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Assessing the sustainability of the silver-impregnated ceramic pot filter for low-cost household drinking water treatment

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Abstract

A low-cost technology to treat water at the household level is the ceramic silver-impregnated pot filter (CSF). The CSF consists of a pot-shaped filter element that is placed in a plastic receptacle. The ceramic pot filter is a promising treatment system to supply safe drinking water especially to people living in rural areas. The focus of this study was to assess the sustainability of a household drinking water treatment system based on five criteria: (i) accessibility, (ii) water quality, (iii) water production, (iv) functionality, and (v) environmental footprint. The removal of *Escherichia coli* and protozoan (oo)cysts was found to be significant, which was supported by the reduction in diarrhoea cases observed by CSF users in a recent field study. The retention of MS2 bacteriophages as an indicator for virus removal was, however, found to be unsatisfactory. It is therefore recommended that research on virus removal by CSF continues, especially in relation to the colloidal silver application and other potential additives. The criterion of water production was shown to be the limiting factor, because it reduced substantially during treatment of surface water. The fast clogging of the CSF during the first hours of use was caused neither by inorganic nor organic fouling, but by colloidal particles. Two direct effects may be identified from the decreasing flow rate: frequent scrubbing and higher water prices. Frequent scrubbing results in a higher risk of recontamination and breakage. Based on this finding the authors recommend an optimization study to increase the initial flow rate without sacrificing the removal efficiency.

Keywords: Ceramic; Filtration; Silver; Drinking water; Sustainability

1. Introduction

One of the targets established in the Millennium Development Goals is to halve the proportion of people that do not have sustainable access to safe water and basic sanitation (United Nations Millennium Project, 2006). The World Health Organization (WHO) and UNICEF (2000) assessed that 1.1 billion people do not have access to improved drinking water sources. This is undeniably a major task for, among many others, policy-makers, engineers, and researchers. Pioneers have come up with smart solutions to treat water in the tropics; often adaptations of conventional techniques for local use. Many technologies focus on water treatment at the point-of-use, which is often done within the household. These so-called household drinking water treatment systems contribute to reaching many people in the short-term, even though they demand a certain degree of expertise and commitment by the users. A household water treatment system currently in use by many people worldwide is the ceramic silver-impregnated pot filter (CSF). These pot filters are manufactured in various countries, including Honduras, Kenya, Cambodia, Ghana, and Nicaragua.

The CSF consists of a pot-like shaped filter element that is placed in a plastic receptacle, as shown in Fig. 1. The raw water is poured into the pot and slowly percolates through

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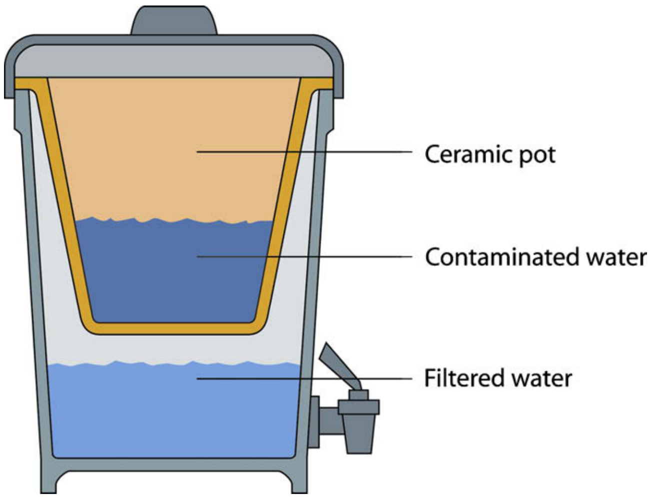

Fig. 1. Ceramic silver-impregnated pot filter (CSF).

the ceramic element into the receptacle. A small tap is used to withdraw water for drinking. The ceramic pot filter is a promising treatment system to supply safe drinking water especially to people living in rural areas. The major advantages of the system are that it is locally manufactured, and that the operation is straightforward for uneducated users. Even though CSF shows great potential to contribute to the Millennium Development Goals, it is vital at this stage to determine whether CSF truly is a *sustainable* household water treatment system. To assess the sustainability of a household drinking water treatment system five criteria are identified: (i) accessibility, (ii) water quality, (iii) water production, (iv) functionality, and (v) environmental footprint. The focus of this paper is to assess the sustainability of the ceramic silver-impregnated pot filter for low-cost household drinking water treatment.

