies tend to have short lifespans, labor-intensive or only single-use. Two major examples are chlorine-based disinfectants and flocculent/disinfecting powders. Often times, chlorine-based POU methods, such as WaterGuard and Aquatab, are not socially acceptable because they change the taste and odor of water [11,12]. However, they are very simple to use and distribute, therefore they are often used in emergency settings. Air RahMat is a liquid 1.25% sodium hypochlorite solution sold by PT Tanisha. The cost to users is $0.0005/L of treated water. This product has sold to 200 million Indonesians, however reports have shown sales dropped after the first year of sales. Similar to other chlorine-based POU methods, the change in the taste and odor of water is unappealing to many end-users[7].

Table 5.4. *Marketing strategy for competing products*

Product	Consumer Segment	Partners	Customer Relationship	Distribution Channel
Pur Sachet	Low-income class (<$1/day) & NGO dependent	Procter & Gamble, local NGOs	Social marketing via NGO	Large NGOs (IRC), Aid agency (USAID)
Bottled Water	Upper ($50+/day)& Middle ($10-50/day) class	Nestle	Home delivery, Recycling, Branding, Media outlet	Grocery stores (SPAR & Shoprite)
JIK (chlorine)	Lower ($2-10/day) class & Persons living on <$1/day	Local Retailer	Multiuse: Also used as detergent	Grocery stores (SPAR & Shoprite)
Ceramic Filter	Direct sales to high income class	Global Retailers	Based on Retailer	Global Retailers
Silver-embedded ceramic tablet	Middle ($10-50/day), Lower ($2-10/day), & low-income class (<$1/day)	Local retailer & Local NGOs,	Social marketing networks, local endorsement	Large NGOs (IRC), Aid agency (USAID) & Grocery stores (SPAR & Shoprite)

PUR is an example of a flocculent/disinfecting powder. It is a single-use packet sold by Proctor and Gamble (P&G). This technology is a packet containing disinfectant and coagulant agents, but requires multiple steps and additional materials for treatment of water. Each packet treats 10 L of water. Initially, the product sold at $0.10 USD per sachet to the commercial market, but sales were very low. Therefore, P&G revamped the business model and took a non-commercial route targeting NGOs. Now P&G sells more than 200 million sachets at a production cost of $0.04 per sachet [13] . Although sales are high, the product has not been a strong, profitable product for P&G. This is partially because of user compliance. The method is not very simple to do. It is time-consuming because it requires multiple steps and it also requires additional materials to complete the treatment process. For many end-users, the PUR sachet is more complex than traditional methods such as boiling.

None of the mentioned POU methods provide continual disinfection, and PUR and chlorine-based POU methods are not reusable. The silver-embedded ceramic tablet addresses these challenges because it can be used for 6 months to treat 10 L of water. Since it is residing in the water storage container and releasing silver at a controlled rate, it provides continual disinfection. From preliminary cost analysis, the silver-embedded ceramic tablet can be manufactured domestically for $2-3 USD and sold at a price point of $5-10 USD internationally. Making it one of the least expensive water treatment technologies on the market today. As a result, the silver-embedded ceramic tablet may be appealing to end-users for the commercial retail market in addition to bulk purchasing groups, such as large aid agencies and NGOs.

5.6 Market Strategy

5.6.1 Distribution channel

Market data has been compiled to understand how to reach specific consumer archetypes in the target market. In Figure 5.4, these steps have been outlined beginning with regulatory approvals by various government agencies.

Economic buyers, such as non-profit organizations, usually distribute technologies directly to end-users for free or through a microfinance strategy to empower the community. In the first scenario, on-grounds field managers are the main decision makers as he/she understands the needs of the end-users the best and relays that information to headquarters. In the second scenario, NGOs are working with local partners to develop more sustainable solutions that may include micro-financing and local sales. Again the on-site project manger will be the main decision maker however, local business partners will have an influential role in the decision making process. End users who will be able to afford the product will be reached through the commercial retail channel, retail stores. In both of these scenarios, it is not only important to meet the end-users needs but also provide a product that is economically sustainable for local businesses.

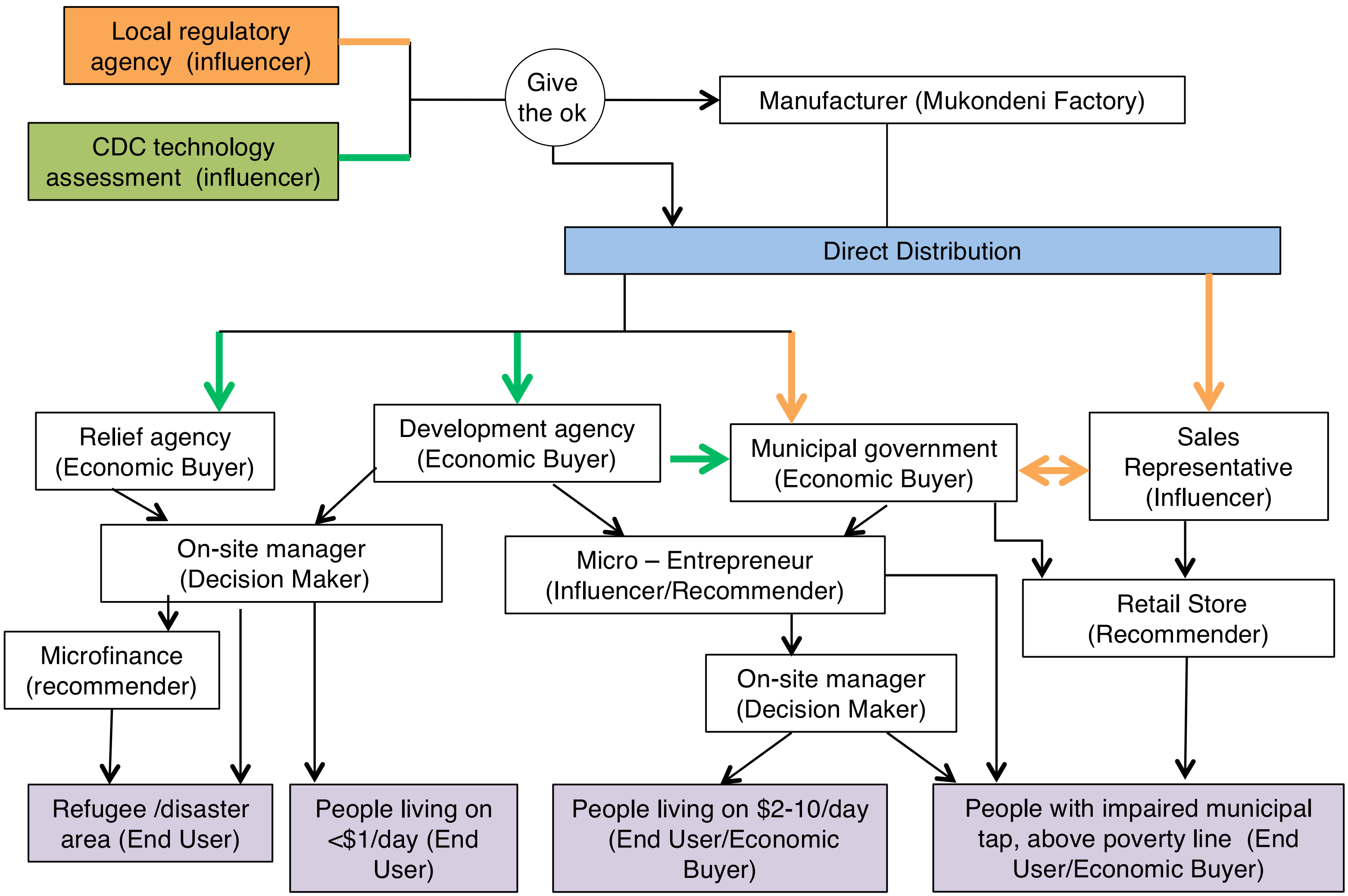

Figure 5.4. *Distribution channel flow chart for POU water purification technology for IMWTS target market*

Given the production cost and long-term use of the silver-embedded ceramic tablet, it is a product that would be applicable for these various consumer segments. Current products and potential competitors have only been able to target a couple of the consumer segments outlined in Table 5.2. The major challenges with these products include high cost per liter of treated water or high distribution costs. In Table 5.4, the target consumers and distribution channels for competitor products are outlined. As is shown, the silver-embedded ceramic tablet's ease of transportation and low price point enable it to address a wider range of consumer segments.

Table 5.5. *Five-year financial projection for silver-embedded ceramic tablet*

	Year 1	Year 2	Year 3	Year 4	Year 5
Sales					
Units	126,000	220,500	385,875	675,281	1,181,742
$/Unit	5	5	5	5	5
Total Sales	$630,000	$1,102,500	$1,929,375	$3,376,406	$5,908,711
Distribution	$31,500	$55,125	$96,469	$168,820	$295,436
Net Sales	$598,500	$1,047,375	$1,832,906	$3,207,586	$5,613,275
Costs					
Cost/Unit	2.14	2.14	2.14	2.14	2.14
Total Unit Costs	$354,640	$471,870	$825,773	$1,445,102	$2,528,928
Gross Margin	$243,860	$575,505	$1,007,134	$1,762,484	$3,084,347
Fixed costs	$496,526	$317,651	$330,357	$346,875	$367,687
Loss (20%)	$48,772.0	$115,101.0	$201,426.8	$352,496.8	$616,869.4
Profit	($301,438)	$142,753	$475,350	$1,063,113	$2,099,790

5.6.2 Sales strategy

Through on-ground partnerships promotional strategies can be established with end-users and retail markets. Data suggests that local NGOs, clinics and churches are strong channels to establish relationships in communities. Endorsement by these local establishments builds consumer trust and attracts end-users. Furthermore, local clinics and churches understand the needs of the end-user more in depth. Some of these partnerships and relationship-building goals may be attainable through partnerships with existing NGOs. Learning from previous companies, such as P&G, targeting health organizations is key to relate importance of safe drinking water to human health. Other promotional strategies include social media and news agencies. This will be effective in connecting with NGOs and multi-national corporations.

Table 5.6. *Required Start-Up Funds*

Fixed Assets	Amount
Equipment	40,000
Total Fixed Assets	40,000
Operating Capital	
Legal & Accounting Fees	10,600
Rent Deposits	2,000
Utility Deposits	2,731
Warehouse & Office Supplies (monthly)	27,597
Advertising (monthly)	200
Licenses	5,000
Start-up R&D	100,000
Total Operating Capital	148,127
Total Required Funds	**$188,127**

5.7 Financial Projections

Based off of WTP data and manufacturing cost analysis, the silver-embedded ceramic tablet can be retailed for $5 USD to provide a 60% profit margin. The price point is competitive against to current products (Table 5.3) and fits well with the WTP analysis of end-users. Median WTP was evaluated during the field study in Limpopo Province, South Africa, and found to be $5 USD (Figure. 3.21). Manufacturing costs were calculated through cost analysis of the pilot production facility developed in Charlottesville, Virginia. At a production rate of 500 ceramic tablets per day, the unit cost would be $2-3 USD.

Table 5.7. *Total Expenditures for Year 1*

Fixed costs	Monthly	Annually
Rental space	$3,000.00	$36,000
Equipment		
Kiln, Press, Mold	-	-
Contract Services	$416.67	$5,000.00
Packaging & Distribution	-	-
Supplies	-	-
Warehouse & Office Utilities cost	$105.58	$1,266.90
Salary		
Wage Part-time		$0.00
Fulltime (3 employees)	$10,811.00	$129,732.00
Sales	$1,600.00	$19,200.00
Legal & Accounting Fees	$1,250.00	$15,000.00
Insurance	$100.00	$1,200.00
License/Trademark Fees	$416.67	$5,000.00
Research & Development	$8,000.00	$96,000.00
Total expenditures	$25,699.92	$308,399
Total Expenditures + Capital Cost		$496,526

Given the growth in the market and the high profit margin of the silver-embedded ceramic tablet, total profit is expected to reach close to $2.1 million by the fifth year of production. Initial capital costs are estimated to be $496,526 and net gain in profit is expected to start in the second year.

The current retail price and financial projections fits well with the Limpopo community of South Africa. As an international company, worldwide distribution is an important company deliverable. Therefore, one major cost factor would be shipping. Many of the communities that are in need of a product like the silver-embedded ceramic tablet most likely live in remote locations. As a result, the price of the silver-embedded ceramic tablet may vary from location to location. Furthermore, partnerships with local government and NGOs will be important to perhaps subsidize these costs. Therefore, WTP and revenue models will need to be reanalyzed to account for local market constraints.

Table 5.8. *Cash flow for Year 1 of Start-up*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals
Income													
Product A	21,000	21,000	75,600	75,600	75,600	75,600	75,600	47,250	47,250	47,250	47,250	21,000	630,000
Total Income	21,000	21,000	75,600	75,600	75,600	75,600	75,600	47,250	47,250	47,250	47,250	21,000	630,000
Cost of Sales													
Product	11,811	11,811	42,521	42,521	42,521	42,521	42,521	26,575	26,575	26,575	26,575	11,811	354,338
Total Cost of Sales	11,811	11,811	42,521	42,521	42,521	42,521	42,521	26,575	26,575	26,575	26,575	11,811	354,338
Gross Margin	9,189	9,189	33,079	33,079	33,079	33,079	33,079	20,675	20,675	20,675	20,675	9,189	275,662
Total Salary	10,811	10,811	10,811	10,811	-	-	10,811	10,811	10,811	10,811	10,811	10,811	129,731
Total Fixed Cost	14,889	14,889	14,889	14,889	14,889	14,889	14,889	14,889	14,889	14,889	14,889	14,889	178,667
Net Income	-16,511	-16,511	7,379	7,379	18,190	18,190	7,379	-5,025	-5,025	-5,025	-5,025	-16,511	-11,116

Table 5.9. *Assumptions for Financial Projections*

Assumption		Source
Sales		
	Assume we can make at least 500 silver-embedded ceramic tablets per day using current pilot production facility	Primary
	Sales: We assume 100% sales on silver-embedded ceramic tablets produced per year	Primary
	Assume company will grow at a 75% in sales (100% returning customers and 25% new customers, each customer purchasing 2 silver-embedded ceramic tablets per year)	
	Lifespan of a silver-embedded ceramic tablet is 6 months	Primary
	Retail price based off of Willingness to pay survey among the rural end-users who would be earning the lowest income out of all consumer segment	Primary
	Assuming sales would be high in Summer due to high volume of service projects during those months	
	Taxes (federal taxes 12-27%)	Secondary
	Loss (20%) without improvement over time	
Start-up costs & Operating costs		
	Warehouse Rental rate in Charlottesville, VA	
	Utilities & supplies cost cover one month of production	
	Travel & Advertising Costs cover the first month	
	BBT business checking account monthly charge if we do not keep balance	Primary
Salary & Wages		
	There will be 3 fulltime employees with salary & benefits	
	Number of hourly employees based off of required labor for monthly production rates	
	Employees paid hourly at minimum wage ($7.25-8)	Dep. Of Labor
	Production hours: 7 hours per day, 5 days a week, 21 days per month	
Production Expenditures		
	Production supply costs based off of current rates used at pilot facility	Primary
	Warehouse utility costs based off of current rates from pilot facility	Primary
	Cost of silver-embedded ceramic tablet/Unit = cost of supplies, labor (hourly wage) & distribution costs per unit	Primary
	Silver per gram based off of China company	Alibaba.com
	Production costs (Unit cost) does not decline over time. Production efficiency does not improve over time.	
	Distribution costs consist of 5% of sales	

5.8 Acknowledgements

I would like to thank Ms. Carly Krause, Dr. James Smith, Mr. David Dusseau, Mr. Satish Tamboli and the NSF I-Corp teaching team for their contributions and mentorship.

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Chapter 6

Conclusion

This dissertation investigates a novel method to embed silver in porous ceramic media that has resulted in two innovations. First, this method of embedding silver in ceramic porous media provides an entirely new methodology to organically infuse metallic silver at the nanoscale level in ceramic media. Second, this new methodology has been applied to a novel water purification technology, a silver-embedded ceramic tablet, for applications as a point-of-use (POU) water treatment in developing communities. Through the work conducted in this project, the development, optimization, field performance, social acceptance and economic sustainability of this novel silver-embedded ceramic tablet has been evaluated.

The results of this work provide a fundamental understanding of the processes and mechanisms regulating silver nanopatch formation and silver release. Laboratory results demonstrate that fabrication materials, such as clay mineralogy, initial mass of embedded silver and particle size of sawdust regulate silver release, and diffusion and sorption are important factors in regulating mechanisms of silver release. In regards to field performance, the silver-embedded ceramic tablet worked just as well in the short-term as other single-use POU methods, such as chlorine tablets. Long term data suggests the silver-embedded ceramic tablet is helps reduce rates of recontamination when used with CWFs, and therefore is an effective secondary POU method. Results from the field study also demonstrate high user compliance and cultural acceptance.

Disinfection experiments were conducted on the silver-embedded ceramic tablet to better understand silver disinfection capabilities against various harmful waterborne pathogens, such as protozoa and viruses. The tablet was effective in reducing viability of both *C. parvum* and MS2 bacteriophage. This data also provided insight on silver disinfection kinetics and mechanisms for protozoa and viruses, which there has been limited research on.

Although the laboratory and field data are promising, there is a third major factor that determines whether a promising technology will succeed as a sustainable product in the real world, economic sustainability. It is the interplay of effective technical performance, high social acceptance and economic sustainability that often times determines whether a POU technology that performed ‘above and beyond standards’ during laboratory testing will perform similarly in the real world. As the final portion of this work, the ceramic tablet’s economic sustainability was evaluated by developing a business model based off of information collected about market demand from customer discovery interviews and estimating operational costs through a prototype production facility. Overall, the low production costs, simple production process, locally-sourced materials, ease of transport and distribution in addition to high user compliance and technical performance suggest the silver-embedded ceramic tablet is an effective POU technology.

There are shortcomings to this work, such as testing being limited to only two volumes of water, 200 mL and 10 L. For future applications, a larger range of volumes will need to be evaluated for POU applications. These challenges were addressed somewhat through the field study, however further research will be required. Also, investigating disinfection efficiency among various waterborne pathogens was conducted under controlled laboratory settings, which does not directly mimic pathogen infectivity in mammalian cells. Further laboratory analysis needs to be done in a mammalian mouse model to directly study disinfection properties of silver and the silver-embedded ceramic tablet on infectivity of protozoa. The impact on human health will need to be further investigated through a human health field study. In regards to economic sustainability, manufacturing processes need to be optimized for large-scale production. Additionally, further product development needs to be conducted to ensure consumers are using the product properly; such incorporating an indicator on the tablet, so after 180 days of use the consumer is aware the tablet needs to be replaced. Also, oftentimes in developing world markets imitation products may saturate the market, therefore strategies to ensure authenticity is important. Long term considerations for this technology would also include, methods for sustainable bulk disposal of silver. Although ceramic is recyclable, silver embedded within the media is not and may require additional procedures for extraction for purposes of recycling and proper disposal.

Having said this, the results from this project provide the foundation for future research. The basic understanding of embedding metallic disinfecting agent in porous ceramic media could be applied to other metallic disinfecting agents, such as copper, in future experiments. Copper has been shown to be effective in disinfecting viruses and bacteria, and also work synergistically with silver. It is without saying that a technology like this could be of value to anyone who requires disinfection of pathogenic microorganisms in their drinking water, making it relevant to billions of people worldwide. To date this novel method of embedding silver in ceramic has not been investigated, and the results of this project contribute significantly towards future development of the technology.

Appendix A: Methods, Materials and Discussion of Sodium Thiosulfate Treatment

Sodium Thiosulfate Treatment of Water Samples. Sodium thiosulfate was added to water samples collected in disinfection experiments to stop the disinfectant action of silver at the time of sample collection. Prior to adopting this procedure, experiments were performed to insure that the disinfection action of the silver was stopped within minutes of sample collection and to insure that sodium thiosulfate did not have toxic effects on *E. coli*. To ensure sodium thiosulfate treatment did not interfere with *E.coli* viability in samples, *E.coli* samples were treated with 60 mg/L of sodium thiosulfate (26.4 mL per 1 mL of sample) for 2 min at room temperature. Samples were treated both with and without ceramic tablets. Disinfection was quantified using IDEXX microbial analysis methods to stay consistent with the experimental methods used in this study (Fig. S4-S4). Samples were run in duplicate, and prepared with 10 mM PB solution with a final *E.coli* concentration of 10^9 cfu/100mL. For samples that were treated with ceramic tablets, the ceramic tablets were made with 90% Redart clay, 20-mesh sawdust, and 50 mg of silver. Results show no difference in die-off of *E.coli* among samples treated with only sodium thiosulfate, sodium thiosulfate and ceramic tablets prior to the addition of and *E.coli*-only samples, ensuring *E.coli* viability and inhibition of silver disinfection. For samples treated with sodium thiosulfate post-ceramic-tablet treatment, there was no difference in bacteria die-off post-treatment, demonstrating silver disinfection is halted during IDEXX microbial analysis (Fig S4-S4). Given the prior published results, sodium thiosulfate treatment was still used after sample collection to ensure silver disinfection was inhibited at each sample collection time-point and during microbial analysis [1].

