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Development of improved low-cost ceramic water filters for viral removal in the Haitian context

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Abstract

Household-based water treatment (HWT) is increasingly being promoted to improve water quality and, therefore, health status in low-income countries. Ceramic Water Filters (CWF) are used in many regions as sustainable HWT and have been proven to meet WHO microbiological performance targets for bacterial removal (2-4 log); however, the described viral removal efficiencies insufficient to significantly reduce associated risk to viral infection.

With the objective of improving the viral removal efficiencies of ceramic water filters, new prototypes with different oxide compositions and firing atmospheres have been developed and evaluated. For removal efficiencies human adenoviruses, MS2 bacteriophage and *Escherichia coli* were quantified in all prototypes. A new model of CWF that was fired in a reductive atmosphere presented virus and bacteria removal efficiencies greater than 3.0 log and 2.5 log, respectively, which would fulfill the viral targets that are recommended by the WHO. Ceramic characterization of the selected filters, which were fired in a reductive atmosphere, showed that a larger specific surface area than those of control filters and higher fraction of a positive Z-potential fraction are the most likely explanations for this increase in virus removal.

Abbreviations

BET Brunauer, Emmett, Teller

CFU colony forming unit

CWF ceramic water filter

E.coli *Escherichia coli*

GC genomic copies

HAdV Human adenoviruses

HWT household water treatment

ICAITI Instituto Centroamericano de Investigación y Tecnología Industria

IEP Isoelectric Point

IU International Units

JCPyV JC Polyomavirus

LRV log reduction value

NoV (GI and GII) Norovirus (Genotype I and Genotype II)

nPCR nested PCR

PCR polymerase chain reaction

PFU plaque forming units

qPCR quantitative PCR

RT-PCR reverse transcription PCR

SD standard deviation

WaSH water, sanitation and hygiene

WHO World Health Organization

XRF X-ray Fluorescence

Introduction

The World Health Organization estimates that 780 million people worldwide (42% in Sub-Saharan Africa) were still without access to improved sources of drinking water in 2010 (Onda, LoBuglio, and Bartram 2012). Estimates of global young-child (<age 5 years) mortality from 2010 suggest that 2 million young children die due to diarrheal disease, and approximately 1.4 million (70%) of these are localized in low-income countries (Bryce et al. 2005; Black et al. 2010; Liu et al. 2012). Recent data on diarrhea burden in low-income countries has reported 685.000 diarrhea deaths related to the deaths attributable to inadequate water and sanitation in 2012 (Prüss-Ustün et al. 2014). The etiological origins of diarrhea had been traditionally associated with bacteria and protozoa; however, in the last years, improved diagnostic methods have made possible detection of other etiological agents, such as enteric viruses, which altered the distribution of the most common cause of diarrheal illness worldwide into enteric viruses (e.g., norovirus, rotavirus, adenovirus) (Huilan et al. 1991; Parashar et al. 2003; Kotloff et al. 2013).

Large numbers of viruses are excreted in human feces and urine into the environment, and, even at low concentrations, they can cause illness when ingested (Leclerc, Schwartzbrod, and Dei-Cas 2002). Consequently, sewage and fecal contamination, if not well contained and treated, is the main source of microbiological risk in water and food. In countries with poor sanitation systems, such as in Haiti, where only 17% of the population has improved sanitation (Onda, LoBuglio, and Bartram 2012), microbiological contamination in water sources is a major cause of morbidity and mortality.

Most potable water-treatment methods are not suitable or available for the majority of rural areas in low-income countries without reliable access to safe drinking water. For those populations, household water treatments (HWT) have been promoted to improve water quality and prevent diarrhea because of two important characteristics: low cost and the capacity, from some of them, to be produced locally. Among all of the technologies tested at the laboratory and field levels, ceramic water filters (CWF) have shown the highest impact on long-term health due to the high adherence of users and their capacity to reduce approximately 50% of the diarrhea incidences (T. F. Clasen et al. 2004; T. Clasen et al. 2005; Joe Brown, Sobsey, and Loomis 2008; Preez et al. 2008; Hunter 2009; Levine, Ave, and Francisco 2010).

Currently, the most widely available, locally produced model of CWF is based on a design developed in 1981 by the Guatemalan industrial research institute ICAITI (*Instituto Centro Americano de Investigación y Tecnología Industrial*) and recently updated by The Ceramics Manufacturing Working Group (The Ceramics Manufacturing Working Group 2011)

The performance of this CWF with and without colloidal silver has been investigated over the years by researchers who have studied its efficiency at reducing waterborne pathogens in the laboratory and in the field. In the literature, the removal efficiency of bacteria by CWF is described to be within the range of 2 to 4 logs using the standard types of silver-impregnated CWFs (Halem 2006; Oyanedel-Craver and Smith 2008; The Ceramics Manufacturing Working Group 2011); however, viral removal efficiencies have been shown to be much lower, between 0.21 and 0.45 log in CWF impregnated or not impregnated with silver described by Salsali H, McBean E 2011 study, and around 1.5 log reduction in Brown & Sobsey 2010 study with no significant differences between impregnated and non-impregnated filters.