As mentioned before the ceramic filter element is manufactured with local materials and skills. A mixture of clay, sawdust and water is pressed into a pot shape with press moulds. Once the filter element has its shape it is fired in a kiln and the sawdust is combusted to leave porous material. The filter element is impregnated with a mixture of colloidal silver, for assumed disinfection purposes, before distribution to the costumers. The fact that the filter element is produced by a single entrepreneurship supports the local economy. For the manufacturing method the only energy consumption is the firing of the kiln, the environmental impact depends on the energy source used by the manufacturers. For example, in some regions woodcuttings from rubber trees are a more sustainable source than forest wood. Apart from the kiln, the manufacturing method and natural sources needed for this treatment system are very environmental-friendly. Nevertheless, at this stage the authors cannot provide a reliable overview of the environmental impact. However, the treatment process itself does not consume energy or chemicals, indicating that this system might prove extremely sustainable. The operation of the system is relatively simple, and the users' effort is equal to traditional household water storage. The only maintenance procedure is the scrubbing of the filter element when clogging causes the flow rate to reduce to unsatisfactory levels. The frequency of scrubbing has an impact on the functionality of this system and will therefore be discussed later in this article in relation to the water production. The accessibility of CSF to the users depends on two factors, the affordability and the availability. Because the pot filters are locally produced it may be assumed that availability of the filter element and other spare parts poses no problem. This is, however, based on the assumption that the filters are only distributed in the area where the factory is situated. Affordability depends on the costs of the complete system and replacement of spare parts. The purchase of a filter is obviously cheaper when transport costs can be kept low. With respect to the affordability, the distribution of the filter should thus be limited to area around the factory. The frequency of replacement mainly depends on the lifespan of the filter element. During this lifespan the filter has to live up to the users' expectations to produce both sufficient and safe drinking water. These requirements correspond with two of the criteria to assess the sustainability of household water treatment systems; (ii) water quality, and (iii) water production. In this paper these two criteria are further elaborated before discussing the relationship with the other criteria.

2. Water quality

The performance of CSF has been investigated over the years by an increasing number of researchers. Even though filters are currently manufactured in many countries worldwide, the Nicaraguan pot filters are most frequently investigated. Researchers have studied the produced water quality both in the laboratory and in the field. In general, the drinking water quality improvement by a treatment system is determined by the removal of pathogenic microorganisms, heavy metals, nitrogen, turbidity, colour and odour, but also emerging organic micropollutants such as pesticides and pharmaceuticals. In regions where CSF is implemented the initial focus is to reduce the number of diarrhoeal cases; therefore the main function is to remove pathogenic microorganisms. The removal efficiency of bacteria, protozoa and viruses is mainly done using indicator organisms.

In the literature, the removal efficiency of bacteria by CSF is most often tested by determining the retention of *Escherichia coli* (Lantagne, 2001a; Fahlin, 2003; Campbell, 2005; Van Halem, 2006; Duke et al., 2006). Although the number (n) of measurements per study varied widely, $n = 1$–19, the overall impression is similar for most studies with a log(10) reduction value of 2–3. In most studies the maximum log(10) reduction was not found, because the *E. coli* counts were zero in the filtered water (Lantagne, 2001a; Fahlin, 2003; Campbell, 2005; Duke et al., 2006). Based on this finding Van Halem (2006) spiked extremely high concentrations of *E. coli* K12 to reach the highest possible reduction for CSF, resulting in a log(10) reduction of 7. The removal efficiency of (indicators of) protozoan oocysts is not as frequently measured as *E. coli*. Lantagne (2001a) performed experiments with *Cryptosporidium parvum* oocysts and *Giardia Lamblia* cysts, and found log(10) reduction values of 4.3 and 4.6, respectively. Van Halem (2006) observed similar results for the removal of sulphite reducing *Clostridium* oocysts, with an average log(10) reduction of 4.3 for the pot filter produced in Nicaragua. The above results clearly show that CSF effectively removes both *E. coli* and protozoa (oo)cysts from the contaminated water. Fig. 2 depicts the achieved log(10) reduction values of *E. coli*, protozoan oocysts and MS2 bacteriophages found in previous research for the Nicaraguan pot filter. The latter was used as an indicator for viruses and, being by far the smallest pathogen, most difficult to retain by CSF. Log(10) reductions below 1 (Lantagne, 2001a; Van Halem, 2006) are unsatisfactory for a sustainable treatment system. Considering these results found for the Nicaraguan pot filter, however, it is noteworthy that Van Halem et al. (2007) observed similar results for filters from Cambodia and Ghana. UNICEF/WSP (2007) assessed the health gains through CSF implementation in 80 Cambodian households, and it was found that diarrhoeal cases decreased significantly. Overall it may thus be concluded that CSF improves the drinking water quality, and has the potential to supply safer water to households worldwide.

