

Critical parameters in the production of ceramic pot filters for household water treatment in developing countries

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ABSTRACT

The need to improve the access to safe water is generally recognized for the benefit of public health in developing countries. This study's objective was to identify critical parameters which are essential for improving the performance of ceramic pot filters (CPFs) as a point-of-use water treatment system. Defining critical production parameters was also relevant to confirm that CPFs with high-flow rates may have the same disinfection capacity as pots with normal flow rates. A pilot unit was built in Cambodia to produce CPFs under controlled and constant conditions. Pots were manufactured from a mixture of clay, laterite and rice husk in a small-scale, gas-fired, temperature-controlled kiln and tested for flow rate, removal efficiency of bacteria and material strength. Flow rate can be increased by increasing pore sizes and by increasing porosity. Pore sizes were increased by using larger rice husk particles and porosity was increased with larger proportions of rice husk in the clay mixture. The main conclusions: larger pore size decreases the removal efficiency of bacteria; higher porosity does not affect the removal efficiency of bacteria, but does influence the strength of pots; flow rates of CPFs can be raised to 10–20 L/hour without a significant decrease in bacterial removal efficiency.

Key words | bacteria removal, ceramic pot filter, flow rate, material strength, point-of-use water treatment

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HIGHLIGHTS

- Fifteen batches of ceramic pot filters (CPFs) were manufactured in a pilot production line in Cambodia.
- Pots with higher flow rates were developed by increasing the proportion of rice husk in the clay mixture.
- Ceramic pot filters were tested for flow rate, removal of bacteria and material strength.
- The most critical parameter for the removal efficiency of bacteria appears to be the pore size of CPFs.

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INTRODUCTION

The need to improve access to safe water for the benefit of public health in developing countries is widely recognized. Ceramic pot filters for point-of-use water treatment began appearing in these countries in the late 1980s and early 1990s. Since then, the performance of CPFs for water treatment has been evaluated by many investigators.

In a field study (Clasen *et al.* 2004), ceramic water filters were distributed to households in Bolivia. This resulted in a 70% lower diarrheal disease risk for individuals from households that used water, which was purified with CPFs, compared with controls of households without CPFs. A meta-regression study (Hunter 2009) demonstrated that the CPF was the most efficient household water treatment system out of four evaluated systems, especially in the long term. An extensive literature survey was conducted in South Africa (Mwabi *et al.* 2011) on various household devices that are suitable for the inexpensive treatment of water on a household basis. Four types of household treatment devices were selected for further study: biosand filter, bucket filter, ceramic candle filter and silver-impregnated porous pot filter (SIPP). The performance of the four types of filter was evaluated in terms of chemical and microbial contaminants (*Escherichia coli*, *Vibrio cholerae*, *Salmonella typhimurium*, *Shigella dysenteriae*) removals. The highest bacterial removal efficiency was recorded by the SIPP (99–100%) and the lowest by the bucket filter (20–45%) and the biosand filter (20–60%).

The CPF (Figure 1) is a life-saving point-of-use water treatment system produced in small factories in many developing countries. The main treatment goal is disinfection, i.e. removing pathogens from the feed water. CPFs are produced locally by more than 35 factories in 18 countries (Rayner *et al.* 2013). It is a relatively simple production process. The CPF is made of a mixture of clay, a burn-out material such

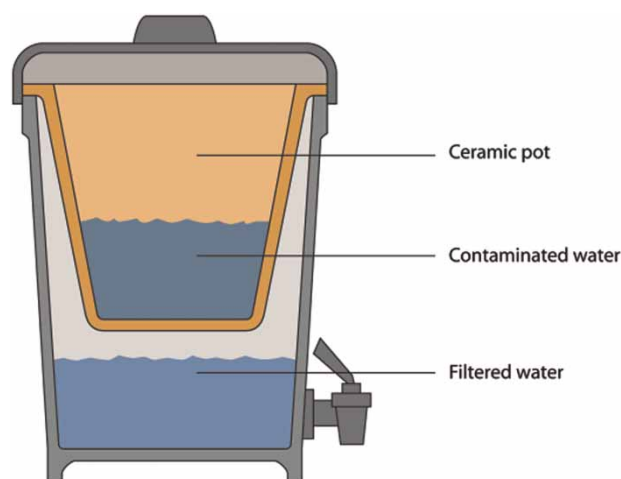


Figure 1 | Ceramic pot filter with receptacle.

as rice husk and water. When the clay pot filter is fired in a kiln the rice husk burns, thereby leaving pores in the ceramic material (Hagan *et al.* 2013).

However, the CPF is also known for the production of low quantities of water. The porous pot is currently filtering water at a rate of 1–3.5 L/hour (LPH). In addition, flow rates decrease with time due to clogging by suspended particles in the feed water (van Halem 2007). Although, scrubbing has been shown to temporarily increase the flow rate, filters typically do not return to their original flow rate after scrubbing and flow rates continue to decrease over time – often to less than 0.5 LPH – which can be insufficient to meet a family's drinking water needs.

Resource Development International Cambodia (RDIC) has been making CPFs in Cambodia since 2003. By 2007 RDIC had distributed approximately 60,000 filters throughout Cambodia, and internationally. The handbook of RDIC (Hagan *et al.* 2013) contains detailed information on the production and uses of CPFs, which are an affordable, accessible and appropriate technology for empowering households, school class rooms, and work places to manage their own drinking water quality. CPFs are suitable for treating the most common risk to drinking water – contamination with biological pathogens – as well as for removing general macro contaminants. Chemical and heavy metal contaminants cannot be treated with ceramic water filters in their current form. CPFs can be used in conjunction with:

- piped water systems where the quality of that water cannot be assured;
- surface waters where biological contamination is the highest risk to safe drinking water;
- ground waters.