On the other hand, the levels of viral removal by the actual model of CWF would not be effective in decreasing the microbial risk regarding the prevalence and concentration of viruses in surface waters, which has been recently reviewed and showed a prevalence as high as 2-4 logs/L of human adenoviruses (HAdV) in surface waters from different geographical areas worldwide (Bofill-Mas et al. 2013).

Regarding the question of viral retention/inactivation in clay structures, different approaches have been presented in the literature, which have faced the challenge of viral removal from water:

A substantial body of literature on virus attachment to various, positively charged particles and surfaces, especially metal oxides and positively charged media in the environment such as clays, which are rich in ferric oxides, exist (Landry et al. 1979; Gerba 1984; Loveland et al. 1996; Zhuang and Jin 2003).

Brown & Sobsey (J Brown and Sobsey 2009) found that metal oxides such as α-FeO(OH) (goethite), Fe_3O_4 (magnetite), Fe_2O_3 (hematite) and Al_2O_3 (alumina) that were amended to clay material could effectively capture bacteriophages (up to 8 log) from a solution, although no assays were performed using real filters. Moreover, ceramic depth filters with added Magnesium Oxide (MgO) showed an improved viral removal, however, the experiments presented high variability in performance with filter operation time, being discarded for drinking water production (Benjamin Michen et al. 2013).

Other factors related to hydrophobic interactions, surface environment and chemistry could also be important in virus-media adsorption and inactivation. It also has been described in the context that firing ceramics in reductive atmosphere has an effect on the surface charge of the piece and therefore can have an effect on viral retention (Wegmann, Michen, and Graule 2008). The shift of the IEP into positive charge at pH 7 makes this material interesting for being used in a virus adsorption filter considering the fact that most enteric viruses have a net negative surface charge (B Michen and Graule 2010).

We hypothesized that the efficiency of the removal of viruses from water using CWF might be increased by using CWFs that were produced with clays amended to natural oxides (Fe2O3, Fe3O4, Al2O3), which increase the positive charges. Moreover, clays from Girona (Spain) and Haitian local clays were used to create CWF by firing in a kiln with a reductive atmosphere, which might affect viral retention as described previously.

This study has as a main objective to design a CWF applicable in Haiti and other areas presenting improved efficiencies for the removal of human viral pathogens from water. Moreover, the concentration of viral pathogens in urban sewage and water sources in Haiti has been tested by evaluating if concentrations of viruses in urban sewage are similar to those in other reported studies worldwide (Bofill-mas et al. 2013), thus highlighting the need for developing improved CWFs that also remove water-borne viral pathogens.

Methods & Materials

Environmental screening was performed in the Metropolitan Area of Port au Prince, the capital of Haiti. Sampling took place in July 2011 during the rainy season. Water samples of 10 L were collected for viral analysis from 6 sampling points: two different sites along the main river (*Riviere Grise*) that flows through the cities (each by triplicate) that are potentially used at domestic level, one borehole and three different sites (at least in duplicate) at open canals that receive domestic wastewater and discharges directly into the Caribbean Sea.

Water samples were analyzed within 6 hours after collection to determine *E. coli* concentration at the University of Quisqueya facilities in Port au Prince using direct plate analysis on ChromoCult© Coliform

Agar (Merck) (ISO 8199:2005). On the same day, viruses were concentrated from the 10L water samples by flocculation using a protocol based on organic flocculation with skimmed milk (Calgua et al. 2008). The resulting, neutralized floccule was kept at -20ºC until shipment to Barcelona for analysis of viruses by PCR. Floccules of a total 10 L sample were then centrifuged and resuspended in 10 mL of phosphate buffer before nucleic acid extraction of 140 µL. Viral nucleic acids from concentrates were extracted using the QIAamp Viral RNA Mini Kit® (Qiagen, Valencia, Spain) following the manufacturer’s instructions. Each sample was eluted in a final volume of 80 µL. Human adenoviruses (HAdV), JC polyomavirus (JCPyV) and norovirus (NoV) were quantified using qPCR and qRT-PCR as previously described (Jothikumar et al. 2005; Bofill-Mas et al. 2006; Pal et al. 2006), and direct samples and their 10-fold dilutions were tested. Standard controls were used in all assays, including negative and positive controls (viral suspensions of HAdV2 and clinical samples that were positive for NoV), with external controls for inhibition using standard DNA (Albinana-Gimenez N et al. 2009).