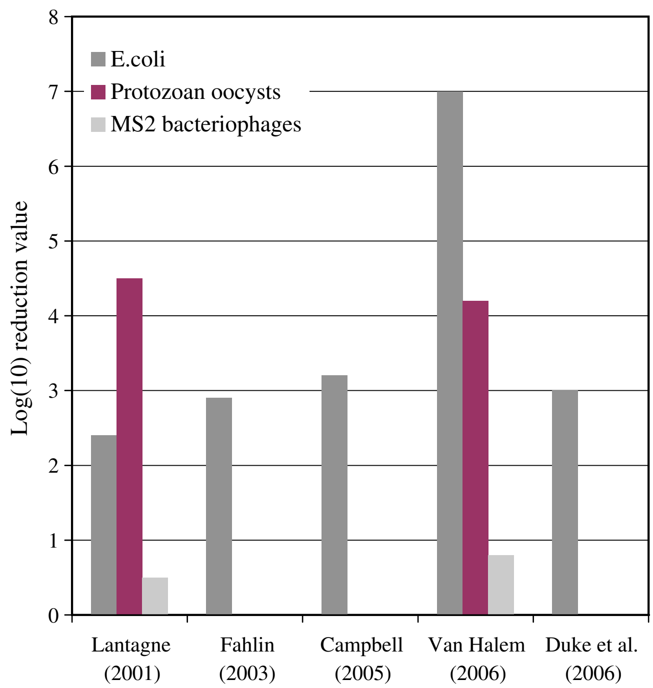

Fig. 2. Overview of the removal efficiency of *E. coli*, protozoa oocysts, and MS2 bacteriophages by the Nicaraguan ceramic silver-impregnated pot filter.

One of the properties of the ceramic silver-impregnated pot filter is the addition of a colloidal silver layer. The method of application and source of silver varies per manufacturing location, but probably a solution of silver nitrate is brushed on the filters at most factories. Nevertheless, the leaching of silver from the filter material was observed at all three manufacturing locations. In Fig. 3 the leaching of silver is given for six filters per location during the first twelve weeks of operation. The concentrations are far below the WHO guideline of 100 μg/L, so consumers are not threatened by argyria, a permanent skin condition (WHO, 2006). Previous research has shown for filters with this silver impregnation, slightly better removal of fecal coliforms (Lantagne, 2001a) and *E. coli* K12 (Van Halem, 2006). The colloidal silver is applied for assumed disinfecting purposes; however, some remarks have to be made on the sustainability of this application. CSF has been indicated to have a lifespan of over 5 years (Lantagne, 2001b; Campbell, 2005), but implementers recommend a life of 1–2 years (UNICEF/WSP, 2007). Either way, the leaching of silver will diminish after a few months of use. It is very likely that the observed better removal of coli-