The biggest physical constraints to using CPFs are:

- volume of water production – which can be limiting for very large organizations;
- where primary health risk associated with source water is chemical such as arsenic, manganese, etc.

The objective of this research project was to identify critical production parameters which are essential for improving the quality assurance of CPF production by factories in developing countries, with a specific emphasis on:

1. variations in rice husk:clay ratio;

2. maximum kiln temperatures;
3. rice husk particle size variations.

Defining the critical manufacturing parameters is an essential step to work towards a kind of product certification (van Halem 2009) and is relevant to confirm that CPFs with high-flow rates might have the same disinfection capacity as pots with normal flow rates of 1–3.5 LPH (Bloem 2009).

MATERIALS AND METHODS

Experimental setup

At the production site of RDIC, a small production line was constructed in 2010, where pots were made under more controlled conditions compared to the full-scale factory. Firing was performed using gas in a small temperature-controlled kiln. By changing the composition of the product, we produced CPFs with much higher flow rates. In this research project, 15 batches of six CPFs were made out of a mixture of clay, laterite and rice husk. The quality of the filter pots was assessed among others by mercury intrusion porosimetry tests, measuring initial flow rates, doing bacteria removal challenge tests with *E. coli* and characterizing the material strength by measuring the modulus of rupture of pot filters.

RDIC uses ground rice husks as the organic burn-out material in their ceramic filters. Rice husk is a waste product from rice production in Cambodia and is readily available. Rice husks are bought from different local suppliers and are provided in rice bags pre-ground. In November 2010, RDIC started sieving its ground rice husk at a particle size of 1 mm or less as part of their quality control process. RDIC takes into account the differences in properties of rice husk of wet and dry seasons. Samples of rice husks from both the dry and wet seasons, analyzed by Delft University of Technology, showed slight differences in the particle size distributions. The rice husk from wet season contained more particles of >0.8 mm but also more particles of <0.25 mm than the rice husk from dry season. So the rice husk of dry season had a more uniform particle size distribution.

RDIC is situated near a brick factory, where clay is locally mined and extruded into bricks before drying. RDIC uses unfired extruded bricks as a raw material for convenience.

They are cheap and easy to transport to the RDIC clay pot filter factory, and the extrusion process enhances the plasticity of the clay material. Clay plasticity is greatly influenced by the clay's particle size, water content and aging. The level of plasticity in a clay sample can be assessed by coiling the clay around a finger. A plastic clay will not crack or break during this test. Since 2005, RDIC has been adding laterite, a soil containing iron oxide, to the clay. Laterite is said to bind and inactivate viruses (Hagan *et al.* 2013) but Bloem's (2009) studies found no difference in virus removal with laterite. The characteristics of samples of clay and laterite taken from RDIC were investigated and analysed by the Technical Centre for the Ceramic Industry (2011) in the Netherlands. The particle size distribution of both materials in addition to the specific surface area and chemical composition of the clay were determined.

Rain water harvested from the roof of the research shed was used in the filter-making process. The manufacturing process of the filters had various important steps from raw material preparation to firing and cooling. The process was described in the final report of this research (Gensburger 2011) and the filter factory manual of RDIC (Hagan *et al.* 2013). The main steps are briefly described here.

Raw materials in the clay mixture

The same clay used by RDIC was added to laterite and rice husks. The clay bricks were crushed into pieces and milled into a fine powder. All raw materials (clay, laterite and rice husk) were sieved through a 1 mm mesh sieve. RDIC's standard recipe for six pots is 30 kg of clay, 9.7 kg of rice husk, 1 kg of laterite and approximately 14.5 L of water. The raw materials were mixed dry for 10 minutes and after adding water the raw materials were mixed again for 15 minutes. The more rice husk was added in the clay mix, the more water was needed to obtain satisfactory consistency for pressing.

Preparation of the clay pot

The wet clay mixture was formed into cubes of approximately 9–10 kg for pressing. The cubes were pressed into the filter pot shape by using a hydraulic press. After pressing, the filter rim was wetted with water. Each filter was marked with a serial number (batch and pot number, e.g. B13 P5).

The freshly pressed filters were left for several hours to harden and then polished by hand. The filter elements were left in the shade to harden further until the next day and then turned upside down to polish their bottoms. During the drying process the pot weights were recorded daily to estimate when the batch would be dry enough to be fired. On average, the pots were sufficiently dry after 10 days.