Positive samples of HAdV by qPCR were amplified by nested PCR(Allard and Albinsson 2001) and purified using the QIAquick PCR purification kit (Qiagen, Valencia, USA). Both strands of the purified DNA amplicons were sequenced with the ABI PRISM™ Dye Terminator Cycle Sequencing Ready Reaction kit with Ampli Taq® DNA polymerase FS (PerkinElmer, Applied Biosystems, Foster, CA, USA) following the manufacturer's instructions. The results were analyzed using the ABI PRISM 3730 XL automated sequencer (PerkinElmer, Applied Biosystems), and the sequences were compared with the nucleotide sequences present in GenBank using the BLAST program of NCBI (National Center for Biotechnology Information; www.ncbi.nlm.nih.gov/BLAST).

The production of CWF took place in the ceramic workshop of *Josep Matés* (Fonteta, Girona, Spain). Several batches of small-scale-sized filters (1:2.5) were produced by following the production instructions from The Ceramics Manufacturing Working Group, and different compositions were tested. After analyzing the microbiological removal efficiencies, a real-scale-size filter was created to test the selected prototype. Small-scale-sized prototypes with different amended oxides and different firing atmospheres (oxidative *vs* reductive) were obtained with clay and rice husks from La Bisbal (Girona, Spain). The natural oxides that were selected for testing included Fe_2O_3, Fe_3O_4 and Al_2O_3 and were added at 16% weight into the milled clay before forming the filter. Each clay batch was mixed with pulverized rice-husk that was screened with a sieve (250 μm) at 23% weight. Filters were pressed in a plaster mold, removed, stamped with a number and dried before firing at 950-990ºC for 8–9 h in an oxidative atmosphere, except for those produced to test the effect of different firing atmospheres. Those filters with no added oxides and the same proportion of rice-husks were fired in oxidative or reductive atmospheres (two replicates per atmosphere) with three different origin clays from La Bisbal (non-calcareous) and two samples from Haiti: Artibonite clay (calcic based) and Aquin clay (non-calcareous).

Firing in reductive atmosphere consist on firing in a traditional kiln with wood up to the desired temperature (950-990ºC) and then to seal the kiln with the last coal inside the firing chamber. By this technique the oxygen consumes totally and a reduction atmosphere affects all clay components as the iron oxide from the clay that becomes ferrous oxide, then we can observe how within the wall, the colour is grey, not brown neither red.

After firing, the filters were cooled down and immersed in water over night. The flow rate was measured after filling the wet filters with water, and filters with acceptable flow rates between 1–3 L/hr were approved for consequent analysis. No colloidal silver solution was added at any step. A modification of the filtering protocol was also tested by adding a 5-cm layer of crushed ceramic sitting inside the pot in the final prototype to increase the removal efficiency. Ceramic gravel was produced with crushed clay from broken filters fired in reductive atmosphere. After manual crushing, gravel was sieved with a superior 2.0 mm and inferior 0.5 mm sieve size. Five centimetres layer was selected as the maximum depth to keep an acceptable flow rate.

Finally, two replicates of the final prototype in real scale (1:1) were performed to evaluate the long-term efficiencies and applicability of the best-performing prototypes. The total numbers of filter units analyzed are shown in Table 1.

To characterize the chemical and mineralogical composition and texture of the raw material that was used and the ceramics that were obtained in this work, several assays were performed on a representative sample after homogenizing the material: X-ray Fluorescence analysis using a Sequential X-ray Spectrophotometer Phillips PW 2400, X-Ray diffraction by an automatic PANalytical X'Pert system, pore size distribution measurements by MIT (Mercury Intrusion Porosimeter, AutoPore IV 9500 Series, Micrometrics©), gravimetric nitrogen Brunauer–Emmett–Teller analysis using a Micromeritics ASAP 2000 Micropore Analyzer and Z-potential distribution analysis using Zeta Master of Malvern Instruments.

Prototypes of the small-scale filters were prepared and tested using fresh water spiked with *E. coli*, Human Adenovirus 2 (HAdV2), DNA virus, and the coliphage MS2 as a representative of smaller sized ssRNA viruses (27 nm). Water from the tap (with turbidity <5 NTU and pH 8) was conditioned by adding sodium thiosulfate at 10% to inactivate free chlorine and stocks of challenge microorganisms were added to reach a minimum final concentration of 10^5 IU/mL.