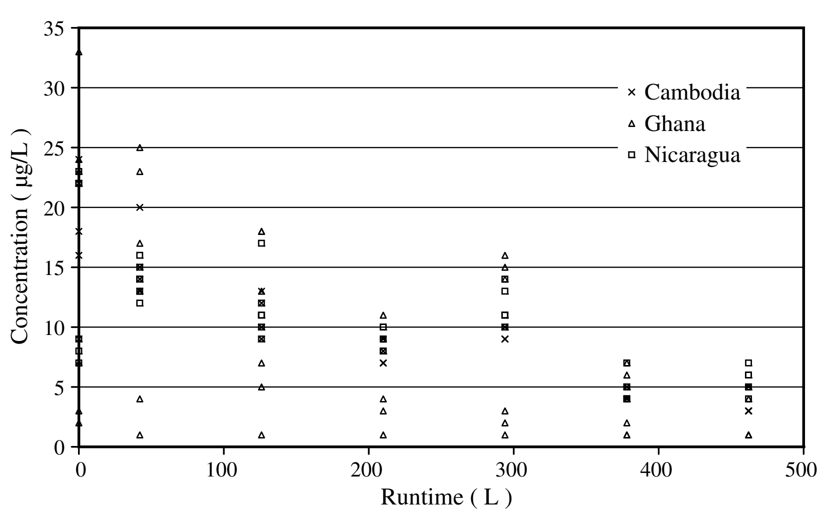

Fig. 3. Leaching of silver from the filter material of 6 filters per manufacturing location. Total filter runtime is 12 weeks, with a production of 6 L per day.

forms by filters with the application of colloidal silver is caused by the contact with silver in the receptacle. Since the silver concentrations in the receptacle decrease in the course of the first weeks of filter runtime this may not be assumed a sustainable disinfection step. In addition to this finding, the authors are sceptical about the improvement of CSF by the addition of a colloidal silver layer based on the following (Van Halem, 2006):

- The removal of *E. coli* K12 was already found to be very high without the application of silver,
- The retention of sulphite reducing *Clostridium* spores was equally effective by filters with and without silver, and
- The retention of MS2 bacteriophages was observed to be better by filters without the silver application.

This final observation suggests additional research on the effect of silver and other potential additives for the removal efficiency of viruses in CSF.

3. Water production

The flow rate of the pot filter is used as a quality check at the factories; filters within the 1–3 $L\,h^{-1}$ range are approved to be sold. Rejected filter elements are destroyed and crushed for recycling purposes. The percentage of discarded filters differs per factory, but an experienced facility should be able to achieve less than 15% waste. During operation the filter element will clog, resulting in a decreased water production. Therefore maintenance of the filter is needed to prevent the filter from complete clogging. The manufacturers' advice is to scrub the inside of the filter element with a stiff laundry brush once the flow rate reaches an unsatisfactory low level. Previous research has shown that the water production decreases significantly during treatment of surface water (Lantagne, 2001a; Hwang, 2003; Van Halem et al. 2007). After a month of operation, values as low as 0.5 $L\,h^{-1}$ were found. Van Halem et al. (2007) observed that the prescribed manual scrubbing restores the water production instantly. Although this results in a higher flow rate, long-term clogging is not prevented with this cleaning method. Another recent study (UNICEF/WSP, 2007) monitored the use of CSF in the field and found that users scrub their filters on average 2.3 times a week. Originally this was intended to be necessary only once a month. This frequency is potentially worrying, since for thorough cleaning the filter element must be taken out of the receptacle. Obviously, with frequent cleaning the risk of breakage and recontamination increases substantially. It may therefore be concluded that fast clogging and consequently frequent scrubbing potentially affect the water quality and lifespan of the filter element. This is supported by the Cambodian field study where they found that 64% of disuse in the 328 interviewed households was because of filter element breakage (UNICEF/WSP, 2007). A sustainable household water treatment system should provide sufficient water for a family long-term, and according to the WHO guidelines for drinking water quality (2006), a daily consumption of at least 3 L per person is needed. With an average family size of 5 persons the water production of the CSF should be a minimum of 15 L per day. Since this amount is not evenly spread over the whole day, the flow rate per hour should be at least 2 L and is preferred to be higher.

The water production is evidently an important criterion to determine the sustainability of CSF. However, little is known about the cause of clogging. Therefore three hypothetical clogging mechanisms known from membrane filtration technology were investigated: decrease in flow rate caused by (a) organic fouling of the filter by accumulation of natural organic matter (NOM), (b) inorganic fouling, *i.e.*, the precipitation of calcium carbonate ($CaCO_3$) in the filter pores, and (c) physical fouling by inert particles/colloids. Once the mechanism is known, a sustainable cleaning method can be developed to retain a high flow rate.