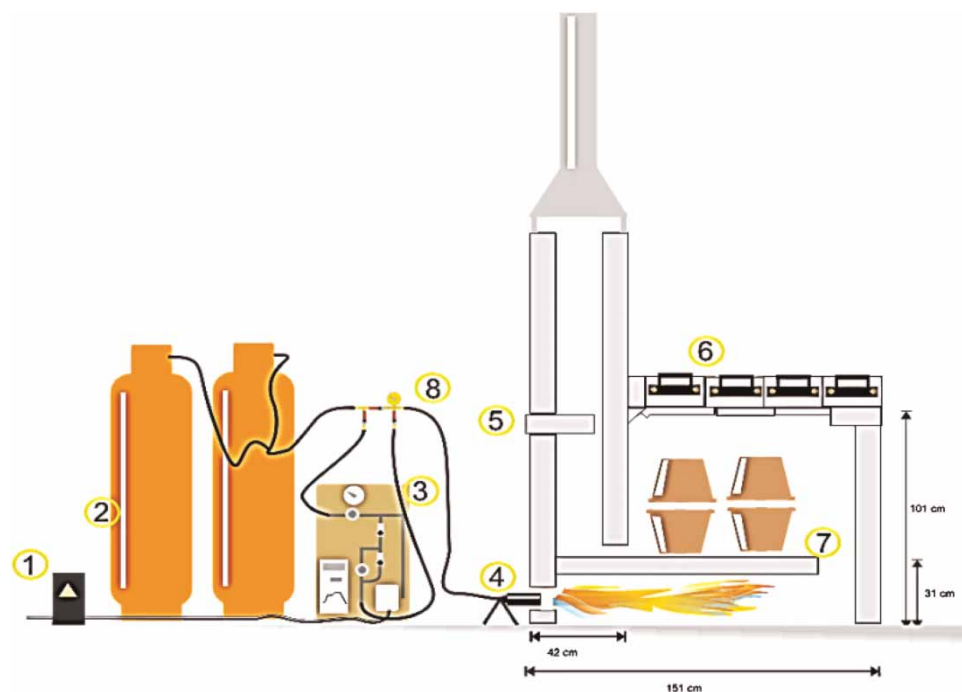
Manufacturing the ceramic pot filter

The temperature curve of the full-scale kilns of RDIC was surveyed with thermocouples at three different kiln height locations. The maximum temperature was approximately

885 °C. The research kiln (Figure 2) had a maximum capacity of six pots. There were five thermocouples to record temperatures inside the kiln throughout the firing process: four were next to the filter pots and one thermocouple was connected to the temperature regulation system. Before stacking the kiln, the pots were inspected for cracks.

The filters at the bottom were placed on spacers and the filters on top were placed on the filter below with spacers in between to allow circulation. The standard firing programme was set to:

1. fire up to 520 °C at the rate of 100 °C/hour;
2. stop heating for 1 hour at a plateau of 520 °C;



1. Power stabilizer
2. Gas bottles
3. Regulating system attached to wooden board
4. Burners
5. Chimney regulator
6. Roof parts
7. Internal floor
8. Switch manual-automatic regulation

Figure 2 | Research kiln with temperature regulation system.

3. continue firing at the rate of 100 °C/hour until the maximum temperature of 885 °C is reached;
4. close the gas supply, shut the kiln and let the filter pots cool down naturally.

The firing and cooling curve was recorded using data loggers. Firing took place in approximately 10 hours and the kiln was then left to cool down naturally for 24 hours.

The processes taking place in the kiln during the transition from clay to CPF are described in Best Practice Recommendations of The Ceramics Manufacturing Working Group (2011).

Application of silver solution

The silver solution was prepared by mixing 100 g AgNO₃ and 1500 mL of deionized water. Then, 100 mL of concentrated silver solution was diluted with 18.1 L deionized water, being enough solution for approximately 60 filter elements (Hagan *et al.* 2013). The same silver nitrate solution was also used in other studies (Lantagne 2001; Fahlin 2003; Van Halem 2007; Bloem *et al.* 2009; Brown & Sobsey 2010). A

total of 70 mg of silver was used for each filter element by the application of about 200 mL of silver solution to the inside of the filter pot and 100 mL to the outside.

Overview of manufactured batches of pot filters

The various conditions at which each batch of pots was produced and the purposes of making each batch for testing parameter variations are summarized in Table 1.

Flow rate test

The flow rate of the filters was tested using a constant head method. The filters were soaked in bacteria-free water for 24 hours. The dry receptacles used for collection of filtrates were weighed and the weights (WD) were used as references. Next, the soaked filters were placed inside their receptacles. The filters were filled with influent up to 18 cm from the bottom and repeatedly re-filled to this level for 1 hour. Filters were then removed and the weights of the receptacles with filtrates were recorded as W (wet receptacle). The net flow rate was calculated as W-WD.

Table 1 | Conditions and purposes for making batches of ceramic pot filters

Batch no.	Season	Rice husk in clay mix			Testing parameter variations		
		Quantity kg	Particle size mm	Firing Maximum temperature °C	Rice husk in clay mix		Firing Maximum temperature
					Quantity	Particle size	
B4	Dry	13	0–1	885	x		
B7	Dry	9.7	0–1	885	x	x	x
B12	Dry	9.7	0.5–1	885		x	
B13	Dry	12	0–1	885	x		
B14	Dry	9.7	0–1	685			x
B17	Dry	14	0–1	885	x		
B18	Dry	11	0–1	885	x		
B19	Wet	9.7	0–1	950			x
B20	Wet	9.7	0–1	800			x
B21	Wet	13	0–1	885	x		
B22	Wet	9.7	0–1	885		x	
B23	Wet	9.7	0–1	885	x	x	x
B24	Wet	11	0–1	885	x		
B25	Wet	12	0–1	885	x		
B26	Wet	14	0–1	885	x		

Test for removal of *E. coli*

The *E. coli* tests were performed at the RDIC Resource Laboratory facilities. Membrane filtration was used to determine the *E. coli* concentration of the influent and effluent samples of the filters. *E. coli* served as an indicator of bacteria. Samples of influent and effluents of the CPFs were filtered in duplicate through 47-mm diameter and 0.45- μm pore size cellulose ester filters of Millipore. Influent samples were diluted before filtering through a membrane filter. The membranes were incubated on agar for 16–24 hours at 37 °C. RAPID *E. coli* 2 Agar of BIO-RAD was used.