To quantify the efficiencies of bacterial reduction, *E. coli* (Spanish Collection of Type Cultures, CECT 515) was cultured in Tryptone Soya Broth (TSB) and quantified after filtration and PBS dilution by plating on Trypticase Soy Agar (TSA).

The viruses spiked were: HAdV2 and MS2 as DNA and RNA viral models, respectively. HAdV2 was cultured in A549 cell culture and quantified by qPCR (Bofill-Mas et al. 2006). MS2 was obtained from the American Type Culture Collection (ATCC 15597-B1), was multiplied by adding MS2 suspension to a log-phase host culture (Salmonella WG49, CECT 4625) and was enumerated following the double agar layer procedure. At the same time, Norovirus GII obtained from clinical samples was used to spike-challenge the water samples to add evidence for the viral removal of the selected filters.

To assess the capability of the ceramic filter prototypes and to eliminate viruses and bacteria, the small filters (1:2.5) that were amended with metal oxides and filters fired in different atmospheres (reductive *vs* oxidative) were tested in a set of microbiological-removal efficiency studies. Each prototype was tested at least in two parallel filters. After production, the ceramic filters were saturated in mineral water overnight, and blank tests were performed by pouring mineral water through the filter. One liter of the challenge water was filtered in each test at least twice for each prototype.

Log reduction values (LRV) were calculated by subtracting the log10 of the final concentration from the log10 of the initial concentration, and mean values and standard deviations were calculated. The Wilcoxon rank sum test was applied to detect significant differences in LRV between tested filters prototypes *vs* the control filters (no added oxides + oxidative firing); p-values are shown in Table 6.

The black filter (fired in a reductive atmosphere) with an extra 5-cm layer of ceramic gravel (2-5 mm) was the selected prototype based on the microbiological reduction values of the previous experiments. To evaluate its long-term performance, the WHO-testing recommendations for HWTS (WHO 2011) were used with two 1:1-scale prototype replicates of fired pieces with a final diameter of 320 mm and height of 230 mm. The performance of the selected models was monitored for over 1000 filtered liters and a daily dosing of 40 liters of dechlorinated, municipal tap water. Challenge waters were spiked with the selected microorganisms (as in previous experiments) once per week and allowed to filter for 4 hours before the effluent was collected to evaluate filter performance. Water quality parameters such as pH and flow rate were measured daily.

Results and Discussion

The results obtained in the water samples in Haiti showed high levels of human fecal contamination in the superficial waters of the Metropolitan Area of Port-au-Prince during July 2011 and are summarized in Table 2. HAdV were detected in high amounts in water from open canals that were considered to contain urban sewage (4.35E+04 GC/100 mL, 6/6), as well as at the two river-water-sampling sites (1.03E+02 GC/100 mL, 4/6) and at the borehole level (3.9E+04 GC/100mL). These results are in accordance with previous studies, which showed the abundance of HAdV and its use as indicators of human contamination (Bofill-Mas et al. 2006). Important viral enteric pathogens that produce gastroenteritis were also detected: HAdV type 40-41, NoV GI and NoV GII, which emphasizes the importance of implementing water and sanitation programs that are focused on the reduction of viral infections in the population. *E. coli* mean levels were

1.93E+04 cfu/100 mL (6/6) in the river samples and 1.74E+06 cfu/100 mL (6/6) in the sewage samples. The mean values of another viral indicator of human origin, JCPyV, were quantified, and the mean value in sewage was 3.46E+02 GC/100 mL (5/6); it was not detected in river samples, but it was found in borehole water. Noroviruses were quantified, presenting NoV GI mean values of 2.12E+02 GC/100 mL (2/13), and NoV GII mean values of 2.12E+03 GC/100 mL (2/13).

The results obtained using the bacterial standards, viral indicators and tested pathogens are a strong indication of the need for using household-based water treatments and improving CWFs that reduce the level of viral contamination in water.

The prototypes of the CWFs that were developed in this study and tested for microbiological efficiency are shown in Table 1. At the same time, the analysis of the chemical composition of the clays used to produce those CWFs indicates that silica is the major component, and the main difference between the three clays is the calcium content: Artibonite clay had the highest percentage (Table 3). After firing, all prototypes presented acceptable levels of water filtration capabilities and robustness. The main mineralogical differences between the ceramics that were fired in reducing and oxidizing atmospheres were the presence of magnetite or hematite, respectively, as quartz and feldspar were the dominant phases in both samples. Moreover, we observed that, in oxidizing conditions, the proportion of calcite ($CaCO_3$) in the ceramic was lower and the content of gehlenite ($Ca_2Al(AlSi)O_7$) was increased because, in this case, the decomposition was more efficient. However, during reductive firing, the atmosphere seems to restrain the decomposition, which indicates remaining values of calcite (Table 4). Pore-size-distribution studies of the two firing conditions did not show significant differences between ceramics fired in different atmospheres regarding the pore size distribution showing larger dimensions than viral diameters (Figure 1). Nevertheless, significant differences were found regarding the analysis of the surface area of the ceramic filters, which indicated that filters fired in a reductive atmosphere had greater surface areas, with a mean value of 6.65 m^2/g, than the filters that were fired in an oxidative atmosphere, with a mean surface area of 2.41 m^2/g (Table 5). Moreover, studies of Z-potential distribution of ceramics comparing both firing conditions shows a fraction of the crushed reductive clay being positive, suggesting a potential effect into viral absorption (Figure 3).