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Appendix B: Surveys

Study Number: ____________

MadiDrop (Silver-embedded Ceramic Disk) Beginning of Study Survey,

June 2013 – August 2013

Demographic Data

1. Age: _______ 2. Gender: ____________

3. What is your family status? (Circle one.)

Single Married Divorced/separated

Widow/widower

4. What is your education level? (Circle one.)

Some primary Completed primary Some secondary

Completed secondary Some university Completed university

5. Number of adults in household. (Including you.) ___________

6. Number of children in household. __________

Ages of children: ___________________________________

7. What is your occupation? ______________________________

8. What is your monthly income?

Less than R250 R250-R1000 R1000-R1500

R1500-R3500 R3500-R7500

More than R7500

Water Practices and Storage

1. *Primary* source for drinking water? (Circle all that apply.)

Piped into house Unprotected well Tanker truck

Piped into yard/plot Protected spring Cart with small tank

Public tap/standpipe Unprotected spring

Bottled water

Protected well Rainwater Tube well/borehole

Surface water (river/dam/lake/stream/canal) Piped into neighbor's house

Piped into neighbor's yard/plot Other: ________________________________

2. *Secondary* source of drinking water? (Circle all that apply.)

Piped into house Unprotected well Tanker truck

Piped into yard/plot Protected spring Cart with small tank

Public tap/standpipe Unprotected spring

Bottled water

Protected well Rainwater Tube well/borehole

Surface water (river/dam/lake/stream/canal) Piped into neighbor's house Piped into neighbor's yard/plot Other: ______________________________________

3. If you do, why do you change from using your primary source to your secondary source?

4. How often do you change from your primary source to secondary source?

___________ per day / week / month (Circle one.)

5. What do you use for your drinking water storage container? (Circle all that apply.)

Ceramic vessels Jerrycan Plastic Bottles

Metal buckets Small pans No Container

Other:__________________ Plastic buckets

Cooking pots

6. Where is the water stored? (Circle one.) Inside

Outside

If inside, which room? (Circle one.)

Kitchen Bathroom Dining room

Other: ________________ Bedroom Living room

7. Are the storage containers covered?

All covered Some covered None covered

8. Do you clean your storage vessel? (Circle one.) Yes No

If so, how often?

If so, how do you clean your storage vessel?

9. What do you use to get the water from its storage?

Pour directly Use cup with handle Use cup with hands Spigot Other: ___________________________

10. How much water is in the storage container? ______________ liters / cups (Circle one.)

11. How often do you refill the storage container? (Circle one.)

0-3 4-6 more than 6

Per day / week (Circle one.)

12. Do you use anything to clean/purify the water in your storage container?

If so, how much does it cost you?

Would you improve it in anyway and how?

13. Please rate the quality of the water (taste, health & visually appealing) when collected at its source. (1-being very poor, 5-being very satisfactory).

Taste: 1 2 3 4 5

(Circle one.)

Safe to drink: 1 2 3 4 5 (Circle one.)

Visually appealing: 1 2 3 4 5 (Circle one.)

14. Please rate the quality of the water towards the end of storage.

1 2 3 4 5 (Circle one.)

Study Number: ___________________

MadiDrop (Silver-embedded Ceramic Disk)

End of Study Survey, June 2013 – August 2013

Script: "Hello, my name is ___. Thank you for allowing us to work with you these 5 weeks. We appreciate your time. This is our last house visit for now, but we hope to come back during the summer to test the water and performance of the MadiDrop again. We will let you know beforehand if we do come back. For now though we will be concluding our work by asking you a few questions about how you used the MadiDrop & how you liked it. Thank you again for your cooperation."

1. Was the MadiDrop easy to use? Yes No
   (Circle one.)
2. How long did you wait to drink water after you used the MadiDrop? Did you wait from:
   zero up to 3hrs from 3 up to 6 hours from 6 up to 9 hours 9 hours or more
3. How often did you refill your storage container? _________________ per
   day / week

"Now I would like to ask you a few questions about how you liked using the MadiDrop, especially compared to other methods you have used to clean your water"

4. How did the MadiDrop compare to other methods you have used to clean your water? (Circle one.)
   Much worse Worse About the same Better Much Better
5. Does the treated water taste better or worse than other methods you have used to clean your water?

Much worse Worse About the same Better

Much Better

6. Does the treated water smell better or worse than other methods you have used to clean your water?

Much worse Worse About the same Better

Much Better

7. Does the treated water look clearer in comparison to other methods you have used to clean your water?

Very cloudy Cloudy About the same Clearer

Much Clearer

8. Have you noticed any health improvements since using the MadiDrop? Yes

No

If yes, what sort of health improvements?

9. Would you improve the MadiDrop in any way? If yes, how?

10. Would you use the MadiDrop to clean your water?

11. Would you use the MadiDrop alone or in addition to your current water treatment method?

12. *"How much would you be willing to pay for the MadiDrop? Would you be willing to pay, for instance, 40 R?"* (response) "*OK, thank you.* "

"And would you be willing to pay [refer below]?"

If yes, increase bid by 10R

If No, decrease bid by 5R

[Continue increasing or reducing the price until the respondent has determined the highest price they are willing to pay.]

Final price point:

13. How do you prefer to learn more about the MadiDrop, through?

School Clinic Newspaper TV Church

14. If you had to replace your MadiDrop or if your neighbor wanted a MadiDrop, where would be the best place to buy them?

SPAR/Shoprite Cooperative Church Clinic School

"This concludes the survey questions and the water collection portion of the study. As I mentioned earlier, we hope to come back in 4-5 months to re-evaluate the MadiDrops again. [Students use hand motion to iterate returning in 4-5 months]. Please continue using it as you have been. Thank you again & have a wonderful day!"

Study Number: ___________________

Does this participant have a MadiDrop with their Filter? If yes, continue. If no, refer to alternative exiting survey

MadiDrop (Silver-embedded Ceramic Disk) End of Study Survey,

June 2013 – August 2013

Script: "Hello, my name is ___. Thank you for allowing us to work with you these 5 weeks. We appreciate your time. This is our last house visit for now, but we hope to come back during the summer to test the water and performance of the filter & MadiDrop again. We will let you know beforehand if we do come back. For now though we will be concluding our work by asking you a few questions about how you used the filter & how you liked it. Thank you again for your cooperation."

1. Was the MadiDrop easy to use? (Point to MadiDrop in bottom of bucket to distinguish MadiDrop from filter) Yes No (Circle one.)

2. How long did you wait to drink water after you used the MadiDrop? Did you wait from:

zero up to 3hrs from 3 up to 6 hours from 6 up to 9 hours 9 hours or more

3. How often did you refill your storage container? _________________ per day / week

"Now I would like to ask you a few questions about how you liked using the MadiDrop, and Filter, especially compared to other methods you have used to clean your water"

4. How did the MadiDrop & Filter compare to other methods you have used to clean your water?

Much worse Worse About the same Better Much Better

5. Does the treated water taste better or worse than other methods you have used to clean your water?

Much worse Worse About the same Better Much Better

6. Does the treated water smell better or worse than other methods you have used to clean your water?

Much worse Worse About the same Better Much Better

7. Does the treated water look clearer than other methods you have used to clean your water?

Very cloudy Cloudy About the same Clearer Much Clearer

8. Have you noticed any health improvements since using the MadiDrop? Yes

No

If yes, what kind of improvements?

9. How did you use the MadiDrop?

Used it after the water was filtered Used it before the water was filtered

10. Did you ever remove the MadiDrop from the bucket? Yes No

If yes, why did you have to remove it?

10. Did the MadiDrop create any problems with using the filter? Yes

No

If yes, please describe.

11. Would you improve the MadiDrop & Filter system in any way?

If yes, how?

12. Would you use the MadiDrop & Filter to clean your water?

13. Would you use the MadiDrop alone?

If no, why not?

14. Would you use the Filter alone?

If no, why not?

15. *"How much would you be willing to pay for the MadiDrop and Filter? Would you be willing to pay, for instance, 200 R?"* (response) "*OK, thank you. "*

"And would you be willing to pay [refer below]?"

If yes, increase bid by 10R

If No, decrease bid by 5R

[Continue increasing or reducing the price until the respondent has determined the highest price they are willing to pay.]

Final price point:

16. "*Let's say you could purchase each piece separately (MadiDrop & Filter). Would you prefer to purchase them separately?"*

If yes, why?

17. "*How much would you be willing to pay for the Madidrop by itself? Would you be willing to pay, for instance, 40 R?"* (response) "*OK, thank you. "*

"And would you be willing to pay [refer below]?"

If yes, increase bid by 10R

If No, decrease bid by 5R

[Continue increasing or reducing the price until the respondent has determined the highest price they are willing to pay.]

Final price point:

18. "*How much would you be willing to pay for the Filter by itself? Would you be willing to pay, for instance, 130 R?"* (Response) "*OK, thank you. "*

If yes, increase bid by 10R

If No, decrease bid by 5R

[Continue increasing or reducing the price until the respondent has determined the highest price they are willing to pay.]

Final price point:

19. How do you prefer to learn more about the MadiDrop & Filter?

school clinic newspaper TV church

20. If you had to replace your MadiDrop & Filter or if your neighbor wanted a MadiDrop, where would be the best place to buy them?

SPAR/Shoprite Cooperative Church Clinic School

"This concludes the survey questions and the water collection portion of the study. As I mentioned earlier, we hope to come back in 4-5 months to re-evaluate the filters again. [Students use hand motion to iterate returning

in 4-5 months]. Please continue using it as you have been. Also, please feel free to clean (ABOODI) the filter and MadiDrop from this point on. You can clean the bucket and filter by rinsing and scrubbing it with boiling water. Do this 2 or 3 times every month. [Student should demonstrate with their hand how to rinse bucket out and how many times a month! Make sure the spigot is open and rinsed as well.] This should help keep it clean. That is all for now, thank you again & have a wonderful day!"

Appendix C: Customer Discovery Interviews

#1

Rose, Business owner

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Rose is an older woman and friend of the Gateway Inn owners in Louis Trichardt, Limpopo Province, South Africa. She is a long time resident of the area. Rose has a borehole at home and believes her water to be of good quality. For this reason she does not treat her water and to her knowledge, has not had any health problems related to water quality. However, she was interested in our technology and recognizes the great need for water purification in the villages outside of Louis Trichardt. She believes that the technology could be quite popular and that our organization may receive some support from residents in Louis Trichardt.

Most important value propositions according to Rose:

- Distribution through **local** retail stores that
- A water purification technology that would treat water to prevent illnesses
- Eliminate the need to retreat water

Important factors but not essential:

- Reduce cost spent on treating water and/or illnesses from unsafe water
- Method that is energy independent
- Reduce the time spent on treating water each day

The key partners identified by Rose:

Most important are government regulatory agencies (e.g. EPA). Would be nice to have partnerships with global business (Nestle, P&G). Partnerships with NGOs for distribution and microfinance are not as important, nor is collaboration with the South African Small Enterprise Development Agency.

Key Insights

Water quality from neighborhood to neighborhood varies, or at least people think it does. Many have personal boreholes

#2

Geoffrey, Assistant Manager for SPAR – Elim Branch

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Geoffrey is an assistant manager at Spar, a grocery and home goods retailer in Elim, Limpopo Province, South Africa. He showed us water storage and purification products currently available in the store. For water storage, the store carries 20 liter plastic buckets complete with a lid and spigot. He explained how some buyers retrofit the buckets to install an electric coil that is capable of boiling water in the bucket. The purpose of boiling is twofold: (1) water purification and (2) cooking preparation. Geoffrey also introduced us to a product called JIK, which is a bleach detergent. He said that when visiting an area clinic, regardless of the purpose of the visit, patients are recommend to treat their water with JIK. Treatment involves adding 1 tablespoon to 20 – 25 liters of untreated water and to let it sit overnight before drinking.

Most important factors according to Geoffrey:

- Advertisement through health systems (clinics), churches, community meetings
- Distribution through local retail stores is preferred over relief agencies and NGOs
- The product should eliminate the need to retreat water, prevent illnesses related to water, be energy independent, reduce the time spent on treating water each day

Important factors but not essential:

- A technology that did not change the odor or taste of water.
- The product be partnered with government regulatory agency, but not necessarily South African Small Enterprise Development Agency

Key Insights

A couple of water purification solutions sold in grocery store. Liquid-chlorine water purification was also used to wash clothes, could be toxic is not used properly. Other water treatment devices were buckets, but expensive and not very practical.

#3

Marcus, Manager of South African Small Enterprise Development Agency

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Topic of interview: Marketing and Branding in South Africa

Marcus is the manager for the Thohoyandou branch of the Small Enterprise Development Agency (SEDA), an agency of the South African Department of Trade and Industry (DTI) in Limpopo Province, South Africa. SEDA implements standards and common national delivery network for small enterprise development. It also aims to develop, support and promote small enterprises throughout South Africa. To attain these goals SEDA provides assistance to small businesses such as business training, advertising, and certification. Marcus has been working with the Mukondeni Cooperative since July of 2012 to improve their business operations. Thus far he and SEDA have provided cooperative governance training, basic business skills training, and external product testing. In the next couple months he and SEDA plan to finance testing and certification of the ceramic technology through the South African Bureau of Standards (SABS). Additionally, SEDA plans to help the Mukondeni Cooperative establish a better corporate identity and attain promotional material (e.g. website, business cards, road signage).

Most important factors according to Marcus:

- Continue research and development
- Distribution through local retail stores
- Approval and partnership with governmental regulatory agencies
- Strong marketing and branding strategy

Important factors but not essential:

- Micro-Finance program

Key Insights

Projects related to water purification in SA may need to partner with SEDA in order to work in local communities and understand the South African governmental regulations on production standards.

#4

Sara, Receptionist of Gateway Inn

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Sara was born and raised in Louis Trichardt, Limpopo Province, SA. She drinks from the tap. She comes from a middle class Afrikaan neighborhood and had never traveled through the rural areas outside of Louis Trichardt. She believes the water conditions in the villages are much worse. Because she lives in a wealthier neighborhood, she doesn't see the need to treat the water unless she wants it to taste better. Sometimes she purchases bottled mineral water because of the taste, however that can get expensive. Overall she wasn't too interested in treating her water, but could see how others in the region may need it.

Most important factors according to Sara:

- Drinking water should retain the natural taste of water

Important factors but not essential:

- Distribution through local retail stores
- Prevent illness related to poor water quality
- Reducing the cost of treating water

Things that aren't as important to Sara:

- Eliminating the need to retreat water
- Reduces the time spent each day to treat water
- Endorsement by NGO or global business

Key Insights

Sara does not personally have a major concern with safe drinking water. Any treatment methods she would use would be for aesthetics. She realizes the need for clean drinking water in rural communities surrounding her town, however doesn't seem to have insight on what those needs are.

#5

Lisa, Host of Gateway Inn

In-person meeting

Consumer segment: Person living in impaired municipal water system, living in suburban/urban areas (upper-middle class)

Lisa went to school in Pretoria, SA and lived there for many years. She recently moved back to Mesina. She works in Louis Trichardt now. All of the places she has been cover the entire geographic area we are focusing our research on. Lisa does not treat her water in Mesina or Louis Trichardt. She is very adamant about her water being extremely clean (South African water being really clean). She does acknowledge it is a different story for water in rural and suburban areas. Lisa also comes from the upper white community in Mesina. It was almost as though she did not want to admit to having the same type of water as many other South Africans who live in the villages. There is definitely a class distinction in the region. She did however express a lot of concern due to livestock feces and water quality in the rural areas. She felt our technology could really be something the rural areas could use.

Most important factors according to Sara:

- Distribution through local retail stores
- Eliminate the need to retreat water
- Keep the natural taste of water
- Prevent illness related to waterborne pathogen
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Global business (Nestle, P&G)
- Government regulatory agencies (e.g. EPA)

Key Insights

There are different socio-economic classes in Louis Trichardt have very different perceptions of their municipal water qualities. The upper-middle class does not like to be lumped in with the poorer rural class. Majority of these people probably don't have clean water (we actually conducted research ourselves a few years back on this matter), but the members are not aware. If they do treat their water, they need something local. Price is less of an issue for someone like Lisa.

#6

Mike, waiter at Gateway Inn

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Mike is a native to Louis Trichardt (Limpopo province, SA). He does not trust the municipal tap so he installed a borehole in his yard. He believes the water from the borehole is clean to drink. He does not treat it. However it did cost him

10,000-20,000 Rand (1,000-2000 USD) to install. He must maintain it himself. He has not tested the borehole water to make sure it is clean, but he believes it is better than the tap. Installation of boreholes is not a common method of getting clean water. Majority of the community can't afford to have private boreholes, especially those living in more rural areas. They tend to boil their water.

Most important factors according to Mike:

- Providing a method for micro-financing water purification products
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Distribution through local retail stores
-

Important factors but not essential:

- Advertisement through churches
- Endorsement by NGO or global businesses and/or government regulatory agency
- Eliminating the need to retreat water
- Keep the natural taste of water

Things that aren't as important to Mike:

- Advertisement through health systems
- Reduces the time spent each day to treat water

Key Insights

People need to install their own boreholes to get clean water. People in Mike's neighborhood do not trust the municipal tap. If they do not have a borehole because it is expensive, therefore the alternative is to boil their water.

#7

Peter, sales associate for Outdoor Camping Store

Consumer segment: commercial retail, outdoors/recreational retail

Peter works in an outdoor recreational store in a mall in Louis Trichardt, Limpopo Province, SA. He lives in the area and it is a city known to have household water problems. He drinks from the tap usual. He believes water conditions depend on the neighborhood in Louis Trichardt and wealthier neighborhoods tend to have perfectly fine drinking water. Other areas of South Africa are not the same. As a result, he always takes iodine tablets when he goes hiking or camping in South

Africa. His store was sold out of purification tablets. This would be the third store in the region we found this item to be sold out! People like using the tablets because they are simple and quick, however do change the taste of water. They use this because there isn't an alternative at the same price point.

Most important factors according to Mike:

- Distribution through local retail stores
- Eliminating the need to retreat water
- Keep the natural taste of water
- Providing a method for micro-financing water purification products
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Approval by government regulatory agency

Things that aren't as important to Mike:

- Advertisement through health systems, churches
- Reduces the time spent each day to treat water
- Endorsement by NGO or global businesses

Key Insights

Water purification tablets were sold out again at a camping store! There is no other product at this price to be a competitor. As a result people are willing to put up with the taste as long as they know the water is clean.

#8

Grace, Sales Associate, CNA Cell Phone Retail Store

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Grace was a sales associate in a CNA cell phone company retail store in Pretoria. She is originally from Limpopo province, but living in Pretoria. She often cleans her water by boiling. She is aware of the health risks associated with poor-quality water. As a result, she often cleans her water by boiling. This was not typical of Pretoria residents, thus we wonder if her concern about safe drinking water is due to her originally being from Limpopo province, where municipal water quality is very poor in many regions. She mentioned that many people from Limpopo boil their water to make sure they don't get sick.

Most important factors according to Grace:

- Distribution through local retail stores
- Eliminating the need to retreat water
- Keep the natural taste of water
- Providing a method for micro-financing water purification products
- Prevent illness related to poor water quality
- Reduces the time spent each day to treat water
- Reducing the cost of treating water

Things that aren't as important to Grace:

- Advertisement through health systems, churches & TV advertisements
- Endorsement by global businesses

Key Insights

Grace boils water because she doesn't want to get sick. Boiling is the cheapest alternative that does not change odor or taste of water. Would prefer a purification system that is locally available.

#9

Juan, Sales Associate, Outdoors hiking store (Pretoria, South Africa)

In-person meeting

Consumer segment: commercial retail, outdoors/recreational retail

Juan is from Pretoria. He loves to hike and camp. He has been living in the Pretoria for years. He does not see the need to purify his water at home, however does use chlorine tablets when he goes hiking. We stopped by another camping store as well and noticed they were sold out in iodine tablets. This was the second time chlorine/iodine tablets were sold out in an outdoor/recreational store. It is summer vacation right now and we are in a very outdoor/recreational community. Overall Juan would be comfortable paying for water purification tablet (<$10), he would use it only recreationally though. So he would need something mobile, effective and lightweight.