The *E. coli* testing procedure used for the first batch series (B4–B18) was adapted for the second batch series as technical problems arose. Problems started at the beginning of the monsoon season when the well water being utilized became highly contaminated. To overcome this problem, rain water passing through the UV-disinfection system was used instead of well water. For the second set of batches (B19–B26), the *E. coli* was re-suspended in 0.1% peptone water and the concentration of bacteria was estimated by spectrophotometry. This estimation by optical density was not very accurate. As a result, the spiked influents varied in concentration between 10^5 and 10^4 cfu/mL.

Results of our tests seemed to indicate that these variations of influent concentrations of *E. coli* were as expected, and not related to the measured \log_{10} reduction values (LRVs).

The \log_{10} reduction value is used to describe the removal efficiency in case the bacteria removal approaches 100%. The LRV can be calculated with:

$$\text{LRV} = \left\{ \frac{\text{no. } E. coli \text{ Influent}}{\text{no. } E. coli \text{ Effluent}} \right\} \log_{10}$$

Thus, 1 LRV = 90% reduction, 2 LRV = 99%, 3 LRV = 99.9%, 4 LRV = 99.99%, and so on.

Strength test

Strength testing was used to determine the modulus of rupture (MoR) of a sample, which is an inherent characteristic of the material. The variable tested was the break load. It is the load that can be put on the centre of a sample before it

breaks. It can be easily deduced from the mass added to break the sample. A particular test device was designed by an organization called Groupe Energies Renouvelables, Environnement et Solidarités (GERES) only for ceramic and cylindrical samples. Samples were put on three little balls so that the charging module would be exactly in the middle of the sample. Using a bubble level, the horizontality of the level was checked. Steel weights were put with a step size of 500 g on the plate until the last one added made the sample break. Using the data of sample and test device the MoR (in Mega Pascal) could be calculated from the measured break load (in Newton) with the equation mentioned in ASTM C1161-02c 2008. The experimental steps were as follows.

Four discs were cut from the bottom of a filter and three filters per batch were used for the test in order to have a sample size of 12. The discs were labelled and brought to the GERES facilities, where a total of nine batches of samples were tested. The batches (B21–B26) had all been fired up to 885 °C but varied in the ratio rice husk to clay, and therefore in porosity. The next batches (B7, B14, B19 and B20) all contained 9.7 kg of rice husks per 30 kg of clay but were fired up to different maximum temperatures. The last batch B12 contained 9.7 kg rice husk per 30 kg clay, and was fired at 885 °C, but only included rice husk particles between 0.5 and 1 mm instead of all particles smaller than 1 mm. Two samples cut out of normal RDIC water filters were also tested as a control test. For every batch sample, the average MoR was calculated.

Parameter correlation test

For a clear presentation of the experimental results, box-and-whisker graphs were used. To assess whether significant correlations were also found between two parameters, the Pearson correlation coefficients were calculated from the experimental data sets.

Performance criteria

In the literature, there are no generally accepted criteria for assessing the performance of filter pots. As a basis for evaluating the characteristics of the produced CPFs, three main criteria are selected for this research:

1. flow rate (initial): $FR \geq 2.5$ L/hour;
2. \log_{10} reduction value for *E. coli*: $LRV \geq 2.0$ \log_{10} units;
3. modulus of rupture: $MoR \geq 1.5$ mega Pascal (MPa).

Filter pots meeting these three criteria are considered to be acceptable for use in water treatment in developing countries. The challenge for this research is to maximize the flow rate while the pot filters still meet the other two criteria.

RESULTS

Characteristics of raw materials

The analysis of raw materials showed that the clay consists almost exclusively of particle sizes smaller than $10 \mu\text{m}$. This results in a very high degree of mouldability after addition of an adequate amount of water. The laterite had a very different particle structure, with a 25% fraction of fine particles, 28% of fine sand and 36% of coarse sand (Technical Centre for the Ceramic Industry 2011).

Variations in the rice husk to clay ratio

Flow rates of filter pots without silver application

Six RDIC standard filter pots were made with 9.7 kg rice husk, 30 kg clay and 1 kg laterite. To increase the porosity of the pots the rice husk concentrations was increased to 11, 12, 13 and 14 kg. For every batch, six pots were mixed, pressed and fired. The combination of six pots was called a batch (i.e. same composition and same firing curve). The first set of batches (30 pots) was made in the dry season and the second (duplicate) in the wet season. The results are shown in Figure 3.

Pot filters with increased rice husk in the clay mix have consistently higher flow rates. The pot filters of series 1 with 12 kg rice husk had 3.8 times higher average flow rates than the pots with 9.7 kg rice husk and pots with 14 kg rice husk had 5.6 times higher average flow rates. It was interesting to note that the average flow rates of the second set of batches were always greater than those of the first set by about 50%

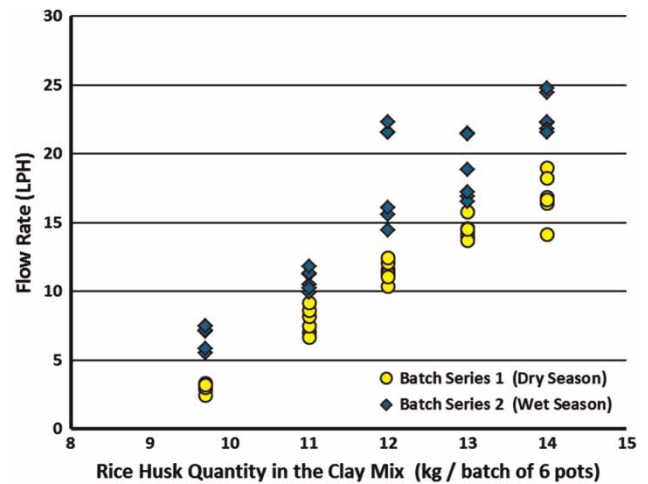


Figure 3 | Influence of the amount of rice husk on the flow rate of the filter pot.

on average. This may be due to seasonal fluctuations in the rice husk quality.