The microbiological removal efficiency of the diverse prototypes was tested with a minimum of 2 filter replicates per prototype, and the results are shown in Table 6. The filter control, which was produced as a reference model of a non-silver-impregnated filter, presented viral and bacterial removal efficiencies of 0.57 for MS2 and 0.68 for *E.coli*, results that are equivalent to previously reported studies (van der Laan et al. 2014).

The prototype ceramic filters that were amended with Fe_2O_3, Fe_3O_4 and Al_2O_3 oxides did not significantly increase the efficiency of disinfection when compared to the control filters. The Log Reduction Values that were observed were lower than 1 logarithm for all types and for each microorganism that was tested, except for the filters with Al_2O_3, which showed a slightly significant increase in *E.coli* removal of 1.34 LRV (p value 0.046). In contrast, filters that were fired in a reductive atmosphere and produced from 3 clays of different origins (Spain and Haiti) had greater removal efficiencies for viruses (HAdV, MS2 and NoV) and bacteria (E.coli) around 3.0 log and 2.5 log, respectively being significant compared to control filters (Table 6). The analysis of the log removal efficiencies among reductive atmosphere filters were no significant ($p>0.05$). These filters achieved the performance requirements for of the HWTS protective technologies that were recently established by the WHO (WHO 2011).

Filters fired in a reductive atmosphere with an extra layer of ceramic gravel were selected to test long-term performance in real size scale and showed consistent removal values after 1000 liters (Figure 2). During the long-term study, logarithm reduction values were between 2.5-4 LRV for the tested viruses (HAdV and MS2), but higher variations occurred for *E.coli*, with a range of 1.5-4 LRV. Flow rates were recorded at 1.5-3 liters/hour and were stable throughout the experiment, and the effluents had a slightly increased pH, from 7 in the input water up to 8 in the output water, as previously recorded (data not shown) (Halem 2006).

The new model of a Ceramic Water Filter made by firing in a reductive atmosphere and without colloidal silver that have been proposed in this paper showed removal efficiencies for viruses and bacteria that were significantly higher than the current standards and what was previously reported in the literature. Furthermore, they reach the WHO targets for HWTS technologies. Black ceramics, which are clay fired in a reductive atmosphere, seems to increment the internal specific surface area and the Z-potential becoming the most feasible model for achieving advantageous results in viral removal of the proposed models. This model seems to be a low-cost option whose production can be easily adapted for a wide-spread model of CWF to increase microbiological effectiveness without increasing costs.

Conclusions

High levels of waterborne viruses are present in superficial waters of Port-au-Prince, Haiti, highlighting the importance to improve household water technologies for viral removal efficiencies. A new prototype of CWF fired in reductive atmosphere, a variation that maintains the product non-expensive, improves viral removal efficiencies up to 3 logs, accomplishing the WHO requirements for HWTS technologies. Long-term assays with this new prototype show consistent removal values after 1000 liters filtered. Ceramics fired in reductive atmosphere show greater surface area and higher z-potential the most feasible explanation for viral disinfection properties of this new model.

This new improved prototype will be easily implemented in CWF factories as firing in reductive atmosphere will just require a specific kiln that can be built with local materials (traditional bricks, sand and concrete) or even current kiln models can be accommodated to fire in reductive conditions. Moreover, the fact that colloidal silver can be replaced by a layer of ceramic gravel will also reduce environmental and toxicity hazards as well as economic cost (around 1 euro per filter). At the same time, the addition of this layer made of ceramic gravel will entail a step of maintenance by users because regular cleaning of gravel will be needed. However, this modification will also improve the microbial performance of the filter and highlights the importance of performing hygiene promotion campaigns alongside the implementation of this product towards users.