Most important factors according to Juan:

- Distribution through local retail stores
- Eliminating the need to retreat water

- Keep the natural taste of water
- Prevent illness related to poor water quality
- Reduces the time spent each day to treat water
- Reducing the cost of treating water
- Approval by governmental agency
- Trusted brand-name

Things that aren't as important to Juan:

- Advertisement through TV advertisements
- Endorsement by global businesses

Key Insights

We randomly saw an outdoors recreational store and decided to stop in. They only have iodine tablets, but they were sold out. This is the second store to have been sold out. The tablets are in high demand given the outdoors/recreational habits of locals.

#10

Molly, Volunteer for PureMadi

In-person

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Molly is one of 8-10 college students that have traveled to Limpopo province, South Africa to establish a ceramic filter factory on behalf of the non-profit PureMadi. During her summer research, she would not drink from tap. Her and her colleagues would collect water from Oasis (water company) 25L tanks at a time. Molly would purchase a container once, and then refill at <$10 USD. The only people who would use this service are upper-class members of the communities (University Professor). Molly has also worked at the University of Venda (on campus) and sees a need for clean water on campus. There is water shortage in the region and stored water tends to be highly contaminated. Bottled water must be purchased from small grocery stores off campus or at the cafeteria. There isn't a proper waste management system, therefore plastic bottles accumulates in the community often.

Most important factors according to Molly:

- Distribution through local retail stores
- Eliminating the need to retreat water

- Keep the natural taste of water
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Approval by governmental agency
- Trusted brand-name
- Advertisement through TV advertisements

Things that aren't as important to Molly:

- Endorsement by global businesses
- Reduces the time spent each day to treat water
- Have recycling program for waste

Key Insights

The local university face clean water issues. Through partnership with the University of Venda we can reach a less frequent but economically well-established consumer archetype. By promoting the technology among university students, we are spreading the word over the entire Limpopo region, as students come from all different areas across the northern province.

#11

EJ Monster, Culture Affairs Officer, US Embassy in South Africa

In-person meeting

Consumer segment: Government agency partnership/Aid agency

EJ has been living in South Africa for 6 months working at the cultural affairs office at the US Embassy in Pretoria, SA. We spent a lot of our time telling him about our project, however he informed us of potential funding sources through US State Department projects partnering with students and universities. He also is helping us set up meetings with the Environmental Sciences Technology Assistant and a USAID representative who work at the Embassy in South Africa as well. His wife is the Environmental sciences assistant. We definitely see an opportunity to connect with EJ's office to for further funding/contract opportunities via gov't agencies. He and his team expressed interest in visiting our factory this June, which we are arranging.

Most important factors according to EJ:

- Continued research and development
- Approval by governmental agency
- Distribution and endorsement by governmental agencies and NGOs

Key Insights

Many partnerships available through US government funded programs. USAID and US Embassy cultural affairs really excited to build community relationships through university associated community projects. Funding opportunities there we need to take advantage.

#12

Rosatina, Kiosk owner in local Elim farmer's market

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Rosatina sells mangos and avocados at a kiosk in a major market place in Elim in Limpopo Province. Elim is a rural community in northern Limpopo in South Africa. She drinks water from a local well, however will boil it at home prior to use. Many of her neighbors do the same. She would be very interested in a simpler method, less time consuming and resource consuming (using firewood) alternative solution to boiling. We described our work with the local community of potters, and she was very interested in learning more. She also suggested we set up a meeting with a community leader (chief, council member, minister) to host a meeting with the community. She says these leaders and the clinic are the most influential people. Others in the community will listen to them about how to clean their water and improve their health. Rosatina is arranging a meeting for us with a council member she knows, so we can set up an information session for her community. Really enjoyed talking to her...I really like how motivated she was to spread the word.

Most important factors according to Rosatina:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Approval by governmental agency
- Partnership with NGOs
- Advertisement through TV advertisements, health systems and churches
- Distribution through micro-finance program
- Distribution through local retail stores

Things that aren't as important to Rosatina:

- Keep the natural taste of water
- Have recycling program for waste

Key Insights

Community development workers are the best to contact about water issues. Spread the word through clinics and churches. Boiling is too time consuming and energy/resource consuming. Simpler method needed purify water.

#13

Megan, Grocery store cashier, SPAR grocery store (Elim, South Africa)

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Megan works at the local grocery store in Elim, Limpopo province, South Africa. Because she works at the grocery store she often buys bottled water ~$2 USD for 5L. She consumes 2L a day at least. She purchases a large quantity of 5L bottles at a lower price than the retail $2 USD by making a combined purchase with other coworkers. Her situation is unique in her neighborhood. Most of her neighbors do not purchase bottled water, because it is too expensive. Instead most of her neighbors boil their water. Boiling is difficult because it uses firewood. Also they must go to a local well to collect water. Megan prefers to buy her water because it taste better than boiled water. Also natural well water from her region is salty. Majority of the people in her community are aware the water is contaminated and it can cause illnesses, which is why they boil their water before consumption.

Most important factors according to Megan:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Reduce time spent on treating water each day
- Keep the natural taste of water
- Distribution through local retail stores
- Advertisement through health systems and churches

Things that aren't as important to Megan:

- Have recycling program for waste
- Approval by governmental agency
- Partnership with NGOs
- Trusted brand-name

Key Insights

Bottled water is a luxury not many people can afford. Usually people boil water. Community is very much aware of poor water quality they drink. If they have the resources they will boil it, however boiling is time and resource consuming.

#14

Melissa, sales associate, Vodacom cell phone retail store

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

In this cell phone store this sales associate had bottled water and a kettle for her personal use during work. Turns out Melissa purchases bottled water and sometimes boils water at home. Her and her colleagues work right next door to a grocery store, so they prefer to get bottled water because it is easily accessible. She do not like the other alternatives water purification technologies, such as a sodium hydrochlorine solution called JIK. The same solution is used to clean clothes and dishes, and basically you use a teaspoon for drinking water and a cup to clean your clothes. People find it weird to use their cleaning detergent for water purification, but they will use it because there isn't a better alternative that is cheaper. The JIK product leaves water tasting bad, and can actually be hazardous if in reach of children or overdosed as mentioned on the bottle.

Most important factors according to Melissa:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Reduce time spent on treating water each day
- Keep the natural taste of water
- Distribution through local retail stores
- Advertisement through media outlets (TV)
- Partnerships with governmental agencies and global businesses
- Trusted brand-name

Things that aren't as important to Melissa:

- Have recycling program for waste
- Advertisement through health systems
- Have recycling program for waste

Key Insights

Melissa preferred purchasing bottled water compared to current treatment methods (include chlorine/bleach solution & boiling). Boiling takes up too much time & only good for small volumes. Chlorine solution tastes unusual & is not appealing (use same product to clean clothes).

#15

Mary, Kiosk owner in Elim Market

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Mary has a mango and tomato stand at the Elim market. She used to work at a daycare that was funded through a US NGO. However the organization ran out of money and she could not make enough money working there. We asked her if she would prefer to have a loan (micro-finance program) she actually didn't prefer it. She was worried she would not be able to make enough money to pay back the loan, the interest and still make a profit. She would find it more appealing if the products she sold were not perishable, however that is not the case right now. Her produce comes from a town 1 hour away, but she must pay for transportation since she doesn't have a car. A business that could be local or provide delivery would be appealing for these potential resellers. She purchases products at wholesale prices at 10% of retail price (which includes price for transportation).

Most important factors according to Mary:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Provide opportunities for local entrepreneurs

Things that are nice but aren't as important to Mary:

- Have recycling program for waste
- Advertisement through health systems, churches
- Have recycling program for waste
- Eliminating the need to retreat water
- Partnerships with governmental agencies and NGOs

Key Insights

Loaning money for business is appealing to business owner depending on the type of business they have. Transportation costs must be pain by Mary. She was in products that were non-perishable with a long shelf-life.

#16

Tina, Potter, Mukondeni Pottery Cooperative (Limpopo Province, South Africa)

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (low-income)

Tina works at the local pottery in Limpopo Province. She has been using the ceramic water filter for 6 months. She really likes it, especially since she doesn't spend as much time cleaning water. She has a lot of children in her household and she has taken the initiative to introduce the filter to schools. On behalf of PureMadi & the cooperative, she goes to schools and does a demonstration of the filter. The teachers really like it product and are interested in getting one for themselves. Tina targeted schools because teachers make the most money in the Ha-Mashamba community. Also, they have a lot of influence on the community, and others would listen to their advice especially since they associate the teachers with their children's well-being.

Most important factors according to Tina:

- Prevent illness related to poor water quality
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Keep the natural taste of water
- Approval by governmental agency
- Trusted brand-name

Things that are nice but aren't as important to Tina:

- Have recycling program for waste
- Advertisement through health systems, churches & media outlets
- Partnerships with NGOs
- Distribution through local retail stores

Key Insights

Teachers are highly respected and well paid in more rural communities. Schools great channel to spread the word and introduce technology through.

#17

Wisani, community development worker, Cooperative Settlement and Traditional Affairs Department in Louis Trichardt, Limpopo Province

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Wisani is a young, active member in a community adjacent to Elim. She was formally a community council member and is currently a community development worker for the Cooperative Settlement and Traditional Affairs Department in Louis Trichardt, Limpopo. Wisani lives in a home that is <u>connected to the municipal water system</u>, which provides water between <u>3 and 4 days a week</u>. Residents <u>must store water</u>, as there is no other source available to the community. Wisani is considering purchasing a water tank for household functions (e.g. shower, toilet, sink). When asked about the quality of the water, she said that she suspects the water coming from the <u>tap may be contaminated</u>. As a result, she <u>purchases bottled water</u> from the grocery store for drinking purposes. When asked if she or other members of her community would be interested in a home water purification device, she noted that she <u>personally would be interested</u>. In her community though, you cannot speak freely in criticizing the quality of the municipal tap because it implies the government is denying residents a basic right to water. Nevertheless, she thinks that a device that could be dropped in water storage containers to purify water contaminated *after* coming out of the tap might be acceptable to municipal officials and well-liked with residents.

Most important factors according to Wisani:

- Prevent illness related to poor water quality
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Keep the natural taste of water
- Approval by governmental agency
- Trusted brand-name
- Distribution through local retail stores

Things that are nice but aren’t as important to Wisani:

- Have recycling program for waste
- Advertisement through health systems, churches & media outlets

- Partnerships with NGOs

Key Insights

Does not trust water from tap. Would like an affordable, easy to use, long lasting water purification system

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#18

Wendy, Community developer, Waterval Regional Office

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Wendy works with the government municipality in Louis Trichardt in the Waterval regional office. People in the community contact Wendy with any of their water problems. She is responsible to manage access to water. She did not think her community needed our technology right now because they have municipal tap that is suppose to be clean (but in private she mentioned she can not speak ill of the municipal tap water – however she boils it at home herself).

If a community did have a water problem, this would be a good solution. She suggested introducing it through a local community meeting. The municipality will organize it, ~1000 attendance and they would explain the technology, demonstrate it works and demonstrate it is supported by the gov't & clinic. The only cost for this type of advertisement would be providing food, rice & chicken. If you do provide food people will likely come back when you call another meeting. She also mentioned the product needs to be approved by the South African Bureau of Standards, which can be done through the Small Enterprise Development Agency.

Most important factors according to Wendy:

- Approval by governmental agency
- Advertise through churches
- Prevent illness related to poor water quality
- Distribution through local retail stores
- Partnerships with NGOs

Things that are nice but aren't as important to Wendy:

- Have recycling program for waste
- Advertisement through health systems, churches & media outlets

- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day

Key Insights

Community meetings reach 1000+ people. A demonstration at such an event would be very effective. Municipal water is clean, however people may still boil water.

#19

Vhenita, Former community development worker, Elim Municipal Water Committee

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Vhenita used to work for the municipal government, but recently resigned to start her own non-profit. Her NGO focuses on providing food and education for people in Waterval. She has applied for funding through local governmental development agencies. They will provide her with seed funding to establish the NGO. While on the water committee for her community she found that her water concerns were addressed immediately but not that the leadership has changed, her complaints are not addressed as quickly. Water is very political in the region. There is support for local leaders who want to start a non-profit in the region.

Most important factors according to Vhenita:

- Approval by governmental agency
- Advertise through churches and health systems
- Prevent illness related to poor water quality
- Distribution through local retail stores
- Partnerships with NGOs

Things that are nice but aren't as important to Vhenita:

- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day

Key Insights

Water is controversial in the region. Close ties to the government helps addressing water needs, however not the case for every community member. There are local community agencies providing funding for locally owned businesses, which we may want to look into as our partners are local community members.

#20 Sarah, Resident of Elim

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Sarah is an older, educated woman we met while she was shopping in the Elim market. She is highly aware of the problems with water quality in the surrounding communities. Sarah sources her water by filling a JoJo tank with water from a borehole. She does not normally treat the water, but sometimes boils if it is visually dirty. She is interested in learning more about water purification technologies and suggested talking to local churches and chiefs to help disseminate knowledge to the communities.

Most important factors according to Sarah:

- Advertise through churches and health systems
- Prevent illness related to poor water quality
- Distribution through local retail stores
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water

Things that are nice but aren't as important to Sarah:

- Have recycling program for waste
- Micro-finance program
- Keep the natural taste of water
- Reduce the time spent on treating water each day
- Approval by governmental agency

Key Insights

Local churches, municipal government, community meetings and local chiefs are best means to disseminate information about a new purification system. Treating water is important but not always implemented.

#21

Dora, Kiosk Owner at Elim Market

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

For her livelihood, Dora sells produce at the Elim market. Because she does not have a tap in her home, she uses water from a community borehole. After collecting water by hand, she stores it in plastic jugs until using it for drinking or cleaning purposes. Dora does not treat the water before consumption, but recognizes the need for clean drinking water. She is interested in affordable technologies to treat her drinking water and would consider purchasing one if it was significantly less than the cost of bottled water in the grocery store. She learned about her poor water quality through her local clinic.

Most important factors according to Dora:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water

Things that are nice but aren't as important to Dora:

- Have recycling program for waste
- Advertisement through health systems, churches & media outlets
- Reduce the time spent on treating water each day
- Approval by governmental agency
- Partnership with NGOs

Key Insights

Bottled water costs $2 for 5L. Affordable water treatment solutions are a major need for people like Dora. Use 20L containers to store water.

#22

Michael, Plastic container store owner, Elim, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Michael sells water containers at 25-50 ZAR ($3-6 USD) for 15L-25L water containers. People use the containers to transport water from their local tap/river/well to their homes. Everyone in this area has a number of them in their home. He purchases them from a seller in Johannesburg (6hrs south) and then must also pay for transportation to Elim. Through Michael we were learning how local resellers purchase their products from wholesalers. Most of Michael's consumers boil their water after collecting in the container or do not clean it at all because it just takes too much time.

Most important factors according to Michael:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Indirect sales through local entrepreneurs
- Reduce the time spent on treating water each day

Things that are nice but aren't as important to Michael:

- Have recycling program for waste
- Advertisement through health systems, churches & media outlets
- Keep the natural taste of water
- Approval by governmental agency
- Partnership with NGOs
- Provide micro-finance program

Key Insights

Locally businesses currently purchase their products from major cities (Johannesburg & Pretoria). They must make arrangements and pay costs of transportation. Many people use 20L-25L water tanks.

#23

Nancy, Potter, Mukondeni Pottery Cooperative, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (making $2-5/day)

Nancy has 5 children with 4 grandchildren. She collects water from a near by river. She received a ceramic filter from PureMadi. Before her ceramic filter, she used to boil water. She really likes using the filter because it removes the dirt in the water. She also likes the design, specifically she likes that the treated water is physically separated from the dirty. Families usually collect water in two or three 20L-water containers at a time. She learned about water sanitation and hygiene from the local clinic and church.

Most important factors according to Nancy:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Advertisement through health systems & churches

Things that are nice but aren't as important to Nancy:

- Keep the natural taste of water
- Approval by governmental agency
- Provide micro-finance program
- Advertisement through media outlets

Key Insights

We discovered a new value proposition for our technology. Our technology enables consumers to distinguish treated water from untreated water, reducing retreatment.

#24

Ann, Potter, Mukondeni Pottery Cooperative, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (making $2-5/day)

Ann was given a ceramic filter by PureMadi, and she learned about the project from the Mashamba municipality. Before this she boiled her water. She had learned through a local clinic she should clean her water. She really likes using the filter. The operating time for the filter is shorter than boiling methods. Her children can clean water with the filter where as before only they were too young to boil the water. She believes schools need this the most because the children in their community get sick a lot!

Most important factors according to Ann:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Advertisement through health systems & churches

Things that are nice but aren't as important to Ann:

- Keep the natural taste of water
- Approval by governmental agency
- Provide micro-finance program
- Advertisement through media outlets
- Partnerships with NGOs

Key Insights

Major advantages to ceramic filter over boiling: can be operated by children, uses less time than boiling (including collecting firewood etc). Easy for children and elderly in family to distinguish between treated and untreated water because it separates treated water already. Schools need this the most given the number of children and how often they get sick. Schools have been receptive to using the filter.

#25

Janita, Potter, Mukondeni Pottery Cooperative, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (making $2-5/day)

Janita works at the Mukondeni pottery cooperative. She also received a ceramic filter from PureMadi. Before this she was collecting water from a water tap. Her water tank is connected to her home and used for drinking, cooking and washing. Even though her water comes from the municipal tap she does not trust it is clean. She boiled drinking water before the filter. She really likes the filter because it is easy to use. She feels her family is healthier, especially her children. She does believe her neighbors would like the filters and would most likely purchase from clinics.

Most important factors according to Janita:

- Prevent illness related to poor water quality
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Advertisement through health systems & churches
- Approval by governmental agency

Things that are nice but aren't as important to Janita:

- Keep the natural taste of water
- Provide micro-finance program
- Partnerships with NGOs
- Distribution through local retail stores
- Eliminate the need to retreat water

Key Insights

She prefers filter over boiling water.

#26

John, college student at Mashamba Technical Institute, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

We met John at a <u>municipal tap</u> where he had come to collect water. I noticed there were 20 water containers that were <u>20L – 25L</u>. People carry their container to the tap in the morning, on their way into town. Then they fill it up and let it sit there until the afternoon. They pick it up on their way home. Containers are left outside without the cover and probably contaminated. Since they live far from work and the tap is on their way to and from work, they have <u>no other means accessing</u> water from municipal tap. I was amazed at how many people leave their water outside like that. They need something lightweight and effective to purify their water.

Most important factors according to John:

- Prevent illness related to poor water quality
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Advertisement through health systems & churches
- Eliminate the need to retreat water

- Distribution through local retail stores
- Provide micro-finance program

Things that are nice but aren't as important to John:

- Keep the natural taste of water

Key Insights

Water storage containers are highly susceptible to getting contaminated! Water purification needs to be lightweight, cheap & portable for these people. Major need in community, where people fill a couple of water containers per household a few times a week.

#27

Alice, resident of Polokwani

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (upper-middle class)

Alice is from a privileged family in Thohoyandou however was raised and currently lives in Polokwani (a highly Afrikaan city). Coming from Thohoyandou, where the water quality is poor, she does not trust the municipal tap anywhere so she uses a very expensive filter attached to her faucet. She can afford to pay a very high price for filtration. When she was growing up, her family would always boil their water. She also noted that many people cannot afford to treat their water the way she does. She recognizes Limpopo's water is dirty. She has a 2-year-old daughter, and she filters her water mainly for her daughter.

Most important factors according to Alice:

- Prevent illness related to poor water quality
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Eliminate the need to retreat water
- Distribution through local retail stores
- Approval by governmental agency
- Trusted brand-name

Things that are nice but aren't as important to Alice:

- Keep the natural taste of water

- Advertisement through health systems
- Have recycling program for waste
- Partnership with global businesses

Key Insights

Upper-middle class income families in the region do treat their water. This is especially true for families with children.

#28

Nikka, waitress at Premier Hotel, Pretoria, South Africa

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

She has lived in Pretoria all her life. She currently drinks straight from the municipal tap and hasn't experienced any health complications. She believes the water in the city is clean to drink; however the water in the villages and rural area are not. If she does encounter water from rural area she will boil it.

Most important factors according to Nikka:

- Prevent illness related to poor water quality
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Approval by governmental agency
- Trusted brand-name

Things that are nice but aren't as important to Nikka:

- Keep the natural taste of water
- Advertisement through health systems
- Have recycling program for waste
- Partnership with global businesses
- Distribution through local retail stores
- Eliminate the need to retreat water
- Simplify treatment method

Key Insights

Not concerned about the water in the city of Pretoria. She drinks from the tap. She is concerned about the water quality in rural areas. She would boil water if it was from the rural villages.