Pots from the second batch series were painted with silver nitrate and tested for flow rate a few days after, the silver-impregnated pots had dried. Results showed an average of 17% lower flow rates of pots with silver than without silver. It appeared that the lower flow rates after silver application were due to clogging of filter pores by the silver coating.

LRVs of *E. coli* of filter pots without silver application

The LRVs of *E. coli* for the first set of batches of filter pots without silver are plotted in Figure 4. For the analysis of the data sets, box-and-whisker plots were used. When plotting LRV of *E. coli* against the rice husk: clay ratio, there did not appear to be a clear correlation. At least it was clear that no significant decrease in *E. coli* reduction efficacy had occurred with increasing porosity and flow rate of filter pots in the dry season.

The LRVs of *E. coli* for the second set of batches without silver are shown in Figure 4. As observed for the first set of batches, there was also no obvious decrease in *E. coli* reduction effectiveness with increasing porosity and flow rate for the second set of batches. Pots out of batch 26 (14 kg rice husk) for example, had almost the same average LRV of 2.2 as of batch 23 (9.7 kg rice husk) with LRV of 2.1. The box-and-whisker plots are used to show the data sets more clearly. The Pearson correlation coefficient $r = -0.06$

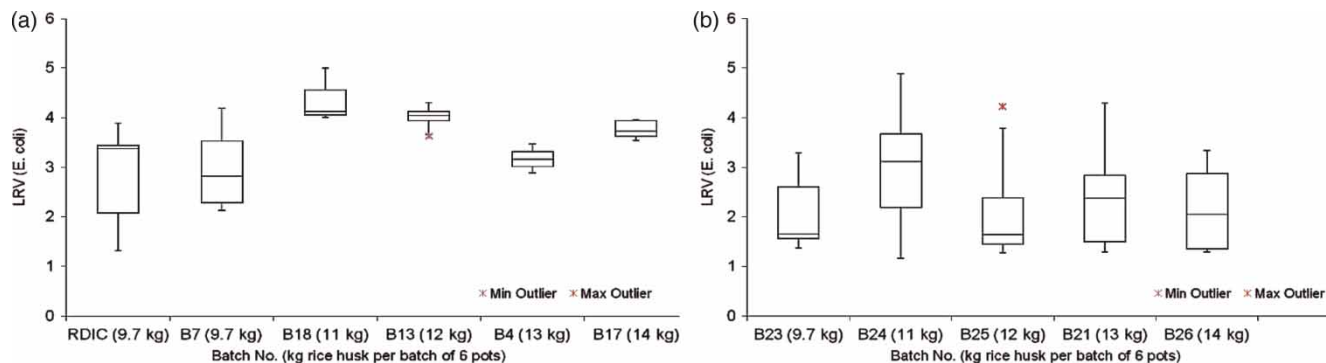


Figure 4 | Box-and-whisker plots of LRVs for pot filters with varying rice husk:clay ratio. (a) First set of batches; dry season; (b) second set of batches; wet season.

indicated no correlation between LRV and flow rate with varying rice husk:clay ratio. With this has been established that for all pot filters in both the wet and the dry season, no significant decrease in *E. coli* reduction efficacy occurs with increasing porosity and flow rate.

In addition, lower average values and higher variabilities were observed in the LRV results for the second set of batches (wet season) compared to the first set (dry season). This may in particular be due to the use of a different kind of rice husks with a higher proportion of the larger particle sizes in the wet season. Furthermore, a sensitivity analysis was carried out to determine how much error in the LRV results could be attributed to the variation in influent *E. coli* concentrations. The analysis showed that this error was very small. The average difference between minimum and maximum possible LRVs was only 0.2. The effect of silver on the LRV during filtration and storage was studied by testing 22 of our pot filters with different silver applications during a long-term loading experiment in natural surface water at Delft University of Technology in the Netherlands (van der Laan 2014). The results showed that the retention time in the receptacles was the dominant parameter for the *E. coli* inactivation by silver, and not the contact time during filtration inside the pots.

Strength test results for filter pots with silver application

The summarized results for the strength of silver-impregnated filters from the second set of batches (wet season) are presented in Figure 5. The box-and-whisker plots showed that there was a clear correlation between the increasing quantity of rice husks in the clay mix and the decreasing MoR values.

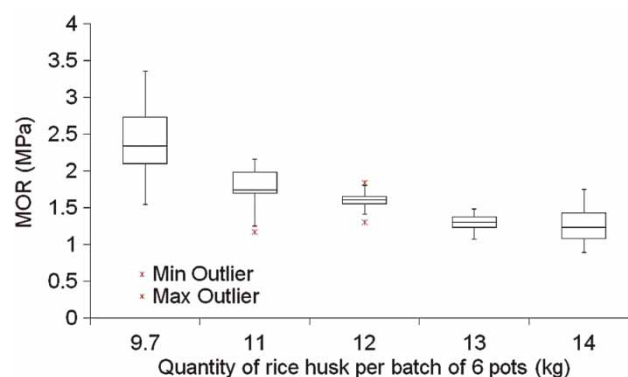


Figure 5 | Box-and-whisker plots of the MoR for filter pots of different porosities.