For these experiments ceramic pot filters from Nicaragua were selected after they had been used for surface water treatment for 12 weeks (Van Halem et al., 2007). During this period of operation the filters were scrubbed when they had reached a flow rate around 0.5 $L\,h^{-1}$; this occurred twice. Before starting the experiments the filters were left to dry completely and then tested for their flow rate again. In all experiments the filters were soaked in water for 48 h to release all air from the filter material. Filters tested for organic and inorganic fouling were placed in a solution of 3 $g\,L^{-1}$ sodium hypochlorite and 33 $g\,L^{-1}$ citric acid solution, respectively, for 20 h. The influence of physical fouling was tested by either backwashing the filter with a vacuum pump or applying force with a high pressure jet. These two methods did not prove to be equally effective, since the force for backwashing was insufficient to reach all the pores. The use of a high pressure jet was more effective; however, it was difficult to be sure that all pores were reached, since it was a rough method. In Fig. 4 the measured flow rates are depicted relative to the initial water production, *i.e.*, the flow rate of the filter when it was new. This representation is chosen to be able to compare filters with different initial flow rates. The figure shows (from left to right) the clean water flux, the flow rate after the first and second scrub – 6 and 9 weeks in operation, respectively, after 12 weeks in operation with canal water, after drying, and after treatment with (a) chlorine, (b) citric acid and (c) high pressure jet.

It clearly shows that after the first scrubbing, on average, the initial flow rate doubles. The authors cannot explain this surprising increase; probable causes are clogging by dirt entrapment during storage and/or sealing of the outer pores during the manufacturing process. Polishing of the wet filter element after it comes out of the press mould causes the latter. The second scrubbing doesn't give such a large increase, indicating that long-term clogging is not prevented with this cleaning method. The water pro-

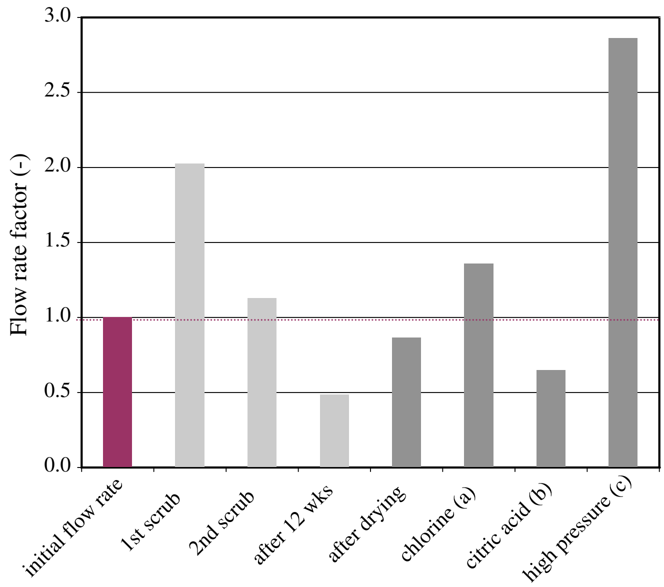

Fig. 4. Flow rates in relation to the initial flow rate (=1.0).

duction of CSF had decreased after 12 weeks of operation to half of the initial flow rate. By drying the filter element the accumulated biomass shrinks, resulting in an increased water production. The flow rate increases even further after the treatment with chlorine, because this oxidizes the biomass in the filter material. Citric acid does not show the same result and it may therefore be concluded that no calcium carbonate is precipitated in the filter element. The force of the high pressure jet should remove most particles and biomass from the filter. The enormous increase in flow rate after high pressure cleaning demonstrates that biomass and mainly particles are responsible for clogging of the CSF.

Following each cleaning procedure (a, b, and c) the filters were loaded with raw canal water from the Dutch canal Schie. Fig. 5 gives an overview of the measured flow rates during the first few hours of operation. Like mentioned before, the filters treated with chlorine, scrubbing and high pressure jet show an increase in flow rate. However, during the first hours of operation rapid clogging occurs in all filter elements. Within 5 h the flow rates are at the same level as just before the cleaning. Furthermore, the decrease in flow rate for all four filters continues in the following 48 h. From these findings, it can be concluded that none of the cleaning methods provides a sustainable increase in water production. Additionally it can be concluded that neither organic nor inorganic fouling are responsible for the short-term clogging. The clogging is too rapid for biomass growth to occur, since the raw water temperatures are very low (8–10 °C) and chlorine was still found to be present in the filter element. An additional experiment was done with water that was pre-treated with a sand filter (1.0–1.6 mm fraction). The rate of clogging was not slowed down compared to filters that were loaded with raw canal water. It may therefore be concluded that instead of suspended particles, colloids are responsible for the clogging in CSF. Pre-treatment with a cloth, as advised by the manufacturers, will thus most likely not slow down the clogging process.