#29

Natalie, Sales Associate, kitchen appliance store, Lynnwood (Pretoria), South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (upper class)

Natalie is an Afrikaan, originally from Johannesburg. She works in a fancy kitchen appliance store. So I would say she not only caters to the upper class but may live under the same conditions as they do too. She drinks straight from the tap as well. She is not concerned about the water quality. She mentioned that access to clean water is not typical for the average South African. However for the northern and eastern Pretoria areas it is common. She warned us not to drink the municipal tap since we are foreigners and especially when we traveled to the rural areas.

Most important factors according to Natalie:

- Prevent illness related to poor water quality
- Approval by governmental agency
- Trusted brand-name
- Simplify treatment method
- Distribution through local retail stores

Things that are nice but aren't as important to Natalie:

- Keep the natural taste of water
- Advertisement through media outlets (TV)
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Partnership with global businesses

Key Insights

Upper-middle class neighborhoods do not treat municipal water and depend on governmental agency to keep municipal water clean.

#30

Mary, cashier at Woolsworth Grocery Store, Lynnwood (Pretoria), South Africa.

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (upper class)

Mary works at a high-end grocery shop. There was only bottled water sold there. There weren't any water filters or tablets, which was what we saw earlier in southern Pretoria at a local grocery store. Mary is trusts her municipal water is safe and clean.

The Lynnwod neighborhood is very happy with their municipal tap, but they are also very much aware their water quality is not what is typically found across South Africa. They all make sure to boil their water when traveling to other cities in South Africa. It was interesting speaking to come black South Africans about water. It seems to be a very sensitive topic, and people almost feel slightly offended or on the defensive when we asked them directly if they treat their water, almost as if it has a negative connotation.

Most important factors according to Mary:

- Prevent illness related to poor water quality
- Approval by governmental agency
- Trusted brand-name
- Distribution through local retail stores
- Advertisement through media outlets (TV)
-

Things that are nice but aren't as important to Mary:

- Keep the natural taste of water
- Partnership with global businesses

Key Insights

People from this community are not concerned about municipal water quality. They drink straight from the tap. They did express caution when drinking water in other regions of the country.

#31

Amy, sales associate, Gizmati Bookstore, Pretoria, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Amy works in Lynwood mall, northern Pretoria area. She drinks straight from the tap water both at work and home. She is not too concerned about water quality in Northern Pretoria. She has never gotten sick from it. The Afrikaaner population in Pretoria is fairly well off, and the municipal government regulates their municipal water system. This wasn't the most useful interview, but led us to think more about what factors are key in developing a community's municipal tap. There is a lot of variation in municipal water systems from region to region.

Most important factors according to Amy:

- Prevent illness related to poor water quality
- Approval by governmental agency
- Trusted brand-name
- Distribution through local retail stores
- Keep the natural taste of water

Things that are nice but aren't as important to Amy:

- Partnership with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Advertisement through media outlets (TV)

Key Insights

Afrikaaner neighborhoods have well-established municipal taps. They are aware of poor water quality in surrounding areas, and make an effort to not drink water from those areas.

#32

Emily, sales associate, Gizmati Bookstore, Pretoria, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Emily is not concerned about water quality in west & north Pretoria. She believes the taps are perfectly fine to drink from. She does however use a Brita filter at home. She prefers the filter because it improves the taste of the water. She spending $25 USD on a filter is not a major expenditure for her household. She mentioned the rich areas of Pretoria (mainly Afrikaaner neighborhoods) have perfectly safe municipal water. However the water quality in the south and east side of Pretoria so not well kept and so water may be visibly dirty and probably contaminated with bacteria.

Things that are nice but aren't as important to Emily:

- Partnership with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Advertisement through media outlets (TV)
- Keep the natural taste of water
- Eliminate the need to retreat water
- Prevent illness related to poor water quality
- Distribution through local retail stores
- Reduce the time spent on treating water each day
- Trusted brand-name
- Partnership with NGO
- Simplify treatment method

Key Insights

Northern and Eastern Pretoria have clean water.

#33

Randolph, construction worker

In-person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

We met Randolph in the bottled water isle of a local grocery store, Pick-n-pay. I noticed Randolph was purchasing bottled spring water. When asked why he didn't just drink tap water, he mentioned he did not trust it was clean. Randolph does not have a steady job and doesn't make too much money from construction. I found it interesting though he purchased 2 bottles of water that would be $1-2 USD for 500mL. This is pretty expensive for him.

Most important factors according to Randolph:

- Prevent illness related to poor water quality
- Approval by governmental agency
- Trusted brand-name
- Distribution through local retail stores
- Keep the natural taste of water
- Partnerships with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Simplify treatment method

Things that are nice but aren't as important to Randolph:

- Partnership with global businesses
- Advertisement through media outlets (TV)
- Provide micro-finance program

#34

Rick, sales associate, Cape Town Camping Outdoor Rec Store

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Previously we had moved away from the hiking market, but I ran into this camping store in South Africa. The most commonly water purification device was <u>iodine tablets ($6 USD for 50 tablets, 50L)</u>. These tablets are available only in outdoor rec stores and used mainly by hikers. Even though iodine tablets are simple water purification technologies, they are only sold in outdoor rec stores.

Most important factors according to Rick:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Partnerships with global businesses
- Reduce the time spent on treating water each day
- Simplify treatment method
-

Things that are nice but aren't as important to Rick:

- Partnership with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Trusted brand-name

#35

Sue, shop owner, Rosebank Mall, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Sue is originally for Zimbabwe, however lived in South Africa for 17 years. Currently she is living in Johannesburg. She considers her tap water to be VERY dirty. It visibly looks dirty, cloudy and brown. She works at the local market in Rosebank mall. She does not have too much money, so she boils her water. She did mention that her family has to pay for electricity and boiling consumes energy. She was interested when we mentioned a locally available purification device. It would be one of her top priority purchases. She does not purchase existing solutions (bottled water & water filters) because they are too expensive ($2.50 USD 5L bottle, $25 USD filter).

Most important factors according to Sue:

- Prevent illness related to poor water quality
- Distribution through local retail stores
- Partnerships with global businesses
- Simplify treatment method
- Eliminate the need to retreat water
- Keep the natural taste of water

Things that are nice but aren't as important to Sue:

- Partnership with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Trusted brand-name
- Purchase technology through local channels
- Reduce the time spent on treating water each day

. **Business Mentor Comment: Lindsey Marshall, Faculty** 02/25/2013This seems like it was a good interview - I think you're starting to narrow in on a potential target market. Can you use future interviews with this customer segment to understand more about the distribution channel, purchasing decisions, etc.?

#36

Bella, resident, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Bella worked at a high-end boutique in the local mall. She was born and raised in South Africa (Johannesburg area). She considers her tap water to be clean and safe to drink. She does not treat it. She considers that to be unique to Johannesburg. She mentioned she would DEFINITELY buy bottled water or boil water if she lived in other cities in South Africa, specifically in Pretoria and Mogandula (East of Limpopo).

Most important factors according to Bella:

- Distribution through local retail stores
- Partnerships with global businesses

Things that are nice but aren't as important to Bella:

- Partnership with global businesses
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Trusted brand-name
- Purchase technology through local channels
- Reduce the time spent on treating water each day
- Keep the natural taste of water
- Prevent illness related to poor water quality

#37

John, resident, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

John is originally from Mozambique. In Mozambique people are boiling their water or purchasing mineral water bottles (5L) if they can afford it. Many cannot afford it, $7 USD. We see similar pains with boiling as before – time, energy and resource consuming. People are aware of the problems affiliated with poor drinking water and would be open to a technology which was effective yet better than the rest by reducing retreatment, time, energy and more affordable.

Most important factors according to John:

- Distribution through local retail stores
- Partnerships with global businesses
- Advertisement through media outlets (TV)
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea

- Reduce the time spent on treating water each day
- Reduce cost spent on treating water and/or illnesses from unsafe water

Things that are nice but aren't as important to John:

- Trusted brand-name
- Purchase technology through local channels
- Provide micro-entrepreneurs opportunities
- Simplify treatment method

38

Tanya, resident, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (<$10/day)

Originally from Zimbabwe, Tanya is currently working in Johannesburg. She works at Villa Blanca and doesn't make much money. She does not treat her water at all in Johannesburg. She drinks from the municipal tap. She considers the water to be clean compared to Zimbabwe and is therefore less concerned. Through her interview, I gained knowledge on water conditions in Zimbabwe.

Zimbabwe borders Limpopo Province in South Africa. Marketing in Zimbabwe is very similar to that of Limpopo Province, because there are many similarities in water needs. In Zimbabwe, majority of people will either boil water or add some detergent. The detergent is used only when absolutely necessary, usually during the rainy season. Boiling is done more often however it takes up time and resources. Boiling may require electricity that is costly and scarce. If not that then it requires firewood, which is time consuming to collect and use to boil, it is a waste of resources. If there was a energy-independent solution for water treatment they would be interested!

Most important factors according to Tanya:

- Distribution through local retail stores
- Partnerships with global businesses
- Advertisement through health systems
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day

- Reduce cost spent on treating water and/or illnesses from unsafe water
- Eliminate the need to retreat water
- Simplify treatment method

Things that are nice but aren't as important to Tanya:

- Trusted brand-name
- Purchase technology through local channels
- Advertisement through churches
- Partnerships with NGO

#39

Danon, resident, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Danon was born and raised in South Africa. He is very much aware of the poor water quality in Johannesburg. As a result, he does not like to drink from the tap. If he does have to he will boil it. At home he buys bottled mineral water, 5L at $6-8 USD. He has grown accustomed to the taste of mineral water and doesn't like the taste of the local tap. As much as he likes the taste of mineral water, he finds it to be a major expenditure. He will go through one 5L container within 4-5 days.

Most important factors according to Danon:

- Distribution through local retail stores
- Partnerships with global businesses
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Advertisement through media outlets (TV)
- Purchase technology through local channels

Things that are nice but aren't as important to Danon:

- Trusted brand-name
- Advertisement through health systems
- Provides recycling program
- Partnerships with NGO
- Eliminate the need to retreat water
- Reduce the time spent on treating water each day

- Simplify treatment method

#40

Nikita, sales associate Tempest Car Rental Store, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Nikita lives by herself and does not consume a lot of water. She does not drink from the tap—that is not an option at all. She uses bottled water, which she gets refilled (5L at a time) for $5.00 USD. She is fine paying this much as she doesn't consumer too much water. However for a larger family this may be expensive. Access to 5L-bottled water is a major issue, because there are no local distributors. She uses the services because she happens to live close by to one, she does not believe this is a common method for clean water used by majority of residents.

Most important factors according to Nikita:

- Distribution through local retail stores
- Partnerships with global businesses
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Advertisement through media outlets (TV)
- Purchase technology through local channels
- Provides recycling program
- Trusted brand-name
- Eliminate the need to retreat water
- Reduce the time spent on treating water each day
- Simplify treatment method

Things that are nice but aren't as important to Nikita:

- Advertisement through health systems

#41

Emily, sales associate at Tempest Car Rental Store, Johannesburg, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Emily does not drink the municipal tap at all! The water from the tap looks dirty and milky, which is very concerning for her. She has previously gotten sick from the tap water thus effective means of treating her water is #1 priority. The municipal tap will even shut off for 2-3days and the water is the dirtiest right after it has been turned back on.

Currently she boils her water and stores it in containers. It is time consuming, but she does not find current options to be useful. 1) Majority of the current filters on market are expensive ($50) with short lifespans (1 month). 2) They are not easily accessible in Johannesburg. It is not practical for her to drive 30 -40 miles away every 2-3 weeks and pay $50 for her water system.

Most important factors according to Emily:

- Distribution through local retail stores
- Partnerships with global businesses
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchase technology through local channels
- Provides recycling program
- Trusted brand-name
- Eliminate the need to retreat water
- Reduce the time spent on treating water each day
- Simplify treatment method

Things that are nice but aren't as important to Emily:

- Advertisement through health systems, churches & media outlets (TV)
- Keep the natural taste of water
- Approval by government agency

#42

Greg Redfern, Critical infrastructure analyst (Virginia)

Phone call

Consumer segment: Natural disaster/relief agency

Greg works in Northern Virginia on water treatment plants and water system grids for the county. He has both personal and professional experience with natural disasters. His family experienced level 5 typhoons while living in Hawaii. They would go weeks with disrupted flow of water and electricity. As a result toilets and clean water were very difficult to come by. He also lived in Alaska, where his family experienced a 8.1 earthquake. They had discontinuous power and water supply. He really liked the idea of having a water purification technology that did not require electricity. When living in northern Virginia, he experienced water shortage during a hurricane. The water grid was damaged (municipal tap) and his family didn't have clean water for days. Clean water in an emergency situation is a top priority following food & heat.

Current challenges Greg identified with water purification devices were that they are either energy dependent, multiple-step methods, one-time use, require assembly or require additional supplies.

What current devices lack:

1) Simple to use – a one step process that doesn't require instruction booklet is major need. In emergency situations people are usual unsettled and are not in the state of mind for multi-step solutions.

2) Self-contained – current solutions require additional materials (buckets to store water, electricity, additional container/tube (etc)).

3) Reusable – chlorine tablets can be used.

4) Energy indpendence – many systems require electricity or some form of power to operate. This will not work in emergency situation.

As a result, organizations like FEMA distribute bottled water or water tanks to families in natural disasters (specifically Katrina). Greg suggested a few distribution channels: FEMA, Walmart, Target, Department of Defense, hardware stores, VA government emergency preparedness office and Boy scouts

Customer relationships: He urged us to contact the state's emergency preparedness office. Both state and federal gov't websites have a page where they recommend major emergency supplies. He suggested we try to get on that list in order to get the stamp of approval from FEMA or state emergency committee. This will help significantly in consumer sales as competitors do not have this and these partners will provide both a channel and awareness to potential consumers about our technology.

Greg identified a lot of needs for this technology in emergency situation, however for this market it is important to partner or sell to major organizations in bulk. The challenge with this market would be the approval process. We have to produce a lot of field data and more laboratory results to demonstrate the product/technology is ready to go. This process could take months to years. By selling directly to end users in South Africa, we are already making revenue while building credibility it works in the most impaired communities. The end-user market in South Africa would be the quickest market we could reach and the easiest.

Most important factors according to Greg:

- Distribution through local retail stores
- Partnerships with aid agencies and NGOs
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchase technology through local channels
- Trusted brand-name
- Eliminate the need to retreat water
- Simplify treatment method
- Advertise through churches and media outlets (TV)

Things that are nice but aren't as important to Greg:

- Advertisement through health systems
- Keep the natural taste of water
- Approval by government agency
- Provides recycling program
- Reduce the time spent on treating water each day

Key Insights

Greg was very excited about the technology. He felt is met a major water pain/need for emergency settings. As a result FEMA and other NGOs distribute bottled water or water tanks to these areas, which is expensive however they don't have a better alternative.

#43

Devan Shah, Mechanical engineer, Krishna Industries, Mumbai, India

Video call

Consumer segment: Local entrepreneurs

Devan Shah is a mechanical engineering working at Krishna Industries and the local university. He is a micro-entrepreneur. He is looking to begin or manage a start up in Mumbai. He saw our technology in the local paper and was interested in franchising to India. Devan was looking to hit the bottom of the pyramid market (people living in villages earning $2-3 USD/day). Current purification methods are not affordable for this group. Current methods are electricity dependent. In many villages in India electricity is nonexistent. The middle and upper class in India use ceramic candle filters ($300 USD), activated carbon systems, or centralized water purification systems. This costs the end user $200-150 USD. The price is not idle for the middle class however people are very much aware of the risks with drinking contaminated water. Therefore they are willing to spend the money. Mr. Shah made a very interesting suggestion to have communities, instead of individual households, invest in ceramic filters. Ceramic filters would apply our technology but are not the cheapest product we could produce. However, they last longer and are more effective at filtering and purifying water. Costing $20-30 USD. This product would be affordable to a community. Channels to distribute the technology through would include temples, schools and clinics. These channels would be responsible for maintenance of the filters. Majority of people retrieve their water from groundwater wells, rivers and farms. The filters would be most idle for these communities, however water collection and distribution of treated water needs to be well organized by the community institution.

Most important factors according to Devan:

- Distribution through local retail stores
- Partnerships with aid agencies and NGOs
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchase technology through local channels
- Simplify treatment method
- Advertise through churches and media outlets (TV)
- Partner with local entrepreneurs

Things that are nice but aren't as important to Devan:

- Advertisement through health systems
- Keep the natural taste of water
- Provides recycling program
- Reduce the time spent on treating water each day
- Eliminate the need to retreat water

Key Insights

Devan, the micro-entrepreneur in India, was very interested in reselling or locally producing such a technology. He would target the bottom of pyramid consumer segment and distribute through temples, schools, clinics.

#44

Steve, ER Technician, UVA Health Systems, Virginia

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Steve is from Athens, Greece. He recently moved to the US. He mentioned there was a major clean water crisis in Greece right now. This is particularly a problem in the surrounding islands. Usually major resorts will have their own water purification systems at the resort. The municipal tap water and system is extremely poor. The water in the islands looks both dirty (sand) and is highly contaminated with microbial organisms.

Even the water used to brush your teeth must be treated. People often use bottled water, or if they can't afford bottled water they boil it. Majority of the water is surface water or contaminated by poor industrial wastewater management. Over years the water table has dropped significantly. Current boreholes and springs are completely dry. The communities are also experiencing economic challenges. As a result, home filtration systems such as Brita are extremely expensive. A device that costs $300 in the US would be priced at $800 USD there. The simplest water purification technologies are not very common, because people don't consider Greece a developing world market. In many ways it is not, however a low cost, effective water purification product seems to be idle for this market. People are highly educated about proper sanitation and water hygiene practices. Therefore they are looking to find a solution that is effective, easy to use and low cost.

Most important factors according to Steve:

- Distribution through local retail stores and online
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchase technology through local channels
- Advertise through media outlets (TV)
- Partner with local entrepreneurs
- Eliminate the need to retreat water
- Keep the natural taste of water
- Reduce the time spent on treating water each day

Things that are nice but aren't as important to Steve:

- Advertisement through health systems
- Provides recycling program
- Partnerships with NGOs
- Simplify treatment method

Key Insights

Greece is facing major drinking water challenges. Water table is dropping and water purification systems are extremely expensive. People are educated and looking for a low cost, effective solution.

#45

Ian Nettleship, Associate Professor, University of Pittsburgh

Phone call

Consumer segment: Research and development

Dr. Nettleship contacted me after reading about the MadiDrop in Ceramic Technology today, which is published by the American Ceramic Society. He said he has several undergrad students working on research projects involving ceramic filters over the past 5 years. He is a ceramicist-processing engineer and he collaborates with the Ceramic Studio at Braddock Carnegie Library. He said he has been studying several issues regarding clay formulation, fugitive phase and silver treatment. He is also looking to tailor sustainable manufacturing practices to specific low-income communities. He indicated that he has read several papers from my research group and that they have been very helpful in his work.He said that he has seen a few approaches that use antibacterial coating on the inside of water containers and similar slow release of copper coils. He said for copper coils, he has found them to be sensitive to water quality.He was interested in learning more about the MadiDrop, including our testing methodology.

Most important factors according to Ian:

- Continued research and development
- Prevent getting fatally ill with diarrhea
- Simplify treatment method

Key Insights

It appears the MadiDrop has stimulated intellectual curiosity in this faculty member, who is already very familiar with ceramic technologies for water purification.

#46

Satish Kumar, Senior manager in R&D, Eureka Forbes LTD., India

Phone call

Consumer segment: Partnerships with global businesses

Dr. Kumar contacted me after reading about the MadiDrop. He works for Eureka Forbes Ltd., India, which he claims is one of <u>Asia's largest domestic water purifier companies</u> and also Asia's biggest direct sales company.He said he read about the MadiDrop from NET and was very impressed by how it works.He wanted to know if he can get this technology <u>for growing markets in India</u>.He said his company would be interested in <u>partnering with us to distribute</u> the product in India. He asked me to explain in detail about the claims we have made for the product (e.g. like bacterial log reduction, longevity, etc.). He still feels the technology is well-suited for the Indian market. He also <u>offered to test some MadiDrops with Indian water</u>.

Most important factors according to Satish:

- Distribution through local retail stores and online
- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Partner with local entrepreneurs

Key Insights

This was an encouraging contact from a company that clearly has great distribution channels. The fact our product has interested one of their senior R&D managers is exciting.