The strong correlation was confirmed by the Pearson correlation coefficient $r = -0.96$ between MoR and quantity of rice husk in the clay mixture of the filter pots.

Maximum kiln temperature variations

Changing the maximum firing temperature can change the pore size instead of the porosity of the pot filter. Three batches of pots were made of the same composition as RDIC standard filter pots and fired up to four different maximum firing temperatures: 685, 800, 885 and 950 °C. The results for flow rate, LRV of *E. coli* and strength of filter pots without silver application are presented in this section.

Effects on flow rates of filter pots without silver

As Figure 6 shows, there was a strong relation between the maximum firing temperature and the flow rate of the pots at kiln temperatures above 800 °C. By increasing the

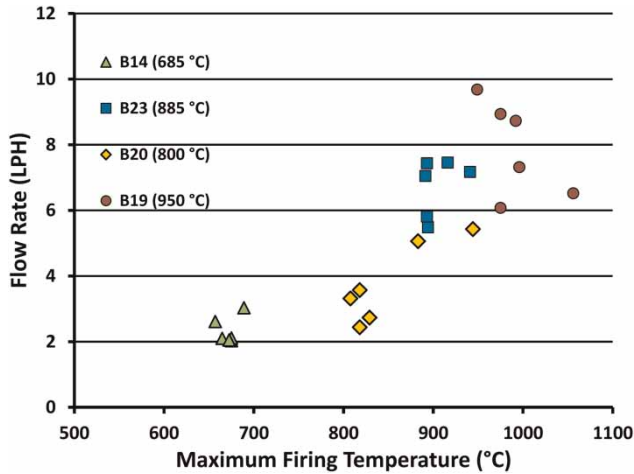


Figure 6 | The influence of maximum firing temperature on the flow rate of filter pots.

maximum kiln temperature from 800 to 950 °C, the flow rate of the pots increased on average per batch from 3.8 to 8.0 LPH.

Effects on LRVs for *E. coli* of filter pots without silver

Experimental results regarding the LRVs of filter pots without silver application fired at different temperatures are presented in Figure 7. The results indicate that an increase in maximum firing temperature from 800 to 950 °C had a small, but no significant effect on the bacterial removal efficacy of the filter pots.

Filter pots fired at 800, 885 and 950 °C had average LRVs of 2.3, 2.1 and 1.9, respectively.

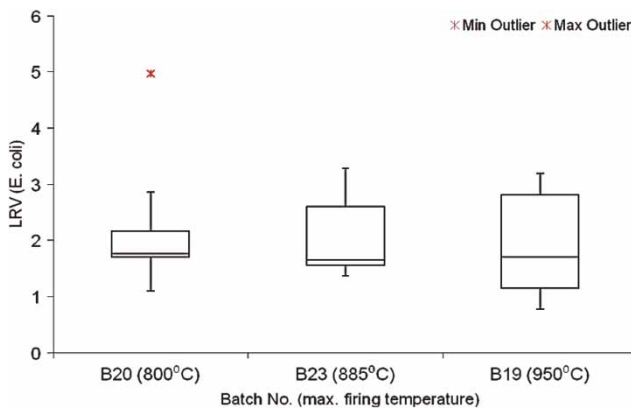


Figure 7 | The influence of maximum firing temperature on the LRV of filter pots.

A small negative effect on bacterial removal efficacy may be due to an increased pore size of filter pots fired at higher temperatures. The mean pore diameters of the filters were measured at the Delft University of Technology in the Netherlands by mercury intrusion porosity tests. The mean pore diameters for batches fired up to 800, 885 and 950 °C were 27.8 μm, 28.9 μm and 30.6 μm, respectively. These results showed that even a small increase of the filter pore size with increasing maximum firing temperature can result in a much higher flow rate. However, this does not necessarily lead to a significant reduction in bacterial removal, but may have a small negative effect.

Effects on strength of pot filters with silver

The results of the strength tests at pots with similar composition as RDIC standard filters with silver impregnation, is shown in Figure 8. The average values for MoR of four batches filter pots are plotted against the maximum firing temperatures. Also the number of samples (N) and the coefficient of variation (Cv in %) per batch are indicated.

Increasing the firing temperature from 800 to 950 °C increased the strength of the filter significantly.

Rice husk particle size variations

The effect of rice husk particle size variation on three batches of pot filters is studied in this section. The quantity of rice husk was the same for all batches, resulting in the

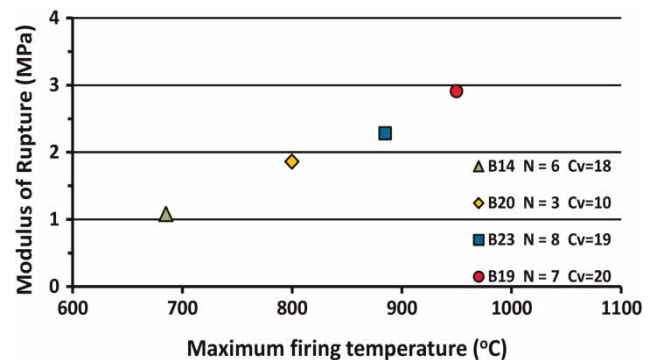


Figure 8 | Average MoR versus maximum firing temperature.

same porosity. Batches 7 and 12 were manufactured during the first series in the dry season. Batch 23 was fired during the second series in the wet season. Batch 12 was produced with rice husks of 0.5–1 mm in size. This rice husk size was obtained after an additional sieving step with a sieve of 0.5 mm and using the remaining rice husk on top of the 0.5 mm sieve.