At this stage a distinction can be made between surface and depth filtration in CSF, as shown in Fig. 6. Surface filtration occurs at the top layer of the filter material, whilst in depth filtration particles penetrate deeper into the material. It was found that fouling of particular matter on the surface of the filter causes short-term clogging. This mechanism is reversed by hand brushing of the filter element. Long-term clogging, however, is not prevented with this cleaning procedure, because depth filtration by particles and biomass

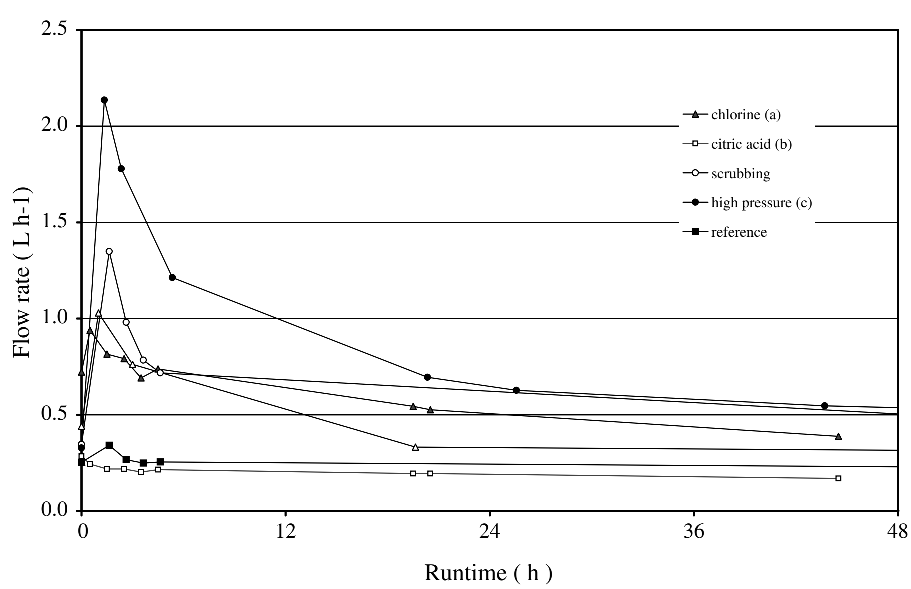

Fig. 5. Flow rate during first 48 h after scrubbing, citric acid (a), chlorination (b), high pressure (c), or with water pre-treated by sand filter.

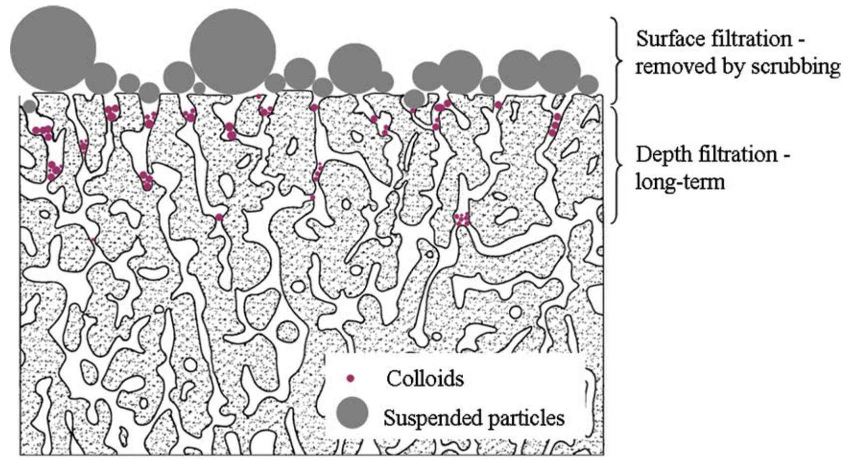

Fig. 6. Diagram of the hypothetical surface and depth filtration by suspended particles and colloids in CSF.

continues over time. The impact of depth filtration can be seen in Fig. 4 between the first and second scrubbing. It should be noted that these results merely give an indication of the required frequency of cleaning, since this depends greatly on the raw water quality. Nevertheless, during the field study by UNICEF/WSP (2007) similar cleaning frequencies were found, namely 2.3 times per week.