#47

Julia Brennan, Health Volunteer, Peace Corps, Uganda

Video Chat

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Julia is a health volunteer working with the Peace Corps in Uganda. She read a story about the MadiDrop and decided to contact us. Through the Peace Corps, she is working with a NGO. She indicated that the villagers she is working with are drinking untreated water. She said that there are "vast numbers" of gastrointestinal infections among the residents. She indicated she has been considering developing a large-scale biosand filter (e.g. a centralized water treatment system), but after hearing about the MadiDrop, she is much more interested in a decentralized technology like our filter or MadiDrop.She also expressed interest in having the filters or MadiDrops made locally to spur local economic development. She wanted to know if I thought it would be feasible to do this in Uganda. She also asked about time scales of expanding PureMadi to other countries.

Most important factors according to Julia:

- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Partner with local entrepreneurs
- Partnerships with NGOs and aid agencies
- Produce technology locally

Things that are nice but aren't as important to Julia:

- Advertisement through health systems
- Provides recycling program
- Simplify treatment method

Key Insights

She felt a decentralized approach to water treatment (e.g. point-of-use) would be better than trying to establish a centralized water treatment and distribution system.

#48

Ajmal, Product development manager, SNL Financial, Islamabad, Pakistan

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas (middle class)

Ajmal lives in the Islamabad, Pakistan. He has lived there is entire life and currently works for SNL Financial on product development. Ajmal purchases his drinking water from a national company, which is part of the Nestle. His water is delivered to his home in 5-gallon container, which is a recycled bottles. It costs $2 per bottle and he purchases 5 gallon bottles 3 times a week, ~$6/week. Ajmal is in the middle class of the Islamabad and says it is fairly common for middle to upper class families to purchase their water. Everyone in Islamabad is aware the municipal tap water is highly contaminated. There are other local companies who treat, filter water. It costs $1.50 per 5-gallon bottle. This is a cheaper version of the Nestle, however people are skeptical of the quality of water when it is not affiliated with a large, well-known company. So not many people purchase from local companies.

For the middle class it is really important for a new business to either build trust in community or partner with a larger company (e.g. nestle) that people trust. Brand and marketing is key to this consumer segment.In the cities, the centralized water system is not maintained well. Even if the water tanks in centralized water treatment centers are clean, people do not trust the water will remain clean by the time it reaches their home. The pipes are often rusted, cracked and covered with biofilm. By the time it gets to their home it is dirty. Groundwater and creating boreholes is not an option as well. Over time the water table has significantly dropped. You would need to drill 400-500 ft. deep in order to access groundwater. The lower class will boil their water if they can, but boiling is not convenient due to time and energy consumption. I asked Ajmal where one could purchase recycled water in Islamabad. He said that you could get clean water at small local grocery stores or convenience stores. This is where people pick up or drop off 5-gallon containers. Another distribution channel is through NGOs. Usually they will purchase the product and distribute among the bottom of the pyramid consumers. There are a lot of NGOs in the area.

Most important factors according to Ajmal:

- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Partnerships with NGOs and aid agencies
- Produce technology locally
- Provides recycling program
- Advertisement through media outlets (TV)
- Direct sales through local retail stores
- Eliminate the need to retreat water
- Keep the natural taste of water
- Simplify treatment method
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Trusted brand name

Things that are nice but aren’t as important to Ajmal:

- Advertisement through health systems and churches

#49

Rodney Suddith, CEO, Sports Outreach NGO

Video chat

Consumer segment: Non-profit partnership

Rodney works for the non-profit Sports Outreach. Their projects are mainly in East Africa: Kenya, Uganda, Ethiopia, South Sudan. The organization is a Christian-based group, which works to improve water systems. They have local partners, where indigenous people run the NGO chapter in each country. Within each country they have established their NGO. Overall they work with two different groups of people:1) people in the slums (less $1/day) who have extremely poor water system if any at all. 2) people in rural areas, recently displaced and/or undergone a traumatizing event (war) recently. Many people in these communities are HIV positive and diarrheal diseases are major issues! The reason current technologies have not been able to address their needs is because, they are not simple to use and are not socially acceptable.

The main sources of water include, open wells with lots of runoff, and cracked pipelines where puddles develop and people collect water. Streams are also an option for rural residents. But all these water sources, especially streams, are highly contaminated with fecal matter from livestock! Their group has made lots of efforts to develop boreholes.

From their research, they have found that much of the water collected from these boreholes becomes contaminated by the time it is used. Usually children will collect the water, walking a distance of 5-8km. They collect water in 5- or 2-gallon containers. Women may boil water at home to treat it. However boiling is fair too time and energy consuming. They would be fine with a longer purification time as long as operating time is shorter. The biggest risk in consuming poor quality water is when children collect water. They often consume the water on their way to and from the water source.

Therefore, boiling water at home is useless if they are also consuming untreated water. Another major challenge is providing clean water for schools. Usually children are the most susceptible to getting sick in these communities and schools do not have adequate access to good quality water. Rodney mentioned there are plenty of NGOs in the area that would distribute the technology and provide micro-financing programs.

Most important factors according to Rodney:

- Eliminate the need to retreat water
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Simplify treatment method
- Purchase technology through local channels
- Partnerships with NGOs and aid agencies

Things that are nice but aren't as important to Rodney:

- Advertisement through health systems

Key Insights

People living on less than a dollar a day and people recently displaced due to conflict are facing major water challenges in eastern Africa. Social acceptance of current methods is a major issue, in addition to affordability.

#50

Jeremy Hutchinson-Krupak, Professor, Darden School of Business, University of Virginia

In person meeting

Consumer segment: Research and development in manufacturing

We are beginning to think about MadiDrop production, and Professor Hutchinson-Krupak has business expertise in manufacturing and material supply. He was quite interested in our product and offered future help and guidance. He made several interesting observations. First, he was sure to emphasize that if we start producing a product, it should work properly. He said if you put out a product initially and it is not really ready, it can be a difficult hurdle to overcome in the future. He also felt that we needed to begin with small-scale production to find out what steps are limiting and/or problematic. He even suggested hiring a few people, instructing them how to manufacture MadiDrops, and see what goes wrong and why. In this way, we will begin to troubleshoot. We need to develop an expiration indicator for the MadiDrop.

Most important factors according to Jeremy:

- Continue research and development
- Producing ceramic filters & madidrops

Key Insights

He encouraged us to start playing around with manufacturing techniques and he urged us not to begin selling our product until we are sure it works as advertised.

#51

Vho Cetina, Manager, Mukondeni Pottery Cooperative, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

VhoCetina works at the local Mukondeni Cooperative in Ha-Mashamba. She is the manager at the filter factory operations. Even though Vho Cetina has been working with us in managing the factory for the past 3 years, she did not physically see or ever use the ceramic water filter we had been describing to her until a few months ago. I think this is a great example of how people in this community are very much aware of the health risks associated with their water. Vho Cetina has been volunteering her time the past 3 years to the filter factory. She oversees the project 9 months out of the year when we are not there. She only has primary school education and her main income comes from the pottery she makes at the cooperative with addition to a little income from managing the factory. She does not speak very much English, but understands a fair amount. She has four children herself but shares a home with her sister-in-law. Her household consists of 8 people or so. She is related to the village chief. This gives her a little more control over the water supply. Within her community, only half the households can receive water at a time when the municipal tap is on. The Chief decides who in the village gets to receive water.

The tap is piped into Vho Cetina's yard and she has three small Jojo tanks she uses to store water in. The water is used for sanitation and cooking. The water she uses for cooking she treats by boiling. Firewood is very costly to her and viewed as a limited resource in the community, therefore she tries not to boil water unless absolutely necessary. She is heavily involved with her local church, which coordinates community events often. When asked where she would purchase something like a water purifier, she mentioned the local church, health center or school. Knowing a little about the ceramic filters, she really would love to use them in community gatherings like weddings and funerals as she finds people often get sick afterwards.

Most important factors according to Vho Cetina:

- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Partner with local entrepreneurs
- Partnerships with NGOs and aid agencies
- Produce technology locally
- Advertise through churches
- Eliminate the need to retreat water
- Reduce the time spent on treating water each day

Things that are nice but aren't as important to Vho Cetina:

- Provides recycling program
- Simplify treatment method
- Reduce cost spent on treating water and/or illnesses from unsafe water

Key Insights

Local residents experience water shortage. Water purification is very important to her. She prefers not to boil and really only does so if she has a guest. She does find water purification extremely important. She would prefer to purchase such a product through a local church, school or clinic.

#52

Mary, unemployed, resident of Limpopo Province, South Africa

Phone call

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

Mary is 42 years old and married with two children, ages 16 and 19. Her husband works at a car maintenance shop in Elim and they make less than R 250/month ($25 USD/month). She uses her public tap as her source of drinking water, but it is very contaminated. It often takes her 20 min to collect water and she usually does this everyday. Her main responsibilities are to take care of the household while her husband works. She is saving her money to send her children to school. She is very much aware that her water is not safe to drink; therefore she tries to boil it. Just a few years ago she received a ceramic filter from the health clinic and she really loves it. She uses it everyday and finds it very easy to use. If she could improve it, she would want a bigger filter in order to filter larger volumes at a time. Right now she can treat 2-3L per hour. Even though her income is low, she would be willing to pay R150 for a filter. She only feels comfortable purchasing water purification technologies from a health care provider. She would not purchase it from a local reseller or non-governmental organization. She does not trust them.

Most important factors according to Mary:

- Prevent getting fatally ill with diarrhea
- Advertisement through health systems
- Reduce the time spent on treating water each day
- Simplify treatment method
- Partnership with aid agencies

Things that are nice but aren't as important to Mary:

- Provides recycling program
- Eliminate the need to retreat water
- Keep the natural taste of water

Key Insights

Mary finds a water purification device important to purchase. She would not purchase locally from a reseller or retail store because she doesn't trust the source.

#53

Pablo, former resident of Columbia

In person meeting

Consumer segment: Large industrial waste management systems

Pablo was raised in Columbia. His family is in the edible oil business in Colombia. Through his family business, his father faces new regulations every year about industrial waste management, specifically the most concerning being sewage water management.

His family owns a number of companies that process bovine fat in order to produce soap, shampoos, make-up, candles, some chocolates, automotive and machinery greases. Bovine fat processing requires a lot of steam to be directly applied to the raw product. Once the steam process is over, the water needs to be cooled and disposed of. This disposing process is very difficult. From his experience, he felt that many of these industries have strict water disposal regulations. After hearing about our technology, Pablo felt it might serve the needs of these large companies to provide more efficient means to properly dispose or treat the contaminated water. Our technology has not been designed for these purposes, however it is an interesting consumer segment to consider when further research and development has been down to see if it applicable to this type of waste water management.

He also recommended looking at beer industries, as they are very worried about water quality as well. Microbreweries are always looking for good water sources and this may help them attain access to more clean water.

Most important factors according to Pablo:

- Prevent getting fatally ill with diarrhea
- Simplify treatment method
- Continued research and development
- Local micro-entrepreneurs

Key Insights

Discovered a potentially new application to for our technology and it may be completely viable. However, this application would require much more R&D for the team and at this time the current market we are considering 'people with impaired water systems' has a more direct need for our current technology. Talking to Pablo was great and very informative. Further made me realize we need to focus our interviews to the segments we have on our canvas.

#54

Bassam Al-Kuwatli, Immigration consultant, Vancouver, Canada

Phone call

Consumer segment: micro-enterprise/distributor

Bassam lives in Vancouver and works as an immigration consultant. He is originally from Syria, and he currently is visiting his wife in Juba, South Sudan. He seemed to be quite intelligent and acutely aware of water problems in the developing world.He told me that in Juba water is transported via trucks from the Nile river. Some residents buy water directly off the truck and this water is not treated. Most of the truck-water is chlorinated and then sold to residents who then carry the water back to their homes and store it until ready for use. There was some concern that the distribution trucks carrying chlorinated water are the same trucks that carry un-chlorinated water, which might reduce the quality of the chlorinated water. He says that he purchases bottled water at 25 cents per liter for drinking and cooking, because he felt that the water from the trucks, even if it is supposedly chlorinated, is not safe to drink.   He felt that locally produced filters or Madidrops would be very beneficial to the community.He also expressed interest in selling MadiDrop produced by us in the Sudan. He seemed to think it would be a very lucrative product and that many people would buy it. He did note that things were very expensive in South Sudan because the country is land-locked.

Most important factors according to Bassam:

- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Local micro-entrepreneurs

Key Insights

It seems that water quality is quite poor in the Sudan and that Bassam was quite interested in selling MadiDrops.

#55

William and Angie Turley, Owners of Finca Los Arboles, Costa Rica

Phone call

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

William and Angie moved to Costa Rica about 10 years ago from the US to develop sustainable farming practices. Their farm grows "Jatropha", a bush tree (2-3 m tall) that produces non-edible nuts that have high oil content and can be used to make fuel. They were interested in finding out about ceramic filters and the MadiDrop.They noted that in most of Costa Rica, the water supply is constant. In the cities, they have water treatment plants that chlorinate the water, but in the rural areas, water is untreated and typically comes from springs. They perceive that even this water is of good quality, although they noted that there likely are pesticides in the water. They said that near the banana and pineapple plantations, the water is completely unusable and if you use it for a bath or shower, it will cause rashes on the body.They said they wanted to speak to me because they felt there was a need for ceramic filters and MadiDrops in Central America. They felt it would be important to make the filters locally.

Most important factors according to William and Angie Turley:

- Purchase technology through local channels
- Local micro-entrepreneurs

Key Insights

Educated people in rural areas of Costa Rica feel the water is safe to drink without further treatment, although there is concern about pesticides.

#56

Lydia Shawel, Graduate student, University of Virginia

In person meeting

Consumer meeting: Person using impaired municipal water system, living in suburban/urban areas

Lydia was born in Ethiopia and lived there until the age of 10. She recently visited Ethiopia a few months ago. Given her professional background in water sanitation and treatment, she was aware of the water issues in the country. She noticed that the middle-class families generally used water piped systems if they were in urban settings. There wasn't guarantee the water was clean, however piped water access was continuous and people did not store it. The upper middle-class purchased bottled water, if they could afford it. Seemed as though everyone was skeptical of the water quality from the centralized system, however few could take preventive measures such as purchase bottled water. She also noticed that majority of people were not happy about the water system given its unreliability. She did travel some to rural areas and noticed that they relied on community taps or surface water. They simply could not afford bottled water. In these communities people stored water in plastic containers.

Most important factors according to Lydia:

- Prevent getting fatally ill with diarrhea
- Eliminate the need to retreat water
- Provides recycling program
- Reduce cost spent on treating water and/or illnesses from unsafe water

Key Insights

Bottled water was the main solution to water treatment issues in Ethiopia, but majority could not afford it.

#57

Grace, potter, Mukondeni Cooperative, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in rural areas

Grace is living in Limpopo, South Africa as a potter at the Mukondeni Cooperative. She grew up there and has 5 children (22, 18, 14, 11 & 1 years old). She makes between 150-350USD /month (approximately $20 USD/month/person). This is a combination of welfare checks and her income from pottery. We would consider her in the submerging market. Her daily activities include taking care of the house, children, providing food, collecting water, and working at cooperative to sell her pottery. She saves her money for her children's education. Her water comes from a private well, but very contaminated. It takes her 10 min to collect water and she usually does so twice a week. She collects 25L at a time**.** She tries to treat her water through a ceramic filter, because of the health impact. She believes it reduces sickness. She is heavily involved with her church and helps coordinate social events, where she brings her filter to provide the community with clean water.

She received her ceramic filter through the local clinic, where she was educated about safe water consumption and waterborne illnesses. She has been using it for 3 years now. She has been using it practically everyday. She enjoys the taste & smell of the filtered water more than the untreated water. The downfall with the filter is that she cleans it everyday. Given her busy schedule, cleaning the filter becomes a hassle.

Most important factors according to Grace:

- Prevent getting fatally ill with diarrhea
- Advertisement through health systems and churches
- Reduce the time spent on treating water each day
- Partnership with aid agencies
- Provide recycling program
- Keep the natural taste of water

Things that are nice but aren't as important to Grace:

- Advertisement through media outlets (TV)
- Simplify treatment method
- Partnership with NGOs
- Eliminate the need to retreat water

Key Insights

She is using a product very similar to ours. Social acceptance is high! She prefers the better tasting water. Health systems & churches are important channel to reach this target audience.

#58

Angela, firewood collector at Mukondeni Cooperative, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in rural areas

Angela lives in Limpopo, South Africa. She makes less than R250 a month (less than $1 USD/day). She is married and has 2 children (26 years old and 18). Angela does not have any educational training. Her key responsibility is to collect firewood to sell in the community for income. Aside form that she is responsible for taking care of children, purchasing groceries, preparing food, collecting water.

Her main water source is contaminated public tap. Takes 30 minutes to collect water. Collecting 20L at a time. She finds it more important to have good quality water than larger quantity of water. Family and neighbors share water supply in her community.

Everyone has a mobile phone. Usually spends money on food, children supplies and medication. She is not willing to spend more than 10% of household income on water treatment technology. However she does recognize water purification technologies help improver her health. Currently she boils her water, but her local church has a ceramic water filter, so she tries to use that if she can.

Most important factors according to Angela:

- Prevent getting fatally ill with diarrhea
- Advertisement through health systems and churches
- Reduce the time spent on treating water each day
- Partnership with aid agencies
- Provide recycling program
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Simplify treatment method

Things that are nice but aren't as important to Angela:

- Partnership with NGOs
- Eliminate the need to retreat water
- Keep the natural taste of water
- Purchase technology through local channels

Key Insights

Hygiene and living conditions are very poor in her community. Collecting and treating water are very time consuming. She finds water treatment technologies important but not in top 5 priority purchases.

#59

Umer Tariq, Financial Consultant, SNL Financial, Charlottesville, VA

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban area

Umer works for SNL Financial, but often travels to Karachi (urban city) in Pakistan. He also was born and raised just outside of Karachi until the age of 18. He spoke about the water quality in Karachi. Privileged families usually get delivered water, which comes from a private company called Ava. The company that delivers filtered water once a week, similar to the big tanks you seen in offices where water is also dispensed. That water is used for drinking and cooking. They also use Jojo tanks to collect water from the municipal tap for hygiene and sanitation purposes, but they do not use this water for drinking. There is often times water shortage in the city.

Majority of people either use bottled water or boil their water. They also use ceramic pots to store their water. This is a traditional method to keep water insulated, however does not disinfect the water. Having said this, use of ceramics to treat water may be socially acceptable and well received in these communities given traditional storage of water. Ceramic water filters are commonly found in villages.

Umer would say majority of people in Pakistan are aware that their water is not clean. Having said this, for a middle-income family purchasing a water filter/purifier does not make the top 5 purchases. They find water to be necessary but not necessarily purchasing a purifier – they are used to the alternative (boiling). But given the frequent use of ceramic pots our technology may be applicable to this current system. Also through more education and awareness, consumers may find water purifiers important products to purchase – especially if they already identify safe water as a necessity to human health.

Most important factors according to Umer:

- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Partnership with aid agencies & NGOs
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Eliminate the need to retreat water
- Partner with local micro-entrepreneurs

Key Insights

There are major water quality and quantity issues in Pakistan. All socio-economic classes face these challenges. Boiling is most commonly used water treatment method.

#60

Rachel Schmidt, Fulbright Fellow, Limpopo Province, South Africa

Phone call

Consumer segment: Person using impaired municipal water system, living in rural area

Rachel has received a Fulbright Fellowship to work in our ceramic filter factory in Limpopo Province, South Africa. Given her technical knowledge of the filter manufacturing process, she is guiding a group of 45 local women potters and teaching them how to make ceramic filters.Rachel said she has adapted well to the foreign culture. She spends most days at the factory, but she notes that the filters are difficult to produce. Subtle changes in the ratio of clay to sawdust can results in filters that don't flow at the rate of 1.5-3 L/hr and have to be destroyed. Just last week, she said that two of the three male filter molds became dented during pressing. Since the molds were not made in S. Africa, they have had to decrease production to try and get them fixed. Also, there is significant rain during the summer, and this makes air-drying the filters difficult. Despite her best efforts over the past few months, the potters have only produced about 200 useable filters. She did feel that they are still learning and that production will likely increase. She said that firing a large kiln is difficult, especially since the potters and she are not used to doing using it.Rachel also noted that water supply is a major problem in the region, even in the cities of Thohoyandou and Louis Trichardt. Oftentimes, the water does not run for days at a time. At best, it is on for about 8 hours per day.

Most important factors according to Rachel:

- Partnership with aid agencies

Key Insights

Filters are difficult to make. Water supply is a big problem in Limpopo Province.