Effects on flow rates of pot filters with various rice husk particle sizes

By increasing the rice husk particle sizes from <1 to 0.5–1 mm, the mean effective pore sizes increased from 28.9 μm for pot filters in batch 23 to 32.3 μm in batch 12. The flow rates of pot filters with different rice husk particle sizes are shown in Table 2.

It was quite clear that flow rates could be increased significantly by increasing the particle size of the burn-out material in the clay mixture.

Effects on LRVs of *E. coli* for pot filters with various rice husk particle sizes

The box-and-whisker plots in Figure 9 show the effect of the increase in the mean particle sizes of the rice husks on the LRVs for *E. coli*. The larger particles resulted in larger pores in the filter pots and therefore in higher flow rates. However, the disinfection efficiency of the filter decreased with the proportion of larger pores. The median LRV declined from 2.8 for filters B7 (rice husk sizes <1 mm, dry season) to 1.7 for B23 (<1 mm, wet season) and to 0.7 for B12 (0.5–1 mm, dry season).

Effects on strength of pot filters with various rice husk particle sizes

Results of strength tests showed that the MoR of pot filters decreased when the size of the rice husk in the clay mix was increased. B12 pot filters (particle sizes 0.5–1 mm)

Table 2 | Flow rates for filters with 9.7 kg rice husk of different particle sizes

Batch no.	Rice husk size mm	Season	Average flow rate LPH	Minimum flow rate LPH	Maximum flow rate LPH	Standard deviation LPH
B12	0.5–1	Dry	10.1	9.3	12.2	1.2
B23	0–1	Wet	6.7	5.5	7.5	0.3
B7	0–1	Dry	3.0	2.4	3.3	0.9

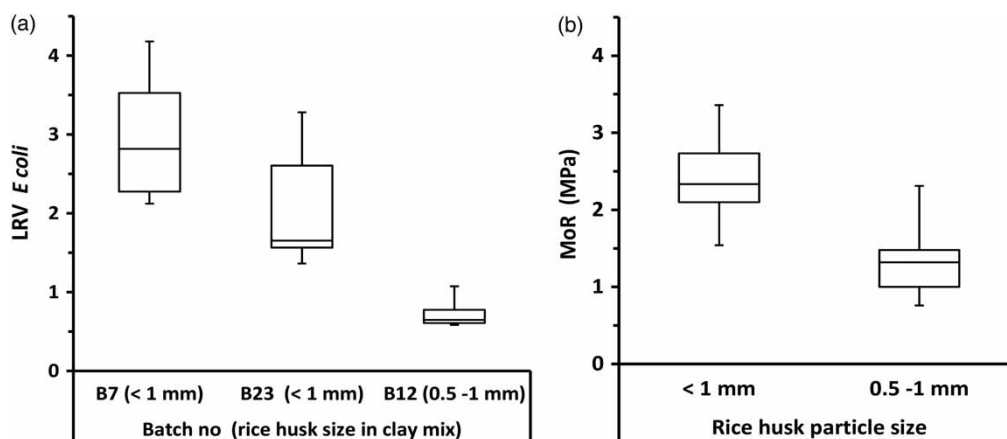


Figure 9 | Box-and-whisker plots of LRV and MoR for pots with different rice husk particle sizes. (a) LRV for pots with different rice husk particles; (b) MoR for pots with different rice husk particles.

had an average MoR of 1.3 MPa, whereas B23 and B22 pot filters (particle size <1 mm) had an average MoR of 2.4 MPa, almost twice higher than B12. In Figure 9, the results are shown in the form of box-and-whisker plots. A clear correlation was seen between the distribution of the rice husk particle sizes in the clay mix and the MoR: the larger the particle sizes of rice husk, the weaker the filter.

Summary of results

To obtain a clear overview of the findings of this study, see the main results presented in Table 3.

DISCUSSION

When applying ceramic filter pots for water treatment, reasonable and feasible criteria should be required. The performance of the ceramic pot filters produced in this study was evaluated against criteria for flow rate ($FR \geq 2.5$ LPH),

\log_{10} reduction value for *E. coli* ($LRV \geq 2.0$), and mechanical strength ($MoR \geq 1.5$ MPa). CPFs that meet these tentative criteria are considered acceptable to be applied as a household-scale water treatment system in developing countries.

In the literature, flow rate criteria varies between 1.0 and 3.5 LPH.

Flow rates decrease with time due to clogging by suspended particles in feed water. CPF do not return to their original flow rate after scrubbing and flow rate will decrease over time until a low value is reached, insufficient to meet the drinking water needs of a family (van Halem 2007). A sustainable household water treatment system (HWTS) should provide sufficient water for a family long term. The flow rate should be ≥ 2 LPH and is preferred to be higher (van Halem 2009). RDIC designed its system to aim for an optimal flow rate of 1.5–3.5 LPH (Hagan et al. 2013). From these considerations, the flow criterion ≥ 2.5 LPH used in this study is reasonable and feasible.

In the literature, criteria for bacteria removal vary from 2.0 to 4.0 \log_{10} reduction.