4. Discussion

The previous sections have provided an overview of the water quality and quantity produced by CSF. Especially the water production is not constant over time and therefore affects the sustainability of the ceramic pot filter. Two direct effects may be identified from the decreasing flow rate: frequent scrubbing and higher water prices. Frequent scrubbing results in a higher risk of recontamination and breakage. This finding illustrates the relationship with two other criteria, namely, (i) accessibility, and (iv) functionality. The effect on the accessibility is potentially supported by the finding that the majority of misuse of the filter was caused by breakage, as determined in a recent Cambodian field study (UNICEF/WSP, 2007). It is clear that the lifespan of 1–2 years might be compromised by scrubbing the filter element over twice a week. The effect of the decreasing water production on the water prices, and thus affordability, can be explained with a short calculation. The costs of the CSF system in Cambodia are between US$4 and 8, and the costs of replacement of a filter element are currently in the US$2.5–4 range (UNICEF/WSP, 2007). Assuming a lifespan of the filter element of only 3 months, a family of five persons consuming 3 L day^{-1} per person would actually pay approximately US$1.8–3/$m^3$. For comparison, after centralized multi-barrier treatment and distribution the price of drinking water in the Netherlands is around US$2. UNICEF/WSP (2007) observed that after 1.5 years still half of the pot filters are in use, which would correspond to a water price of the US$0.3–0.5 range. This seems acceptable, unfortunately it is unknown if by that stage the water production was still sufficient for a family. The effect of regular scrubbing on the criterion of functionality is more complex to quantify, however, it is clear that next the extra work also the risk of recontamination increases with frequent cleaning. Nevertheless, compared to other household drinking water treatment system the ceramic pot filter is still easy in oper-

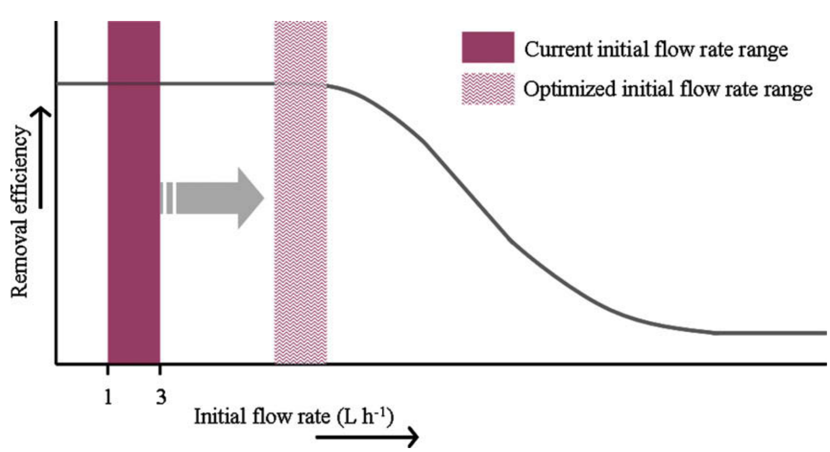

Fig. 7. Probable relation between removal efficiency and initial flow rate of CSF.

ation and maintenance and should score well for this criterion too.

Based on the findings in this study a long-term water production of 15 L day^{-1} per filter is not realistic with the current CSF design. However, since the removal efficiency is very good it might be feasible to increase the initial flow rate. The 1–3 L h^{-1} range that is presently targeted at in the factories is a rule of thumb that could potentially need some adjusting. Perhaps if the initial flow rate is higher, the daily water production can be kept higher as well. Of course, in that case an optimum has to be found between the removal efficiency of pathogens and the initial flow rate. Fig. 7 graphically shows the probable relation between removal efficiency and water production.

5. Conclusions

The ceramic silver-impregnated pot filter was found to score especially well for one of the identified criteria, namely, the water quality. The water quality was excellent with respect to the diarrhoea inducing microbes, apart from the removal of MS2 bacteriophages. It is therefore recommended that research on virus removal by CSF continues, especially in relation to the colloidal silver application and other potential additives. The criterion of environmental footprint was more complex to assess, but the energy and chemical consumption is low compared to other household water treatment systems. The criterion of water production was shown to be the limiting factor, and directly influencing the affordability and functionality of CSF. Based on this finding the authors recommend an optimization study to increase the initial flow rate without sacrificing the removal efficiency.

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