#61

Fariss Samarrai, Journalist, University of Virginia

In person meeting

Consumer segment: Marketing/branding/outreach

This is not quite an interview by me, but I think it represents an interesting development with the MadiDrop.We had a PureMadi fundraising event here in Charlottesville on Friday, February 8th. Prior to that event, we were interviewed by a University of Virginia journalist (Fariss Samarrai). We spoke for almost an hour, and he was fascinated by our MadiDrop invention. He wrote a story that was published as the lead story in UVA Today, the University's daily online news outlet. The story was picked up by the Associated Press and it has gone viral. If you google "MadiDrop, you will now find links to hundreds of news stories about this invention, none of which were there a week ago. I have even been receiving inquiries about the availability of the product from people who want to buy it now. I just received two e-mails from India, including from a venture capitalist, who want to distribute the product there.

Key Insights

This was remarkable press coverage and suggests there is great interest in this product, at least from the media.

#62

Brad Ponack, Ceramic Engineer, FilterPure Inc.

Video chat

Consumer segment: Sublicense technology to existing filter factories

Brad Ponack teaches factory workers at FilterPure's two factories how to make ceramic filters. He has worked extensively over the last 10 years doing this type of work. He is also a ceramic artist. In our conversation, I mostly focused on asking him about flow rates and silver application to his filters. He said that it can be a challenge to get acceptable flow rates. He said that FilterPure tries to fire their filters in a reducing environment (e.g. oxygen-limited) to produce a carbon layer in the filter. He felt that this carbon layer improved the taste of the water and helps improve water safety. But he also said it can slow down the flow rate, sometimes to level unacceptable for users.I asked him about using silver nitrate instead of using silver nanoparticles and he was a little resistant to the idea. He commented that he has worked with silver nitrate before and there can be problems with discoloration of items that come in contact with the silver (e.g. workers would need to use gloves and it might discolor equipment).

Key Insights

It is interesting the FilterPure tries to keep a carbon layer in their filters. This is normally considered by others to be a defect. Brad seemed resistant to change in manufacturing processes involving silver nitrate. So, it might be a hard sell to license our technology of silver application to FilterPure.

#63

Martin Bolton, Industrial Designer, MTech Industrial Design, South Africa

Phone call

Consumer segment: Product research and development

Martin Bolton has created an award-winning design in S. Africa for a lower receptacle for ceramic filters. He said that he became interested in this during his college studies at the University of Venda in Limpopo Province S. Africa. His advisor, Natasha Potgeiter, was studying ceramic filters and she had a sense that the appearance and functionality of the lower receptacle was very important to users. Martin said he placed various prototype designs in households and then surveyed users about their perceptions. He founds that the spigot needed to be raised above the countertop, that the receptacle had to be aesthetically appealing, and that to prevent the outer surface from becoming dirty, there should be a way to place the filter on the counter without getting it's outer surface dirty while the container is being cleaned. He also found it is important for the top of the container to fit tightly on the storage portion of the container and for components to be stackable for easy transport. Based on this feedback, he developed his award winning design. Martin has released his design into the public domain. He indicated that he has not attempt to mass-produce it, as it would require significant funds to build the injection moldings for the plastic component.

Most important factors to Martin:

- Marketing and branding

Key Insights

The filter receptacle is important to users. There is also a significant capital investment that is required to mass-produce custom receptacles.

#64

Matt Mathieson, Risk Management Consultant, Standard Chartered Bank

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

Matt lived in Taiwan for 7 years working for Standard Chartered Bank. Matt was exposed mostly to the upper/middle class of Taipei. He did some traveling outside the city, meeting people in the rural areas. He was most familiar with the urban living situations in Taipei. He found that people would always boil their water, and then use a Brita filter to remove particulates from housing pipe systems. Overall, Matt believed the central water system in Taipei was one of the best in the world. The water was very clean and water facilities were always maintained well. Even though the city water system was great, the household piping systems were not always the best, including rusting/cracked pipes. Sometimes there are particulates that come out of the tap. As a result, residents always boil their water and then use a Brita filter to remove pipe particulates.

People are definitely aware of the risks associated with drinking microbial-contaminated water. Matt believed that a new purification technology would not succeed in the Taipei market, because people are content with boiling water. Also, boiling is also a cultural practice in Taiwan. Residents have even found ways to address the drawbacks of boiling, like how it changes the taste of water. Tea is a huge part of the culture and this is partially due to improving the taste of boiled water. If they don't drink tea, then people are fine with using a Brita filter. Current Brita filters in Taipei cost 20% more than the market price in the USA. Any new technology may have a chance in being successful if they partnered with Brita.

People in Taipei also use Jojo tanks. Unlike South Africa and Nicaragua, building facility managers are responsible for maintaining the tank and ensuring it stays clean. This is another reason Matt did not see a major pain with purifying water in Taipei.

Most important factors according to Matt:

- Prevent getting fatally ill with diarrhea

Things that are nice but aren't as important to Matt:

- Keep the natural taste of water
- Reduce the time spent on treating water each day
- Reduce cost spent on treating water and/or illnesses from unsafe water

Key Insights

There isn't a major for a water purification technology in Taipei unless you partner with an established company, such as Brita. People are very much aware of the risks with drinking contaminated water. They are willing to spend money on the issue, but Brita has a strong presence in the market.

#65

Gabi Chamarro, Financial Consultant, American Express

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

Gabi was born and raised in Nicaragua. Lived there until the age of 18. She currently resides in NYC, working for AmEx. Her family lives in Managua, Nicaragua. She visits Nicaragua twice a year. Part of her family lives in the urban area of Managua, but a large portion also live outside of Managua. Her family outside of Managua actually owns their own coffee & sugar-producing farm.

Every time she goes travels to Nicaragua she drinks bottled water because she is worried about getting sick. Even though she drinks bottled water, she does get slightly sick each time due to indirect consumption of the municipal water (brushing teeth, showering, washing dishes). Overall the municipal water system in Nicaragua is very poor. People use bottled water majority of the time. As a traveler her pain is using water for other things aside from drinking that get her sick (brush teeth, shower, wash dishes). As a resident, her grandma is also worried about getting sick from water in the same way. They are currently not using any method to treat water aside from boiling or purchasing bottled water. Gabi's family is one of the few families in Nicaragua who can afford to treat their water. She makes a point to mention many families can't afford to purchase bottled water.The upper and middle class families in Nicaragua use JoJo tanks (large tanks that collect municipal water). The water is stored and connected to the home for household needs (showering, washing dishes, cooking, etc). Each family is responsible for purchasing these tanks and keeping them clean. Similar to South Africa, residents in Nicaragua often experience shortage of municipal tap water in addition to power outages. Gabi felt it would be extremely useful to be able to microbially disinfect water at the household level, Upper, middle class in Nicaragua are aware of the health risks with drinking unsafe water and are interested in investing money in better solutions.

Most important factors according to Gabi:

- Eliminate the need to retreat water
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water

Things that are nice but aren't as important to Gabi:

- Keep the natural taste of water
- Reduce the time spent on treating water each day

Key Insights

There is a major need to treat water in Managua, Nicaragua, especially for the upper-, middle class. Currently people use bottled water for consumption. But through indirect consumption of water they are still getting sick from contaminated municipal water. Their water situation for the middle class seems very similar to South Africa.

#66

Michael Pennell, Business Owner, Pennell Tanks, Limpopo Province, South Africa

Phone Call

Consumer segment: Reseller to persons using impaired municipal water system, living in suburban/urban areas

Ceramic filters require a lower receptacle with a spigot. I wanted to learn about manufacturing of plastic receptacles to see if a custom-made receptacle could be easily fabricated. This led me to M. Pennell, whose company manufactures and sells large water storage tanks in Limpopo Province, S. Africa. He owns the business with his brother. He told me about his business and product. It appears they are very successful, as in prior trips to Limpopo, I have seen "Pennell" tanks all over the place. He told me that they use a special manufacturing process that is very cost effective to manufacture their tanks. I did not fully understand the method, but it is a fiberglass spinning process and their tanks are not made from plastic. He told me they were interested in water purification. I asked him when he replaces an older tank with a new one, what does he find inside the old tank. He said typically, there is layer of settled particles on the tank bottom and that it is not particularly sanitary by any means (water that enters the tank may or may not have any chlorine residual). I asked him about manufacturing lower receptacles for ceramic filters and he said that they only are set up for much larger containers. He said that if we wanted a custom plastic receptacle we would have to contact a plastics manufacturer (he said there are a number in S. Africa). He also said that for a custom design, it is necessary to make an injection molding. This is a one-time cost, but it is expensive (he estimated that it would cost $20-$30K). Finally, after describing our filters, he indicated he would be very willing to serve as a retailer for the filters. Interestingly, he expressed interest in being the sole source retailer. I also asked him what he thought the retail markup would be for our filter system, and he thought it would be 20-30% of the wholesale price. He felt this was typical of retail stores in the region.

Key Insights

Making a custom plastic lower receptacle has a very large upfront cost. I was encouraged that they were interested in selling ceramic filter systems.

#67

Cornelius Hagenmeier, Professor at University of Venda, Limpopo Province, South Africa

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

Cornelius is a Law Professor at the University of Venda in S. Africa and the Director of that University's International Programs. However, for this interview, I discussed with him his household water use and perceptions about water.As a highly educated resident of Limpopo Province and member of S. Africa's middle class, he was aware of the health risks of poor quality water. He described the problems his family faced in their middle-class neighborhood. He said that water in the best of times only runs about 8 hours per day (typically between 8 am and 4 pm). He also said, that frequently several days pass when no water is flowing. He indicated that there is a large dam that has been constructed near Thohoyandou and that the government hired a contractor to bring water from the dam to Thohoyandou. However, after the pipe system was completed, they discovered that it was defective and full of leaks. Therefore, the delivery system will likely need to be completely replaced and it may take several more years. It is uncertain if funds are even available for this.

He and his family do their best to store water when it is flowing. They fill buckets to flush their toilets, take baths, and for cooking and drinking. Although the piped water is of good quality, they worry that when it is stored in buckets for several days that it may become contaminated. They have noticed that when the water is turned back on, there is visibly turbidity at first. They aspire to purchase a Jojo water tank to place on an elevated platform in their yard. The tank will fill up when water is running, and when it is not, they can gradually drain the for their household water consumption. These tanks and platforms are relatively expensive, so only wealthier families and some large businesses have them. Cornelius is knowledgeable about our filter project and has said he would very much like to have one for his family's household water consumption.

The most important thing to Cornelius:

- Eliminate the need to retreat water

Key Insights

The more-educated S. African middle class experiences significant water supply and quality problems and also understands the link between water and health.

#68

Tanvi Nagpal, Director of Water and Sanitation Initiatives at Global Water Challenge at Johns Hopkins SAIS, Washington, DC

Phone call

Consumer segment: Research and development

I spoke to Dr. Tanvi Nagpal who is a professor at Johns Hopkins University, School of Advanced International Studies. For many years she worked at the World Bank in the East Asia and Pacific Region, Environment and Social Development, focusing on improving access to drinking water, water sanitation & hygiene. Dr. Nagpal is a great resource in understanding the cash flow from government agency down to local distributor/project manager. She believes the biggest challenge with current point-of-use water treatment technologies in developing communities is lack of business sustainability. It is important to develop an approach where the technology is an aspirational product for the lowest class, yet appealing to the targeted group. Given this, the targeted group still requires a very low-cost product. Then branding and marketing the technology well is another vital component, which has been a major challenge given the low-cost requirement.

Currently ceramic-based technologies include ceramic water filters, but they are too expensive. The production cost for ceramic filters is just too high, thus profits are minimal if any. Many ceramic filter factories are dependent on NGO donations/ or government subsidies. From Dr. Nagpal's experience, even having a major company such as BNG or UNILEVEL manufacture and sell these products at local mass production facilities the business is still not sustainable. From her perspective, price and branding were extremely important factors, which need to be addressed first before even investigating the other components of developing a sustainable water treatment technology for developing communities. She put us in contact with Mark Guy and Glenn Austin, who work for PATH and are the lead on the Gates-funded initiative to investigate market and product sustainability of current point-of-use water treatment devices in developing countries. From their preliminary research it is evident that the most effective methods of treating water in developing communities is at the point of use instead of at the point of collection (municipal tap).

The most important thing to Dr. Nagpal:

- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Partnerships with aid agencies
- Distribution through local retail stores

Things that are nice but aren't as important to Dr. Nagpal:

- Rapid purification within 1 hour
- Keep the natural taste of water

Key Insights

Point-of-use water treatment is extremely important and government agencies are looking to fund related projects. Lack of sustainable technology and inadequate business model has led to many failed technologies in this existing market.

#69

Eric, Manager at Blue Ridge Eco Shop, Charlottesville, Virginia

In person meeting

Consumer segment: Outdoors/recreational consumer

The Eco-Shop is relatively unique in Charlottesville in that it specializes in eco-friendly products. They had a number of water bottles that emphasized the lack of BPA (bis-phenol A) plastics. They had a rather complex looking household water treatment system that retailed for $400 and had replaceable, large filters. But the interesting product was an activated carbon packet that is simply dropped in your water container or carafe. The one that is dropped in your water bottle is $8 and the one for a larger carafe is $13. The idea of simply dropping it in your water container was remarkably similar to our idea for the silver-embedded ceramic tablet. The difference though, is that the activated carbon just removes things dissolved in the water (e.g. taste-and-odor causing constituents, pesticides, gasoline hydrocarbons, pharmaceuticals, etc.). It does not remove or disinfect waterborne pathogens and it would not improve turbidity. Still, the concept was remarkably similar. Eric, the manager, said that they have been selling lots of them. At $8 for a small bag, the profit margin must be quite high. It makes me think that we could include activated carbon in our silver-embedded ceramic tablet to improve water taste and make it safe to drink.

The most important thing to Eric:

- Keep the natural taste of water
- Continued research and development
- Eliminate the need to retreat water
- Distribution through local retail stores

Key Insights

There are activated carbon bags that are dropped into the water container to improve odor and taste of water.

#70

Michael, Sales associate, Dick's Sporting Goods, Charlottesville, Virginia

In person meeting

Consumer segment: Outdoor/recreational consumer

This was not a very informative meeting. Dick's Sporting Goods is a popular national chain store and carries plenty of camping and hunting supplies. However, they only had one point-of-use water purification product, which was previously identified in an interview. It was a water bottle with a UV light built into the cap to disinfect water. Fill the bottle, turn on the light, and shake for 60 seconds. It sold for $100. The sales associate was not a camper himself and added any insight, as he could not comment on other products.



They did have one of the UV light bottles open so I was able to take it out of the box and look at it more carefully (and take a few pictures).

The most important thing to Michael:

- Rapid purification (1 hour)

#71

Jon Mellor, Graduate Research Assistant, University of Virginia

In person meeting

Consumer segment: Person using impaired municipal water system, living in suburban/urban areas

Jon is a doctoral student at UVA and also served as a Peace Corps volunteer for two years. He is currently studying the quality of stored household water in S. Africa. He has worked extensively in Limpopo Province, S. Africa. He has recently completed a field study on water quality and sources of contamination at the household level. His study included household from two rural villages in Limpopo Province, S. Africa.In these villages, Jon said that the water source was from the municipality, but it runs only once or week for a few hours. The water is of relatively high quality, but since it is only available at limited times, people fill up water containers and store the water in their homes. Jon has measured chlorine levels in the stored water over time and it drops quickly within the first couple of days of storage. At the same time, coliform bacteria levels increase over time, and he found that this increase is caused by easy-to-biodegrade organic compounds in the water coupled with biofilms that are growing on the walls of the water storage containers. He said people either have narrow-neck containers (which he found are better and have less contamination in general) and wide-neck containers (which are worse, probably because it is easier for people to reach there hands into it or for things to fall into it).People also use other water sources in the community, including a piped system which brings nearby river water to multiple standpipes throughout the two villages. This water is also poor quality and it continues to deteriorate through the distribution system and household storage.Jon concludes that point-of-use water treatment is needed in the villages because currently the stored water is of low quality.

The most important thing to Jon:

- Prevent waterborne illnesses
- Reduce cost spent on treating water and/or illnesses from unsafe water

Key Insights

Water contamination during storage is a big problem in these rural villages.

#72

Doug, Sales associate, Blue Ridge Mountain Sports, Charlottesville, Virginia

In person meeting

Consumer segment: Outdoor/recreational consumer

Doug is a sales associate at Blue Ridge Mountain Sports in Charlottesville. He is also an avid hiker, so he was able to provide insight in product sales and function as well as his own experiences.Blue Ridge Mountain Sports (BRMS) had quite a variety of point-of-use water treatment devices, including chlorine and iodine tablets, filtration devices, and UV light disinfection systems. Doug initially wanted to tell my about the UV light system. This was a slightly different product than we had seen previously in that the light, water bottle, and battery are all one unit. You turn on the UV light and then shake the bottle for 1 minute to disinfect. Doug felt that was the simplest unit. When I asked about problems he noted that it doesn't remove turbidity and the batteries will run out. This unit was about $100 retail. He noted though that you could have a bunch of bottles and just one cap with UV light and battery and you could then move the cap from bottle to bottle and disinfect many water bottles with just the one cap.He also showed me pumps with ceramic candles in them. We have seen these before, and they retail for about $100. Doug said that this is what he uses and he loves it. He says it pumps about a liter per minute and he felt that the water tastes better than other devices. He said inside the ceramic core, there is also an activated carbon layer, which likely improves the taste. He noted that the ceramic can crack if it freezes (water in the pore space expands and cracks the ceramic) or if you drop it. He has done both, resulting the in the loss of his $100 pump.The ceramic pump had an interesting feature. It comes with a C-clamp that will normally not be able to fit around the ceramic core. However, when the ceramic core is no longer any good, the C-clamp will fit around the core. Then the pump needs to be replaced. He has said his current pump has worked fine for almost three years.The other new device I saw had two plastic bags that looked like IV bags. There is a tube and filter between them. You fill up one bag, hang it on a tree at a higher elevation than the second bag, and water flows by gravity through the filter into the second bag. I guess you do this when you find a campsite to get your water ready for the next day.

The most important thing to Doug:

- Makes water safe to drink
- Keep the natural taste of water
- Rapid purification (within 1 hour)

Key Insights

Doug valued the activated carbon in his water pump because it presumably removes taste- and odor-causing constituents in water. He also noted that the ceramic core cracks if you drop the pump or the temperature drops.

#73

Louis, participant in National Outdoors Leadership School (NOLS)

In person meeting

Consumer segment: Outdoor/recreational consumer

The National Outdoor Leadership School is an outdoors/recreational school.

Students spend a total of 3 months on an outdoor adventure, where students spend one month in a forest plain, one month in an Alpine area and one month free to travel anywhere. They actually had a debate whether water purification was necessary in the Alpine areas, because since there are much animals or fecal contamination of the water. Forest and wildlife areas are extremely important to purifier water, because of microbial organisms. They prefer to use Aquamira if they have to purify their water. Aquamira are chlorine droplets. The disadvantage to using Aquamira is that the taste of water changes. They would use it minimally in Alpine areas to conserve the tablets. The advantage to using Aquamira is that it comes in a snap cap and is effective. The competing product is iodine tablets, that come in a glass bottle, which often gets dirty, may break or water gets into the bottle. They prefer not to use filter pumps, because they are heavy and too big.

The most important thing to Louis:

- Prevents waterborne illness
- Eliminate the need to retreat water
- Keep the natural taste of water
- Rapid purification (within 1 hour)
- Distribution through local stores

Things that are nice but not that important to Louis:

- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchasing managers at water purification factories

Key Insights

Different hikers have different needs. They prefer the water purification method does not change the taste of water.

#74

Anita, Rotary Club Member, Rockingham County Rotary Club

Phone call

Consumer segment: Partnerships with aid/non-profit organizations

Anita is a Rotary member in the Rockingham Rotary Club in Harrisonburg, VA. This club is about an hour's drive from UVA. Anita has been in touch with me in the past and is very interested in supporting PureMadi, non-profit organization that works with local communities to establish filter factories. She said her club is a small one and has never had an international project, but she wants to help. I suspect Rotary could be a key partner, particularly if PureMadi has a not-for-profit component.

The most important thing to Anita:

- Prevents waterborne illness
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Eliminate the need to retreat water

#75

Maboud Ebrahimzadeh, Sales associate, The North Face Store, Washington, DC

In person meeting

Consumer segment: Outdoor/recreational consumer

The North Face Store sells one type of water purifier, Aquamira. It costs $15 and treats a total of 30 gal = 113 L. It takes 15 min to treat water, and 30 min if the water is cold or turbid. The shelf life is 4 years. The challenges with the Aquamaria droplets are that you have to top off the water bottle each time a tablet is added. If this precaution is not taken there is the risk of over-treating water. Aquamira is more desirable over iodine tablets, because it is simpler to use, carry and does not change taste of water as much!Hikers and campers will go backpacking for as long as 3 weeks straight and use Aquamira. Maboud felt that there was a much higher demand for water purification technologies in California and Colorado compared to the Washington, DC area. He also felt it was very important for purification methods to treat water within 30 -45 min.