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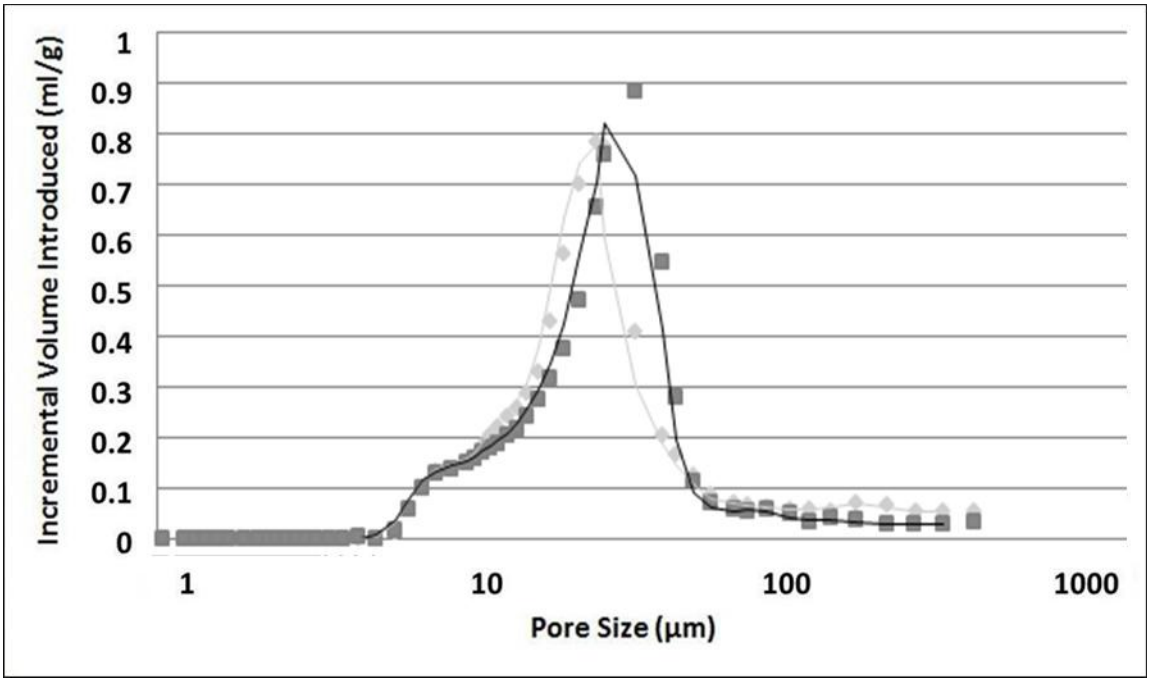

Figure 1 | Pore size distribution of ceramics that were fired in oxidative (squares) and reductive atmospheres (rhombus).

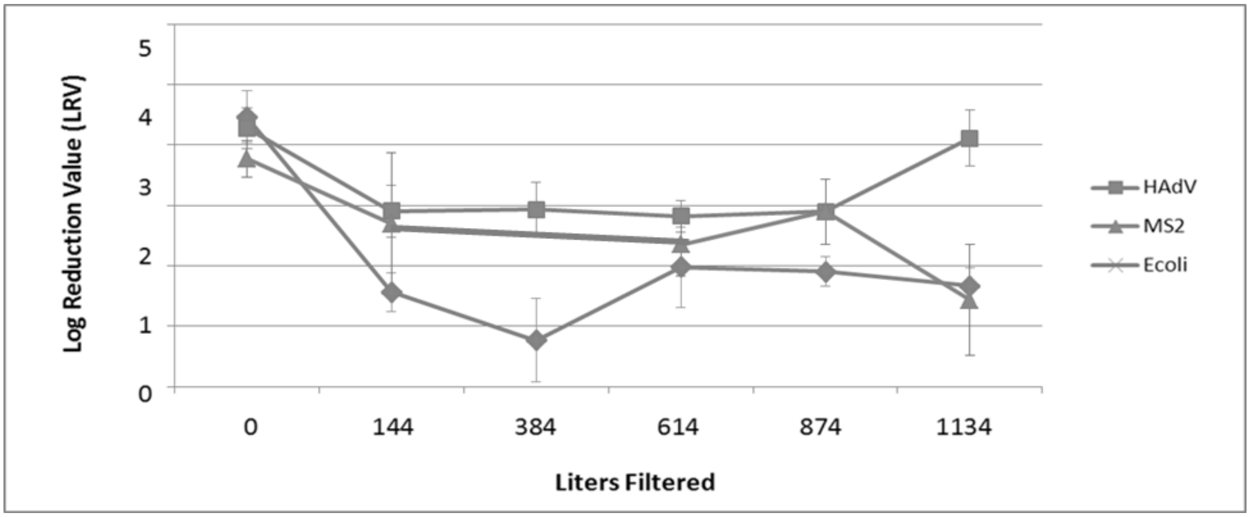

Figure 2 | Monitoring of long-term microbiological effectiveness of the selected CWF (reductive atmosphere + 5-cm ceramic gravel layer).