Microbiological testing of CPFs should be carried out before silver application. A minimum of a 2-log reduction in *E. coli* should be achieved (Ceramics Manufacturing Working Group 2011). The World Health Organization has formulated performance requirements for HWTS and associated \log_{10} reduction criteria for pathogens. For bacteria an $LRV \geq 2$ corresponds with 'protective' and an $LRV \geq 4$ with 'highly protective' (WHO 2011). CPFs are a point-of-use water treatment technology that has shown promise in preventing early childhood diarrhea (ECD) in resource-limited settings. CPF log reduction values should be ≥ 3 (Mellor et al. 2014). From these considerations, the criterion $LRV \geq 2.0$ for *E. coli* removal by CPFs (before silver application), used in this study, is realistic and according to the WHO criterion of 'protective' for pathogenic bacteria.

In the literature, we did not find criteria for the material strength of ceramic pot filters.

The manual of RDIC (Hagan et al. 2013) provides no criteria for evaluating the material strength of CPFs. Many dozens of CPFs with different porosities were produced, transported and tested in this study. Despite intensive treatment there were no noticeable differences observed in fracture sensitivity of CPFs with increased porosity compared to standard CPFs. Therefore, we recommend for material strength as

Table 3 | Summary of variations with making of pot filters and main experimental results

Parameter variations	Batch no.		Average flow rate (LPH)		Average LRV <i>E. coli</i>		Average MoR (MPa)	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Rice husk quantity (kg)								
9.7	B7	B23	3	7	3.0	2.1	2.3	
11	B18	B24	8	11	4.4	2.9	1.8	
12	B13	B25	11	18	4.0	2.2	1.6	
13	B4	B21	14	19	3.2	2.4	1.3	
14	B17	B26	17	23	3.8	2.2	1.3	
Maximum temperature (°C)								
685	B14		2				1.1	
800		B20	4		2.3		1.9	
885	B7	B23	3	7	3.0	2.1	2.3	
950		B19	8		1.9		2.9	
Rice husk particle size (mm)								
0–1		B22	6				2.5	
0–1	B7	B23	3	7	3.0	2.1	2.3	
0.5–1	B12		10		0.7		1.3	
Reference pot filter RDIC			1.5–3.5				4.6	

provisional criterion $\text{MoR} \geq 1.5 \text{ MPa}$ based on our experience with the use of CPF with significant differences in porosity. However, more practical research is needed into the relationship between material strength and fracture sensitivity of CPF to develop a reasonable and acceptable criterion.

Based on all the results obtained, several critical production parameters can be distinguished. Also the results show potential for increasing the water yield of the pot filters by higher initial flow rates. It appeared that the average flow rate of CPFs, measured with constant head, could be increased from 7 to 23 LPH by adding larger quantities of rice husks to the clay mixture, without reducing the bacterial removal effectiveness. The performance of the batches B23, B24 and B25 also shows that the flow rates of pot filters can be increased from 7 to 18 LPH by adding rice husk in higher amounts in the clay mixture and still meet the criteria for LRV and MoR.

The material strength of the filter pot was found to be significantly reduced by increasing the quantity of rice husks in the clay mixture. On the other hand, it appeared that a higher maximum firing temperature had a beneficial effect on the material strength of the filter pot. The performance of the batches B19, B20 and B23 shows that the MoR of pot filters can be increased from 1.9 to 2.9 MPa by increasing the maximum firing temperature from 800 to 950 °C with only a slight but not significant effect on the bacterial removal efficacy.

Further research will be required in order to see if both the bacterial removal effectiveness and the material strength can be maintained to an acceptable level by adding more rice husk to the clay mixture while the filter pots are fired at higher maximum kiln temperatures.

The size of the pores in the filter proved to be the most critical parameter for the effective removal of bacteria, which was determined by an accurate selection of the particle size of the rice husk.

Comparison of the performances of batches B7 and B23 to B12 shows that the flow rate could be significantly increased by the use of rice husk with particle sizes of 0.5–1 mm, but at the expense of meeting the criteria for both LRV and MoR. Unfortunately, this resulted in a considerable reduction in both the bacterial removal effectiveness and the material strength, making the performance of pot filters of B12 no longer meet the criteria laid down.

A notable seasonal effect on the flow rate of pot filters was observed, when comparing the performance of the batches B23, 24, 25, 21 and 26 with B7, 18, 13, 4 and 17, respectively. It appeared that the same quantity and particle size of rice husks yielded a higher flow rate and a lower LRV in the wet season than in the dry season. However, it was found that the performance of the pot filters still meets the criterion for LRV during the wet season. Further research will be needed to determine to what extent this was caused by the use of rice husks from another supplier.

CONCLUSIONS

This research into the identification of critical parameters in the production of CPFs was performed with the aim to increase both the water yield and the quality of CPFs. The main conclusion is that the most critical parameter for effective water filtration appears to be the pore size of the pot filters. An important outcome is the confirmation of the results of a previous investigation (Bloem 2009) that the flow rate of CPFs can be increased to 10 or even 20 L/hour by increasing the porosity of the filter material by the addition of an appropriate amount of burn-out material into the clay mixture, without compromising the bacterial removal effectiveness.

It is established that the flow rate of the pot filter could be increased in three ways:

1. by increasing the porosity of the filter via increasing the quantity rice husks in the clay mixture;
2. by increasing the pore size by means of rice husks with a larger particle size; and
3. by increasing the pore size by increasing the maximum firing temperature.

The bacteria removal effectiveness will only be compromised significantly when increasing the pore size with larger rice husk particle sizes.

The material strength of the CPF will be reduced by increasing the rice husk to clay ratio, but the strength is increased at higher maximum kiln temperatures.

Further research in this area is recommended. It would be interesting to know whether an acceptable level for both bacterial removal effectiveness and the material strength can

be achieved by adding more rice husk to the clay mixture, while the filter pots are fired at a slightly higher maximum temperature.

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