The most important thing to Maboud:

- Prevents waterborne illness
- Eliminate the need to retreat water
- Keep the natural taste of water
- Rapid purification (within 1 hour)

Key Insights

Taste is a major problem with current water purification technologies in the outdoor/recreational market. Size and simplicity of use are also important factors.

#76

John, Sales associate, Bicycle Pro Shop, Washington, DC

In person meeting

Consumer segment: Outdoors/recreational consumer

John works at a bike sports shop. Currently, cyclers will use treat their water with tablets with electrolytes. This made me thinking if we could develop a ceramic tablet that would release electrolytes. The disadvantage of electrolyte tablets is that they must continuously be added to water. This would cost $13 for the pills and $13 for the water bottle.Also, over time, there is an odor and taste left in the water bottle, presumably from bacteria growth in the container.Some bottles are coated with disinfecting agents, and some people don't buy these bottles because they don't want that feature.Oftentimes, they are not facing contaminated water sources during their rides.

The most important thing to John:

- Prevents waterborne illness

Things that are nice but not important to John:

- Eliminate the need to retreat water
- Keep the natural taste of water
- Rapid purification (within 1 hour)

Key Insights

Our product probably would not apply to cyclists.

#77

Farid Ahmed, Graduate research assistant, University of Houston

In person meeting

Consumer segment: Persons using impaired municipal water system, living in suburban/urban areas

Farid was born and raised in Bangladesh. He is doing his graduate research on drinking water purification. Diarrhea is a problem in rural areas. In addition to waterborne pathogens, the water is highly contaminated with arsenic. Chemicals are added to contaminated water to help clean it. Urban areas have very poorly constructed pipe system and water treatment system. In India, chemical contamination is also a major problem because there are high pharmaceutical manufacturing centers in the country that are not disposing waste properly. Ceramic filters are used in cities. There are water tanks in each household, where water is filled by municipality and then stored. The water tans are highly contaminated with microbial organisms. You can visibly see biofilm layers. Often these tanks are not covered.

The most important thing to Farid:

- Prevents waterborne illness
- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Rapid purification (within 1 hour)

Things that are nice but not important to Farid:

- Keep the natural taste of water

Key Insights

In the major cities, filtering water is very important for high to middle income classes. They currently use ceramic filters for point of consumption treatment. For water storage, they use larger outdoor water tanks that are filled by municipality but filled with biofilm!

#78

Matt, Sales associate, Hudson Trail Outfitters, Arlington, Virginia

In person meeting

Consumer segment: Outdoors/recreational consumer

Interviewed Matt who is specialized in water treatment devices for campers and survivalist market at Hudson Trail Outfitters. They had the hand pumps that ranged in price from $100-$70. They also had iodine tablets ($8), Candle-ceramic handheld filter ($300), UV steripen ($100-$200)The advanced camper would prefer the UV steripen and handheld filters, because it could be used for numerous camping trips and numerous people. Turbidity reduces the lifespan of the technology. UV steripen does not work if the water is turbid, therefore a separate filtration method is required.

The most important thing to John:

- Prevents waterborne illness
- Eliminate the need to retreat water
- Keep the natural taste of water

#79

John, Sales associate, Dick's Sporting Goods, Arlington, Virginia

In person meeting

Consumer segment: Outdoors/recreational consumer

Spoke to John, a sales person in Dick's Sporting Good specialized in camping section. They only sell <u>iodine tablets</u> for water purification/filtration technology. They sold for <u>$7.99 per 50 tablets</u>. This would be good for treating a total of 25L. The tablets <u>do change taste of water</u>. There wasn't any major filtration product. When speaking to John, he <u>didn't feel filtering out particle suspensions was a major issue for consumers</u>. It was more important for their water to be microbial disinfected.

Most important factors according to John:

- Eliminate the need to retreat water
- Prevent getting fatally ill with diarrhea
- Keep the natural taste of water

Things that are nice but aren't as important to John:

- Government regulatory agencies (e.g. EPA)

Key Insights

Iodine tablets were the only product available at this store to disinfect/remove microbial organisms. Campers are very concerned about microbial contamination by *Legionella* & *Giardia*. They prefer the product to be reusable and not alter the taste of water.z

#80

Debora Rodrigues, Professor, University of Houston

In person meeting

Consumer segment: Research and development in developing community settings

Debora grew up in Brazil before moving to the US for graduate studies. Debora's research focuses on nanotubes and their applications in toxicology. She is very much aware of the risks with poor water quality and the many types of contaminants. In Brazil, she noticed families would use <u>ceramic-candle filters </u>to purify water. This is especially common among middle- or lower-income families in small towns near Sao Paulo. <u>Locally owned-family business sold the ceramic filter</u>s. Sometimes the water would taste like clay because the filters were handmade. It would take <u>half a day to filter a full container</u>. It was important for them to clean the filters or replace parts. Brazil's socio-economic classes are changing, where middle-income class is disappearing. Therefore, it is unclear if this technology would be <u>economically feasible to the growing lower-income</u> class.

In some cities in Brazil, low-income residents would use well water. However, the infrastructure in Brazil is very poor and many of these wells are close to poorly kept sewage systems. As a result, there are high child mortality rates in these communities too. Their water looks visibly clean and cold which is appealing but residents do not know it is very contaminated. Education on sanitation and hygiene education is lacking in these communities.

She also worked with people who lived in landfills. Community leaders are the influencers! Sao Paulo the major problem with central water system is that the reservoir is very low causing droughts. Also there are many cracks in pipelines and the water would become contaminated. As a result, if people can afford a filter they will use it. The upper- and middle-class families used microfiltration systems and Brita filters. They also have major water tanks in each household where water is filled by municipality and then stored. The water tanks are highly contaminated sometimes, where you can visibly see biofilm layers at the bottom.

Most important things to Debora:

- Eliminate the need to retreat water
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Prevents waterborne illness

Things that are nice but aren't as important to Debora:

- Keep the natural taste of water
- Continue research and development

Key Insights

There is a market for ceramic-based water purification technologies in Brazil. It is an established market (years!). There are potential partners/consumers through existing retail stores in Brazil & community finds clean water very important to health!

#81

Nick, Sales associate, REI

In person meeting

Consumer segment: Outdoors/recreational consumer

Nick works in the camping section the REI store in Arlington, Virginia. His main clients are hiker or campers using water treatment technologies for their outdoor adventures. He described this clients in three categories: long-term campers, short-term campers, and emergency travelers.There were various water treatment technologies in the store. They had the Sweetwater filter pump, micro filtration, (retail price: $100-70 with replacement components costing $45-20). The lifespan of the filter was 2,000-1,000 L with a filtration rate of 1-2 L/min. These would be fore long-term campers. They also sold UV-vis purification pens ($100-70.00), that treated water within 1 min, but require samples to be filtered beforehand. The gravitational filter that is recommended costs $15-20. Water treatment products usually have an EPA stamp on them indicating they meet EPA standards.

Key Insights

Outdoor recreational consumer segments require rapid treatment methods. They are also willing to pay much higher prices for them.

#82

Shazaad, Manager, Timber City Hardware Store, Limpopo Province, South Africa

Phone call

Consumer segment: Persons using impaired municipal water system, living in suburban/urban areas

Shazaad is the manager of Timber City in Thohoyandou, S. Africa. Timber City is the equivalent of a Lowe's here in the US. His store has helped us with creating the <u>infrastructure of our ceramic filter factory</u>. He indicated that he personally would like to have a filter and he <u>offered to sell our filters in his store</u>. He now has moved to the Timber City store in Louis Trichardt, which is the other population center nearest our factory. We should be able to sell filters in both locations.

Key Insights

We were delighted to learn he would sell our product in his stores.

#83

Liz Walker, Technical Advisor for Environmental Health, International Rescue Committee

Phone call

Consumer segment: Relief agency (Large NGO)

Liz was referred to me through Frank Broadhurst, a prior IRC environmental health specialist. Frank first referred me to Emmanuel D'Harcourt, the chief of IRC's health unit, and Emmanuel referred me to Liz. I spent about 30 minutes interviewing Liz on IRC's needs. Because IRC routinely works with point-of-use (POU) water treatment technologies, she shared her experiences. First she noted about half the people IRC works with live in IRC camps, whereas the other half are displaced but live in existing communities. Although they typically work to provide treated water and safe storage containers, refugees repeatedly have outbreaks of gastrointestinal infections due to recontamination of the stored water. IRC most typically has used PuR sachets and Aquatabs. She noted that the PuR sachets are very difficult for the end user to implement because the product requires two containers and fabric filtration in addition to the sachet. This must be used every day. The aquatabs are somewhat easier but still must be applied every day. She said IRC experimented with ceramic filters in Myanmar, and her perception is that they generally worked well.After explaining the MadiDrop, she was quite positive and highly interested. She even asked about how soon they would be ready. She wanted to keep in touch and said that IRC would be interested in trying them out to see how they performed. Her interest was quite high. We will keep in touch with her.

Most important factors according to Liz:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reduces the time spent each day to treat water
- Reusable product
- Keep the natural taste of water
- Avoiding additional use of supplies

Important factors but not essential:

- Reduce the cost spent on treating water
- Distribution through local channels for NGOs

Things that aren't as important:

- Advertisement through health systems

Key Insights
Ideal economic buyers for a product like the MadiDrop. They currently use aquatabs & PuR sachets. Face many challenges with both technologies, most importantly there is risk of recontamination, they are only single-use and labor-intensive methods. They probably would like to do a pilot project with the MadiDrop to build confidence internally for the product.

#84

Derek Chitwood, Director of Rural Development Partners International (China)

Phone call

Consumer segment: small & local NGO

Derek has created a not-for-profit organization that promotes water purification and health in a rural part of China. He has used traditional methods to create a ceramic filter factory, and his factory has produced and sold about 6000 filters in the last 12 months. He is working to expand his infrastructure to produce between 10,000 and 20,000 filters per year. He has signed a non-disclosure agreement with us to learn about our method of applying silver to our ceramic media and to learn about our MadiDrop technology. He has experimented extensively with different silver application methods, but he did not know about our method nor had he tried it. At first, he seemed very unimpressed. However, as our call continued (we were on the phone for over an hour), he seemed more interested and engaged. The idea of the MadiDrop as a sole water treatment technology did not appeal to him. I believe he felt that it would not be as effective as ceramic filters. However, I noted to him that the MadiDrop can be used in conjunction with a ceramic filter and he agreed that would be a good application.Regarding silver, he noted that it was very difficult and very expensive to get silver nanoparticles into China. Therefore, he was very interested in using silver nitrate as a raw material for filter production. Since our silver application method uses that, he thought that would be very helpful and it would reduce his costs of production. Although he didn't say so, I suspect he will experiment a bit with our silver application technology.

Most important factors according to Derek:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reduces manufacturing time
- Reduce the cost spent on treating water

- Raw materials be locally available
- Apply to other ceramic-based technologies or use in conjunction with them

Important factors but not essential:

- Distribution through local channels for NGOs
- Reusable product
-

Key Insights
I liked that he warmed up to our silver application technology. I was disappointed by his negative reaction to the MadiDrop as a stand-alone method. It was good hearing how difficult it was to use silver nanoparticles in his filter production. Provides insight on future applications of the technology and perhaps sub-licensing it to existing filter factors.

#85

Thomas, Foundation Chair for Rotary International

Phone call

Consumer segment: Foundation/NGO (large) provide financing for implementation of MadiDrop in rural communities

Thomas is a banker by day but is an active Rotary Club member. He told me how Rotary International strongly supports programs to improve developing world water. He indicated that typically, a club outside the US will pair with a US club to raise funds, and oftentimes, these funds are matched by the international Rotary Organization. The current matching program is called the Global Vision Program. Thomas said they have an extensive networks of clubs globally. Typically, if the foreign club is in a developing-world market, they only need to provide a small amount of financial support to the effort and the bulk of the funds come from the US club and Rotary International. The funds, after approval, go to the foreign club and they oversee the project and the disbursement of funds. The project funds cannot support international travel or the creation of physical buildings. Thomas also indicated that Rotary International is currently supporting the development of a ceramic filter factory in Ghana with one of their Global Vision Grants.

Most important factors according to Derek:

- Eliminating the need to retreat water
- Prevent illness related to poor water quality
- Reduce the cost spent on treating water
- Raw materials be locally available

Key Insights

Rotary International is a major player in global water and sanitation and they are currently supporting at least one ceramic filter factory in Ghana, Africa. This is a larger NGO that may wish to fund field-testing and pilot studies for the MadiDrop. It is also a good resource for local NGOs to collaborate with and raise capital for projects.

#86

Anita, Outreach Coordinator for PEN (NGO in Pretoria)

In-person meeting

Consumer segment: Local NGO, urban, medium-sized

Anita works for PEN, a Christian based non-profit in Pretoria. It is one of the largest charities in the city and one of the oldest. We were able to visit the project site and clinic at the church. They have a well-established system. The organization has invested money in real estate, through which it makes revenue by renting out apartments and buildings. It has been able to be sustainable by having a well-established business and investment team. Anita told us there are about 9000 homeless in Pretoria, surveys show 4% want to be on the street. Purpose of PEN is to provide support for people to better themselves, not to change people, but help them to improve their situation in the way that they see fit by two ideas: Wellness (health, social programs, etc.) and Wholeness (religious guidance, etc.)

Pen also has a Small Enterprise Development branch. This is a program of PEN, which provides support and education for those interested in starting a small business in Pretoria. The biggest challenge the non-profit faces constantly is money! Given the racial tensions in the region, the second biggest challenge is showing people you are not try to change them but to help them. Water is not one of PEN's main objectives, but through their Wellness initiative, we believe we can partner with them to reach out to their participants.

Most important factors:

- Advertise through health systems
- Distribution through media & church centers
- Providing a method for micro-financing water purification products
- Endorsement and partnership with NGO
- Prevent illness related to poor water quality
- Reducing the cost of treating water
- Reduce time spent on treating water each day

Important factors but not essential:

- Keep the natural taste of water

- Purchase through local channels
- Approval by government regulatory agency

Key Insights
Major opportunities to partner with intercity non-for-profit. They are well established, well known, and multifaceted (micro-finance programs, outreach, education, etc).

#87
Amanda, Volunteer for PEN (Pretoria NGO)

In person meeting

Consumer segment: Local NGO, urban, medium-sized

Amanda is a volunteer at PEN (non-profit) and has lived in Pretoria all her life. She gave use insight on the city's history. Pretoria was originally a white community, where black Africans had to leave the city limits before 6 pm. After 1992 this law was abolished, and many black Africans started moving into Pretoria, resulting in the movement of many white Africans out of the city limits. Joblessness, homelessness, disease, etc. ensued. This explained why so many people had clean water from the tap. Initially the infrastructure of the city was built well and kept up since it was historically a white city. However, the conditions today do not indicate the water is still clean. The upper class neighborhoods have clean water and are happy to buy expensive filters to clean their water. The lower income and highly black communities live over-crowded apartments. Their municipal tap may not be as well kept. They believe their water is clean, but usually it isn't. Also many people work in the city and then go 'home' on the weekend (they go to rural areas). In their rural areas they definitely do not have clean water.

Most important factors according to Amanda:

- Reduce cost spent on treating water and/or illnesses from unsafe water
- Purchase technology through local channels or through Local micro-entrepreneurs
- Prevent getting fatally ill with diarrhea
- NGO partnership for distribution & microfinance
- Advertise through health systems & church centers

Important but not essential:

- Eliminate the need to retreat water
- Keep the natural taste of water
- Reduce the time spent on treating water each day
- Government regulatory agencies (e.g. EPA)

Key Insights
We learned a lot about the history of the city, which is very important in understanding current health and sanitation conditions specific to each neighborhood in the cities. Given this, it is best for us to target certain the neighborhoods to save time and resources.

#88

Vanessa, Physician at PEN Health Clinic & project manger for USAID/SA in Pretoria

In person meeting

Consumer segment: Local NGO, urban, medium-sized

Vanessa is a physician and researcher whose focus is on women and children's health in rural regions of Pretoria. She has recently started a project called First 1000 Days. It has received funding from international agencies. She works in a rural area 6km outside Pretoria. The women in these communities collect water, and often get sick from it. Their communities are overpopulated and have a number of children under the age of 5 (who are most susceptible to waterborne illnesses). A major source of child malnutrition and mortality is due to contaminated water. Their water source is 30 minutes away and one tap services 100-200 people. They basically wait for over an hour to collect water. Then as they travel back the long distance, the water is contaminated if it was even clean to begin with. 80% of these communities are HIV+ (also another group majorly susceptible to waterborne illnesses).

Take away: NGOs and health clinics in major cities are very much interested in water treatment technologies like us for their projects in rural areas. They need something cheap, long lasting, effective, energy independent and adequate for a household of 4-5. Vanessa was interested in collaborating and speaking to us more in the coming months as her project begins. Her NGO is well established financially. They don't require gov't approval as long as they have sufficient scientific data.

Most important factors to Vanessa:

- Advertise through health systems and church centers (Media distribution)
- Micro-Finance programs
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Government regulatory agencies (e.g. EPA)
- NGO partnership (distribution & microfinance)

Important but not essential:

- Keep the natural taste of water
- Purchase technology through local channels

Key Insights
Lots of opportunity to partner with health clinics for further field-testing and R&D. Also great partners for advertising and test market strategies for products.

#89

Adam, Volunteer for Community Enterprise Solutions (CES)

In person meeting

Consumer segment: Large NGO focused on water purification technologies in Central America

Adam worked in rural areas of Guatemala and noticed major water contamination from irrigation practices. There was much bacterial contamination within the local community. Local people were aware of contamination and did not eat many vegetables for fear of disease. He and his group of volunteers looked at two products to improve household water quality: Silverdyne (colloidal silver drops) and ceramic candle filters. Silverdyne cost $2-3 and would last for a few months, but it never took off because of a lack of social acceptance. Residents were not comfortable adding chemical droplets to their water. There was never an "ah-hah" moment where they could see a visual improvement in water quality.Ceramic filters were widely used but cost about $120. CES tried to subsidize filters for $50, but they were still expensive. A bunch were given away for free with the expectation to replace the filter candles, but people did not realize they would have to pay for the candles in the future.We talked about if linking a technology to an NGO would help its adoption, and he said yes.

Most important factors to Adam:

- Prevents waterborne illness
- Reduce cost spent on treating water and/or illnesses from unsafe water

Important but not essential:

- Eliminate the need to retreat water
- Rapid purification within 1 hr

Key Insights
SilverDyne droplets are not socially acceptable. The filters were too expensive in Guatemala. There are major water quality issues in rural Guatemala.

#90

Rochelle Rainey, Environmental Health Advisor in Global Health Bureau, USAID

Phone call

Consumer segment: International aid agency

Spoke with Rochelle about the current POU technologies USAID used in their development projects. Most commonly used POU water treatment was chlorination, PuR sachet, ceramic water filters, biosand filters and solar disinfection. The challenge with locally available and/or manufactured POU products is ensuring they are always meeting manufacturing standards. USAID works with the Center for Disease Control (CDC) to evaluate POU technologies prior to implementation in development projects. CDC will often send a technology specialist to evaluate these manufacturing sites and the performance of the product. USAID will only use the product if it passes CDC requirements. Other products were not socially acceptable to the community, such as solar disinfection and chlorination. Prior to using these products, USAID focuses on the human health impact these technologies may have. For example, how does this device improve human health in a immune-compromised community? If residents do not care for the device then the product is of no use to USAID. Thus USAID strongly recommends field-testing prior to contacting devices. PuR sachets were the most commonly used devices, however they are not always locally available, as Procter & Gamble produces them. Lack of profit has halted manufacturing of PuR sachets. Among users, this product requires additional training and instructions. There are various steps the user must take and this requires the user to have additional supplies, which is not provided with the sachet. So even though it costs $0.10 for a satchet, the additional supplies, buckets and cloth, make it a costly water treatment method. Also, a single sachet treats only 10L of water. It is not designed to treat smaller or larger volumes. This is an issue as families usually need 20L per day, and may need to store water they do not use all at once. This increases the risk of recontamation.

Rochelle also pointed out that USAID is working with municipal governments to have them incorporate point-of-use water treatment devices in their water sanitation and hygiene plans. Therefore, they can also serve as potential customers for POU companies. Then the local government would distribute the technology themselves. USAID is finding this a useful way to raise awareness of waterborne-related illness and effectively reach those who need POUs the most. Overall Rochelle explained the need for a locally available and effective technology, which has a long lifetime, however is easy to manufacture and distribute. She was very excited about our project and she introduced us to her contact at CDC, Rob.