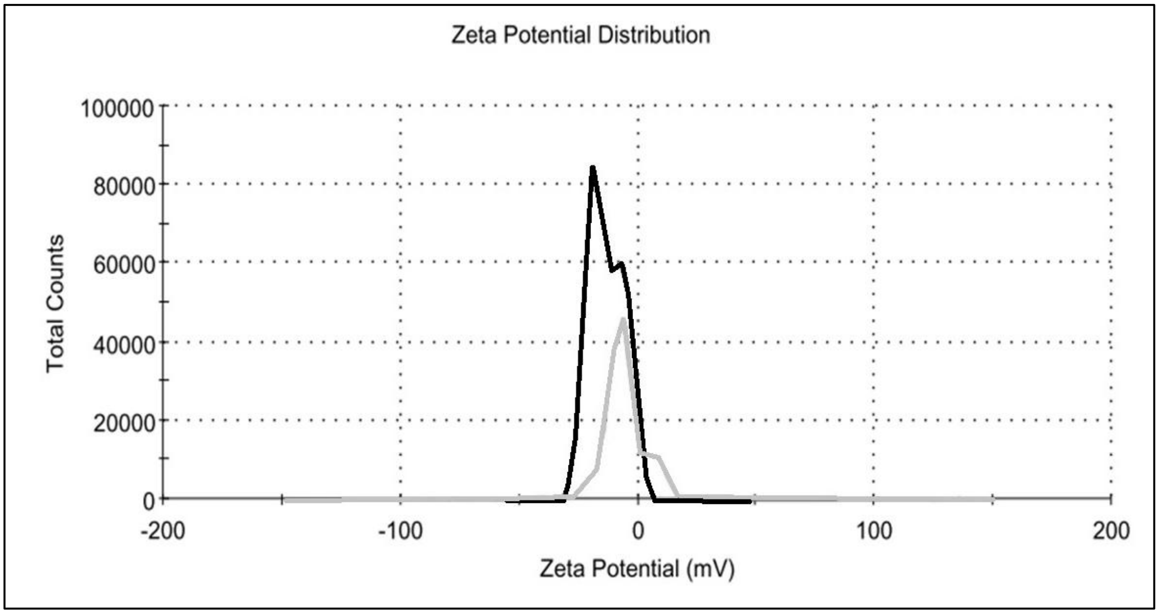

Figure 3 | Zeta Potential Distribution of Clay from la Bisbal fired in Oxidative Atmosphere (black line) and Clay fired in Reductive Atmosphere (grey line).

Table 1. Prototypes of the produced Ceramic Water Filters

Ref	**Ceramic additives**	**Clay origin**	**Firing atmosphere**	**Scale**	**Layer of ceramic gravel (cm)**	**Replicates**
1	None	Bisbal, Spain	oxidative	1:2.5	-	4
2	+ 16% Fe_2O_3	Bisbal, Spain	oxidative	1:2.5	-	2
3	+ 16% Fe_3O_4	Bisbal, Spain	oxidative	1:2.5	-	2
4	+ 16% Al_2O_3	Bisbal, Spain	oxidative	1:2.5	-	2
5	None	Bisbal, Spain	reductive	1:2.5	-	4
6	None	Bisbal, Spain	reductive	1:2.5	5	2
7	None	Artibonite, Haiti	reductive	1:2.5	-	2
8	None	Aquin, Haiti	reductive	1:2.5	-	2
9	None	Bisbal, Spain	reductive	1:1	5	2

Table 2. Microbiological contamination in superficial waters of Port au Prince

Location	**Type**	**N**	***E.coli***	**HAdV**	**JCPyV**	**NoV GII**	**NoV GI**
			cfu/100 ml (positive/total)	**GC/100 ml (positive/total)**			
Cité du Soleil	Canal	1	9.00E+05	1.61E+03	3.25E+01	ND	ND
Bois Chene	Canal	1	3.00E+06	3.91E+03	2.64E+01	3.63E+03	ND
		2	5.00E+06	6.15E+03	1.36E+03	ND	ND
		3	1.70E+05	1.66E+05	ND	ND	ND
Canal Brea, Martisand	Canal	1	1.20E+06	3.31E+04	3.11E+01	ND	ND
		2	1.40E+05	5.03E+04	2.81E+02	ND	2.55E+02
Mean Value Canal			**1.74E+06** **(6/6)**	**4.35E+04** **(6/6)**	**3.46E+02** **(5/6)**	**3.63E+03** **(1/6)**	**2.55E+02** **(1/6)**
Riviere Grise, Croix de la Mission	River	1	1.70E+03	ND	ND	ND	1.68E+02
		2	4.00E+04	7.77E+01	ND	ND	ND
		3	4.00E+03	ND	ND	ND	ND
Riviere Grise, Pont sur la route #9	River	1	1.00E+04	1.17E+02	ND	ND	ND
		2	2.00E+04	7.49E+01	ND	ND	ND
		3	4.00E+04	1.41E+02	ND	6.01E+02	ND
Mean Value River			**1.93E+04** **(6/6)**	**1.03E+02** **(4/6)**	**-** **(0/6)**	**6.01E+02** **(1/6)**	**1.68E+02** **(1/6)**
Tabarre	Borehole	1	2.60E+01	3.94E+04	5.17E+01	ND	ND

ND: Not detected

Table 3. Chemical analysis of clays used to make CWF

Chemical composition	Weight (%)		
	LaBisbal, Girona, Spain	Artibonite, Haiti	Aquin, Haiti
SiO_2	62.87	43.77	66.60
Al_2O_3	15.88	12.86	17.32
Fe_2O_3	5.56	6.96	3.12
MnO	0.07	0.07	0.02
MgO	1.20	3.65	0.45
CaO	1.53	11.94	0.33
Na_2O	0.41	1.16	0.66
K_2O	3.17	1.57	0.19
TiO_2	0.78	0.75	0.24
P_2O_5	0.13	0.14	0.04

Table 4. Mineralogical analysis of ceramics filters fired in different atmospheres in percentages (%)

	Artibonite		**La Bisbal**	
Mineral (%)	**reductive**	**oxidative**	**reductive**	**oxidative**
Quartz	31	23	51	47
Sericite-heated	-	-	44	40
Diopside	11	11	-	-
Calcite	4	2	-	-
Lime	1	0.5	-	-
Gehlenite	4	6	-	-
K feldspar	12	13	3	5
Plagioclase	35	43	-	7
Hematite	-	2	-	1
Magnetite	1	-	2	-

Table 5

Table 5. Specific surface areas of Artibonite and La Bisbal filters that were fired in different atmospheres.

Firing atmosphere	**BET (m^2/g)**	
	Artibonite	La Bisbal
Reductive	6.8713 (± 0.0475)	6.4371 (± 0.0120)
Oxidative	2.6185 (± 0.0281)	2.2036 (± 0.0152)

Table 6. Microbiological effectiveness of different Ceramic Water Filter prototypes in Log_{10} Reduction Values and statistical significance levels from Wilcoxon rank sum test.

			Log Reduction Value				
Ref	Filter	Microorganism	Mean	n[1]	Std. Deviation	P value	
1	CWF-Bisbal-oxidative	HAdV	0.62	18	0.43	ref	
		MS2	0.57	8	1.04		
		NoV	0.96	2	0.32		
		E. coli	0.68	12	0.62		
2	CWF-Bisbal-oxidative + Fe_2O_3	HAdV	0.67	10	0.47	0.74	
		MS2	0.54	2	0.11	0.27	
		E. coli	0.59	8	0.69	0.87	
3	CWF-Bisbal-oxidative + Fe_3O_4	HAdV	0.57	9	0.37	0.72	
		MS2	0.25	2	0.01	0.26	
		E. coli	0.53	8	0.82	0.46	
4	CWF-Bisbal-oxidative + Al_2O_3	HAdV	0.85	9	0.37	0.21	
		MS2	0.26	2	0.03	0.27	
		E. coli	1.34	7	0.55	0.046	*
5	CWF-Bisbal-reductive	HAdV	3.54	14	0.73	<0.001	*
		MS2	2.33	8	0.61	0.02	*
		E. coli	2.32	8	0.85	0.005	*
6	CWF-Bisbal-reductive + gravel	HAdV	4.15	2	0.12	0.008	*
		MS2	2.97	2	0.11	0.024	*
		NoV	3.56	2	0.23	0.667	
		E. coli	2.90	2	0.28	0.035	*
7	CWF-Artibonite-reductive	HAdV	3.36	2	0.62	0.008	*
		MS2	2.98	2	0.12	0.024	*
		E. coli	2.37	2	0.47	0.035	*
8	CWF-Aquin-reductive	HAdV	2.86	2	0.24	0.008	*
		MS2	1.27	2	0.02	0.027	*
		E. coli	2.40	2	0.43	0.035	*

[1] n = number of assays

* Significance levels of 5% or less ($p \leq 0.05$)