Most important factors to Rochelle:

- Direct: Local retail stores

- Indirect: Relief agencies
- Simplify treatment method
- Locally accessible
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Eliminate the need to retreat water
- Aid agencies (on-site manager)

Value Propositions
- Reduce the time spent on treating water each day
- Keep the natural taste of water

Key Insights

USAID prefers to fund projects that have already demonstrated the impact on human health, completed field-testing. Products that can be locally manufactured with low distribution cost would be ideal, but first and foremost these products must meet CDC standards. The best products, such as chlorine & PuR satchets, are not always socially acceptable, affordable and sufficient in providing clean water.

#91

Kyle, Peace Corps – South Africa

In-person meeting

Consumer segment: Large NGO

Kyle **i**s a Peace Corp Volunteer living in Saibasa (Limpopo Province, South Africa). He works on an education project and noticed major water shortage in schools. The schools are over crowded. They communities' water quality is not good and so a lot of children get sick. Schools definitely need a water purification system, and the government will not provide anything more than water from the municipal tap because it believes it is delivering clean water. Therefore, the government may not fund it or allow it. We have also seen that people are very timid about challenging the water quality from the municipal tap. We need to partner with strong community leaders or gov't partnerships programs in order to address this challenge.

Most important factors

- Advertise through health systems and church centers (Media distribution)
- Direct: Local retail stores
- Eliminate the need to retreat water

- Prevent getting fatally ill with diarrhea
- Purchase technology through local channels
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water per day
- NGO and relief agency partnership to help with distribution & microfinance

Important but not essential:

- Keep the natural taste of water
- Government regulatory agencies (e.g. EPA)

Key Insights
Schools are extremely valuable resources in these communities. They are also very tricky to work with because they are so closely affiliated with the government. Schools need clean water!

#92

Sammy, Volunteer, Peace Corps South Africa

In-person meeting

Consumer segment: Large NGO

Sammy is Peace Corps volunteer in South Africa, in a village north of Limpopo Province. Her community does not have clean water, but people often boil it. She uses the commercially available sodium hypochlorite solution to clean her own water sometimes, but also a brita filter. She is completely aware the brita filter doesn't remove pathogens, but just goes with it anyways because there really isn't another easier filter device for her to use. The Peace Corps warns her about the water in Limpopo, but doesn't provide the funding for one. Volunteers often make decisions based off of previous volunteers' experiences and suggestions. They are willing to invest in a solid filter as they all get really sick the first year they are in the country and periodically following that due to water contamination.

Most important factors to Sammy:

- Advertise through health systems and church centers (Media distribution)
- Sales and access through local retail stores
- Eliminate the need to retreat water
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day

Important but not essential:

- Micro-Finance program would be nice
- Reduce cost spent on treating water and/or illnesses from unsafe water
- NGO partnership to help with distribution & microfinance

Key Insights
The commercially available sodium hypochlorite disinfectant is used in extreme scenarios, People don't like to use it because it is the same solution they use to clean their clothes. The user must be taught how to use it properly as it may be hazardous otherwise. Volunteers believe that the best means to educate people and spread the word is through clinics and community meetings.

#93

Scott, Volunteer, Peace Corps South Africa

In-person meeting

Consumer segment: Large NGO

Scott is a volunteer in Thohoyandou (Limpopo Province). He works in the health team, raising awareness for HIV/AIDs. His experience with water and the peace corp was similar to Sammy's. Initially he would get very sick, but then it only occurred once every couple of months. His community does not have clean water and many people boil water. They do not like using the commercially available chlorine solution because it smells funny. Scott filters his own water. He uses a gravity filter bucket that the Peace Corp recommended to him. Advertising through Peace Corp is a major possibility. Peace Corps has had a presence in South Africa for 15 years. The organization will warn volunteers about the risks associated with water, and try to recommend filter methods. Their program is not very well organized in South Africa, and volunteers can definitely use a lot more information about how to treat their water. They are most interested in solutions that are easy to use, effective and locally available in villages they work in.

Important factors to Scott:

- Advertise through health systems
- Direct: Local retail stores
- Eliminate the need to retreat water
- Purchase technology through local channels
- NGO partnership (distribution & microfinance)

Important but not essential:

- Local micro-entrepreneurs
- Keep the natural taste of water
- Reduce cost spent on treating water and/or illnesses from unsafe water

- Reduce the time spent on treating water each day
- Government regulatory agencies (e.g. EPA)

Key Insights
Peace corps could be a channel to advertise. Volunteers are aware of water problems, however the organization does not provide them directly with solutions. Volunteers are a unique consumer archetype in this community.

#94

Bobby Wrenn, Missionary for Beyond Baptism (http://www.beyondbaptism.org)

Video chat

Consumer segment: small NGO

Bobby Wrenn is actually a technology (IT) specialist, who has lived in Texas for 30 years. He has been doing missionary work on the side and recently gotten very involved in beyonebaptism.org. He is now a focused on implementing new technology in the rural areas of New Guinea. He has been a cultural and team leader in the region for years now. Previously he has worked on implementing an off-grid solar system. Bobby describe New Guinea as 90% farmers with lots of jungle area. They have plenty access to groundwater, however the water is not clean and it is evident as there is high prevalence of intestinal parasite infections. Since they mainly use groundwater, the water is fairly clear and doesn't have chemical contaminants. The water seems to be well suited for our technology. The most important factor to Bob was the technology that could be produced locally by a local business or factory. The region he works in is very much isolated. Bobby was really interested in the idea of providing clean water and simulating the local economy. Currently they do not use anything to treat their water. So I wondered if people felt the need to treat water - Bobby assured me that they are putting a lot of efforts in hygiene and sanitation education for the community. Boiling is also not the best solution, as it uses up a lot of time and energy. They are also looking for a solution that can purifier large amounts of water, without altering the taste. In regards to income, people in the village usually earn $300/person/yr. We are dealing with $1/day end-user. Bobby's NGO is looking for a scalable solution for the community. Approximately 300 people are in each village and they collect their water in 5-gallon containers. Their water source is about 1 hr away (walking). Government approval and working with NGOs in the region is not a problem at all-- everything is pretty flexible. It is important though that materials for manufacturing and manufacturing itself be done locally, as it is extremely hard to import constantly. Also the rugged roads make transportation very difficult across the island. Such distribution costs and social acceptance have not made other water treatment solutions feasible for these communities.

Most important factors to Bobby:

- Church centers (Media distribution)
- Purchase technology through local channels
- Keep natural taste of water
- Distribute through help of NGOS & Aid agencies.
- Eliminate the need to retreat water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Simplify treatment method

Important but not necessary:

- Reduce cost spent on treating water and/or illnesses from unsafe water
- Government regulatory agencies (e.g. EPA)

Key Insights
People of New Guinea have major waterborne illness challenges. They need a locally produced and available solution. Social acceptance has inhibited competitors to be successful in this market. Regulatory procedures and partnerships with NGOs is very simple to achieve in the region.

#95

Prashant Maniar, CEO, Encito Advisors

Phone call

Consumer segment: micro-finance NGO & partner for developing projects

Prashant has a consulting company in Mumbai focused on water treatment policies. He used to live in San Francisco for 10 years working on start-ups related to water technologies up until a year ago when he moved back to India. He has worked with major companies in India such as Hindustan Unilever (HUL). HUL owns 60% of the existing water purification market in India. They are selling a $40 USD filter, which they micro-finance to the bottom of the pyramid (BoP) at 8-10% interest. Basically HUL partners with microfinance NGOs for the BoP segment. He felt there was really three ways to go about introducing a new purification technology to the Indian market: (1) directly - coming into the country and setting up shop. He thought one would definitely fail if they used this channel. (2) Have a technology licensing deal with an existing company. He was not convinced existing companies had figured out the sweet spot or had enough flexibility to do this, even though they had the leverage. (3) Do joint venture with a local marketing company, where you provide the technology and the Indian partner would provide the capital and horsepower to investigate the market.

Prashant's knowledge on the Indian market was great to hear, however I think he was way too focused in trying to figure out what we had and how he could make a profit out of it. One really useful thing he said though was that the Indian and African market married each other in regards to water purification technologies. Turns out Prashant had some experience on the ground and was a project manager for a bio-gas company. In his work with that group, he had to visit many villages and figure out how to get this to the BoP. He was describing the villages mentioning that people do not have electricity for 40 km from where they live. To treat water they would boil it, and to boil would require a lot of time and energy!! They need a solution that does not cost them energy (wood, electricity, etc).

Furthermore, there is a major water pollution problem from industrial contamination. Major industries are dumping their effluent in surface water sources, which both cities & villages use for their water source. As a result, there is also a market for water purification technologies for chemical contamination. There are more government policies requiring them to treat the water prior to disposal and recycle 85% of the water they dispose. If people are not collecting water from these contaminated surface water sources, they will use rainwater.

Challenges with rainwater harvesting include the water table dropping in India, and topography is changing. This is not a sustainable solution for the communities, because to gain access to groundwater wells would have be twice as deep. When asked about the middle class's water needs, Prashant described the market in the middle class to be driven by brand and marketing quality. They also have water needs, however the competitors have monopolized the market. Therefore it is really important to meet the needs of the BoP. He also mentioned to reach the BoP you may need micro-financing more than you may need and NGO. This was different from previous interviews, but it seems as though people in India are very much aware of the water challenges and are willing to purchase such a technology with a little micro-financing.

Most important factors to Prashant:

- Eliminate the need to retreat water
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Reduce the time spent on treating water each day
- Simplify treatment method
- Government regulatory agencies (e.g. EPA)

Key Insights

In India you really want to target the BoP. May not need a partnering NGO, but will need a micro-financing partner. Water sources are shared between urban and rural areas. Market is saturated with competitors, yet pricing is major issue.

#96

Ben Armstrong, CEO, WellDone

Video chat

Consumer segment: medium-sized NGO

Ben is CEO at WellDone. WellDone is a spin off from Hattery Labs focused primarily on water challenges in developing countries. Ben worked with Hattery Labs and now is transitioning into WellDone. Currently, WellDone is a non-profit organization focused on developing monitoring devices to track performance of wells. They have been involved with a lot of other water-NGOs. Currently their product is still in its development stages but hope to launch it soon. Until now, WellDone has focused majority of their efforts on customer discovery in these communities as well as running education programs on water sanitation and hygiene.

With the development of their well monitoring device, WellDone hopes to transition into a for-profit company in the coming year. We were put in touch with Ben to learn more about the structure of a for-profit company and learn more about the water market. Through our conversation, we felt WellDone could be potential partners for us. They are working on improving centralized water systems, however even if people collect clean water they still need a mechanism to treat it at the point-of-use. Ben acknowledged this as well and expressed interest in our factory in South Africa. Much of their projects are in African countries and access to such treatment would be really useful to their projects.

Ben's biggest concern was cost, ease of distribution, longevity of the product and mass production capabilities. Their projects and the communities they work with are pretty large (100 people or so), therefore they would need a lot of filters/purifiers at once. Capabilities of scaling up manufacturing.

Most important factors for Ben:

- Continue research and development
- Producing ceramic filters & madidrops
- Direct online sales
- Indirect sales through development agencies, NGOs, relief agencies
- Eliminate the need to retreat water
- Prevent getting fatally ill with diarrhea

Key Insights
WellDone could be a potential partnering NGO. We learned a lot about needing to scale-up.

#97

Emily Simonson, Volunteer, Global Medical Brigades

Phone call

Consumer segment: medium-sized NGO

Emily works for GMB (global medical Brigades). GMB works in four countries: Honduras, Ghana, Nicaragua and Panama. Their main objective is to get professional volunteers to go over to medical clinics. They facilitate in improving patient care, preventative health education and aiding pharmacies. They work with 15 communities in Ghana and one of their biggest projects is promoting water hygiene and sanitation. They have partnered with a local manufacturer of lifestraws. Through the medical clinics they promote and sell lifestraws! This is definitely one channel/customer relationship tactic we can use to make customers aware of our technology. It is working really great for communities in Ghana! Given this though they still heavily subsidize life straws! They began this project a year ago.

Most important factors:

- Advertise through health systems
- Aid agencies or NGOs as on-site managers
- Prevent getting fatally ill with diarrhea

Key Insights

Medical clinics are a great place to advertise and sell water purification products

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#98

Frank Schalla, Volunteer, Global Water Brigades

Phone call

Consumer segment: medium sized NGO (Ghana, Honduras, Panama & Nicaragua)

GWB focuses its efforts in four countries: Ghana, Honduras, Panama & Nicaragua. Water projects are being conducted only in Ghana and Honduras right now. Frank spoke to me about the Ghana projects they are working on.

He is located in central region of Ghana, specifically working among 15 communities in the southern coast. There are major water issues for these communities, both poor access and poor quality. They can only use wells for hygiene purposes not drinking water. They often have hand-dug wells, but they also are only good for hygiene. Boreholes and springs are just not feasible given this region's topography.

Currently, households have 4 options with drinking water:

(1) Surface water: There are 5 surface water sources (ponds/lakes) which people collect water to mainly use for hygiene. They do use it for consumption unless they really need to. Of the 5 ponds, only 2 have a steady volume of water. As a result, the wait time at these ponds was 6-8hrs. These communities also experience dry season for 3-4 months per year. This is however their primary source of water.

(2) Water bag sachets: These water bags sell for $150 cedi = $78.35 USD/ 15L. This 15L supply will come in 30 smaller (500mL) bags. This water has been filtered and treated with UV-vis light, then distributed by a private company located in the capital.

(3) Tank trucks: These large water trucks deliver water (15,000-20,000L). They are much more expensive, but even worse the business contracts and servicers are not dependable or honest always. For NGOs this is a major drawback. This is not an feasible solution for households and must be a community-led initiative. As a result of the challenges, this service is no longer supported by GWB.

(4) Harvesting rainwater: This is where GWB is focusing its efforts on most. Harvesting rainwater has made families less dependent on centralized water systems. As part of the harvesting protocol, much of the turbidity in the water is being removed. GWB is looking for better POU solutions to provide microbial disinfection. Currently, they are using the lifestraw family units but this is expensive.

Currently GWB focuses on 16 families where they have installed rainwater harvesting methods with the lifestraw family unit. The challenge with lifestraws are that they: (1) do not work well, (2) are separate from the rainwater system (3) last only a year, (4) are costly (GBW purchases them at 45 cedi and sells them for 5 cedi).

GWB provides lifestraws within these communities but is facing distribution challenges with lifestraws. GWB purchases lifestraws from a local production facility in the capital of Ghana (a 2.5 hr drive each way).

Community members definitely do realize the health risks with using surface water. However they perceive rainwater as ‘rain from God’ therefore it is pure. However, GWB is working closely to educate the community on how rainfall becomes contaminated due to roofs and dirty surfaces. They have been <u>successful overcoming the social norm</u> and people are very interested in treating even their rainwater. Aside from microbial contamination, rainwater is very susceptible to other pollutants such as asbestos. It is still used in construction projects in Ghana and rainwater running off of the roof is at risk for asbestos contamination.

I also asked Frank about what the technology validation process was before GWB decides to purchase and incorporate these products in their projects. His particular agency does not do a rigorous review of the products. They rather get their hands on them and validate them in the field themselves. Therefore CDC approval or approval from a local regulatory agency is not necessary for them. As long as there was scientific, published data on the technology that was enough for them to consider conducting field testing.

Demographics for the community Frank works in: They are fairly poor families (submerging market). However a water purification device would definitely be in their top 5 products to purchase. They are VERY aware of the risks with unsafe water, pretty remarkable actually. The community does not like outside support, which is a problem. The most successful family members tend to leave the community, and then not give back. Given their financial burdens, GWB does not give away their products away for free. They sell them at a 90% subsidized price. Another really interesting thing is that GWB and other NGOs are working to establish banks and savings for families who cannot afford purification technologies. This way the banks provide them with a savings plan, which also helps them manage their money better too. Therefore we concluded that it is important to partner with local micro-finance projects to bridge the cost gap.

Most Important Factors to Frank:

- Advertise through health systems and Church centers (Media distribution)
- Eliminate the need to retreat water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Simplify treatment method
- Sales and distribution through NGOs, relief agencies and local micro-entrepreneurs

Key Insights

They find it important for new water purification system to fit well into pre-existing water collection system. NGOs are working with local banks to help lower income families afford water purification devices. Submerging market in Ghana finds water VERY important, they are aware of health risks.

#99

Lisa Ballantine, Executive Direction, FilterPure Inc.

Phone call

Consumer segment: Small NGO

Lisa Ballantine lives in the Dominican Republic but grew up in the US. She became interested in ceramic filtration technologies when she was a student in the ceramics program at the University of Northern Illinois working under the supervision of Manny Hernandez. She created her own non-profit organization, FilterPure. She and her husband moved to the Dominican Republic, and while he was a housing developer, she began the first FilterPure factory. Her work coincided with the Haitian earthquake, and as a result, she had a remarkable demand for ceramic water filters. This spurred her to start a second factory in Haiti. She has been selling ten to twenty thousand filters each year. At one point, she received an order for 30,000 filters and she had to turn it down because she would not have been able to produce them fast enough.

Almost all her sales are to NGOs or government agencies. She sells almost no filters through retail stores. The NGOs for the most part give the filters away. Her filters have a retail price around $35, which includes the lower receptacle. Although filter sales have been strong, she indicated that it is sporadic, and sometimes, her DR factory has to switch over to making ceramic bricks if demand slows down. She also puts a very large amount of silver in her filters, and this costs about $5 per filter. She mixes silver nanoparticles in with the clay, water, and sawdust prior to firing the filters. She indicated that she does worry about recontamination of the lower reservoir after water has passed through the filter. She did not seem interested in changing her silver application process, although she was curious about using copper instead of silver.

Key Insights
I was impressed by her large sales to NGOs, although this region of the world is unique in that she was able to capture the large influx of aid dollars following the Haitian earthquake.

#100
Rob Quick, Technology Evaluation Specialist for POU Water Treatment Methods, CDC/OID/NCEZID

Phone call

Consumer segment: Aid agency

Rob works at CDC as a technology specialist, having focused on evaluating water purification at the point-of-use since the 1990s. A lot of his work has been with projects in Central And South America. From his experience, chlorine is the most commonly used method because it is very cheap. It is one of the oldest point-of-use water treatment methods. The challenge has been treating turbid water (reduces effectiveness), the taste and the recurring purchase price. After Chlorine, the most commonly used method in the developing world has been PuR Sachets. P&G has been manufacturing them and Rob specifically likes them because of their efficacy in field performance. Rob did point out that many POU devices have not been validated in the field. This is a major issue, because agencies and NGOs will spend so much money on methods that are not socially acceptable. Providing data demonstrating long-term social acceptability is a major plus!

Rob's most favorite POUs are chlorine & ceramic water filters (Potters for peace). He has worked a lot with these filters in Southeast Africa. The major plus with the filters is that they fit well in the lifestyles of consumers. It is like a kitchen appliance. Also, it is not time consuming or complicated to use. The user just pours water in it and doesn't have to do anything until the water is treated. Even though the filters didn't remove viruses the best, he wasn't too worried because viruses are not the most life threatening pathogens in these regions. The disadvantages of ceramic filters include cost ($14-20) and not removing all microorganisms. He believes the focus for ceramic filters should be providing better purchasing options (subsides, payment installments).

Rob also gave us some insight into the different consumer segments purchasing POUs. For the 'bottom of the pyramid' group, they live on less than $1/day. Their mentality is "if they don't have the money in their pocket at that moment they won't buy it to treat water!" Even if these people recognize the importance of clean water, they just have other, more urgent things they need to spend money on (e.g. food/clothing/medicine), preventive health measures doesn't make the cut. Rob believed the very poor will never be able to purchase these products, but the way to go is through partners (relief agencies) to get this to end users. He also mentioned the 'submerging market', the group of people who make $2-5 /day. This is really the best target market to make POUs aspirational products for them. The other major target would be the middle-income class, as even someone in this group may drive a BMW, but doesn't have clean tap water. Rob mentioned testing a razor-blade model, but again really felt that these technologies had to be given away for free to the bottom billion. If you applied the razor-blade model to the other segments, he really felt the sweet spot for recurring cost should be at annually.

Most important factors:

- Distribution and sales through local retail stores
- Indirection sales through relief agencies and NGOS
- Eliminate the need to retreat water
- Keep the natural taste of water
- Prevent getting fatally ill with diarrhea
- Reduce the time spent on treating water each day
- Reduce cost spent on treating water and/or illnesses from unsafe water
- Simplify treatment method
- Government regulatory agencies (e.g. EPA)

Key Insights
Relief and government agencies are really looking to invest in devices that have demonstrated improvements in human health and successful social acceptance through a field study. Three customer types: bottom billion, submerging market ($2-5 /day) & middle-income class. The bottom of the billion needs to be reached through partners (NGOs, relief agencies) & the other two can be sold to through local stores.