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A B S T R A C T

Ceramic pot filters are considered safe, robust and appropriate technologies, but there is a general consensus that water revenues are limited due to clogging of the ceramic element. The objective of this study was to investigate the potential of high flow ceramic pot filters to produce more water without sacrificing their microbial removal efficacy.

High flow pot filters, produced by increasing the rice husk content, had a higher initial flow rate (6–19 L h^{-1}), but initial LRVs for *E. coli* of high flow filters was slightly lower than for regular ceramic pot filters. This disadvantage was, however, only temporarily as the clogging in high flow filters had a positive effect on the LRV for *E. coli* (from below 1 to 2–3 after clogging). Therefore, it can be carefully concluded that regular ceramic pot filters perform better initially, but after clogging, the high flow filters have a higher flow rate as well as a higher LRV for *E. coli*. To improve the initial performance of new high flow filters, it is recommended to further utilize residence time of the water in the receptacle, since additional *E. coli* inactivation was observed during overnight storage. Although a relationship was observed between flow rate and LRV of MS2 bacteriophages, both regular and high flow filters were unable to reach over 2 LRV.

1. Introduction

Ceramic pot filters are locally produced in over 35 factories around the world with locally available resources, such as clay and rice husk (Rayner et al., 2013; Soppe et al., 2015). The past decade, ceramic pot filters have demonstrated the capacity to achieve high $\log_{10}$ reduction values (LRVs) for pathogenic indicator organisms like *E. coli* (Van Halem et al., 2007; Oyanedel-Craver and Smith, 2008; Lantagne et al., 2009; van Halem et al., 2009; Brown et al., 2012; van der Laan et al., 2014). Hunter (2009) showed with a meta-regression analysis that compared to other interventions, such as SODIS and biosand filters, the ceramic pot filter is the most effective household water treatment and storage intervention. In addition, Ren et al. (2013) found that ceramic pot filters are more cost-effective and environmentally sustainable compared to centralized water treatment systems.

Although ceramic pot filters are considered safe, robust and appropriate technologies, there is also a general consensus that water revenues are limited due to clogging of the ceramic element (Van Halem et al., 2007; Salvinelli and Elmore, 2015; Salvinelli et al., 2017). As part of the quality protocol, filters are tested at the factories for their flow rate, which should be within 1–5 L h^{-1} limits, depending on the factory (Rayner et al., 2013). However, during filtration, particulate matter blocks pores in the ceramics, reducing the flow rates far below 1 L h^{-1}. Obviously, the rate and degree of pore blocking depends on the quality of the source water, particularly the amount of suspended particles (Salvinelli et al., 2016). To prevent water revenues from dropping too low, pot filters can be cleaned by a scrubbing procedure, where the top layer of the ceramic element is brushed and washed. This procedure results in an instant, yet very temporary, flow rate peak, not preventing long-term flow rate reductions as low as 0.2 L h^{-1} (Van Halem et al., 2007; Salvinelli et al., 2016).

The objective of this study was to investigate the potential of high flow ceramic pot filters to produce more water without sacrificing their microbial removal efficacy. In addition, the effect of clogging on the removal of indicator organisms (*E. coli* and MS2 bacteriophages) was assessed. The high flow filters were produced with the same raw materials (same clay, same rice husk), but with lower clay:burnt material ratios, i.e., more rice husk was added to increase the porosity of the ceramic element. The performance of

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high flow filters (n = 22) and reference filters (n = 12) were assessed during three experiments: (1) a long-term falling head clogging experiment to determine *E. coli* and MS2 bacteriophage removal, (2) an intensive continuous loading experiment to identify (ir)reversible clogging mechanisms and (3) an overnight storage experiment with silver (Ag)-painted filters to assess the effect of rice husk content on *E. coli* during post-filtration storage in the receptacle.

2. Materials and methods

2.1. High flow ceramic pot filter production in Cambodia

In total, 34 filters were tested in this study, including four reference ceramic pot filters from the full-scale RDIC factory in Cambodia (rdic.org). These filters were manufactured according to the standard production process, as described by Brown and Sobsey (2010). Standard RDIC filters are made of 30 kg clay, 9.7 kg rice husks, 1 kg of laterite and 14.5 L of water per batch of six filters. The rice husks are finely ground and sieved at a particle size of <1 mm. Since 2005, RDIC has been adding laterite, a soil containing iron oxide, for its assumed binding and inactivation of viruses (Hagan et al., 2009).

The high flow rate filters were produced in a pilot factory at the production site of RDIC in Cambodia. Filters were produced in batches of six, using a gas fired temperature-controlled kiln (Fig. 1). Materials were the same as the normal production line, with only the rice husk content increased: 9.7 (reference), 11, 12, 13 or 14 kg per batch of six filters. Filters with cracks or flow rate outliers were discarded, resulting in the selection of 34 filters.

For the majority of filters, the ceramic element was painted with $AgNO_3$, either in- and outside of the ceramic element or only on the outside of the ceramic element (n = 28). In addition, a selection of 6 filters remained unpainted. The $AgNO_3$ solution used originated from the RDIC factory, where the Microdyn Ag-based disinfectant with 3.2% $AgNO_3$ and 0.6% $Cu(NO_3)_2$ by mass is applied (Brown and Sobsey, 2010). Application consisted of 0.00215 M reagent-grade $AgNO_3$ with 200 mL of solution applied on the inside and 100 mL on the outside of the element. Ag application has been shown to affect the flow rate of the ceramic pots (17%, Soppe et al., 2015) but could also conceal actual microbial removal efficacies by the ceramic element due to residual Ag in the receptacle. Therefore, the samples were taken directly after filtration, preventing any contact time after filtration between Ag and the spiked indicator organisms.

2.2. Experimental set-up

The research consisted of two experimental set-ups: (1) long-term falling head clogging experiment simulating household operation with falling water level and (2) intensified clogging experiment with continuous loading of the filters (see Fig. 2). Table 1 provides an overview of the number of filters that were used for each experiment. All ceramic elements were placed in a

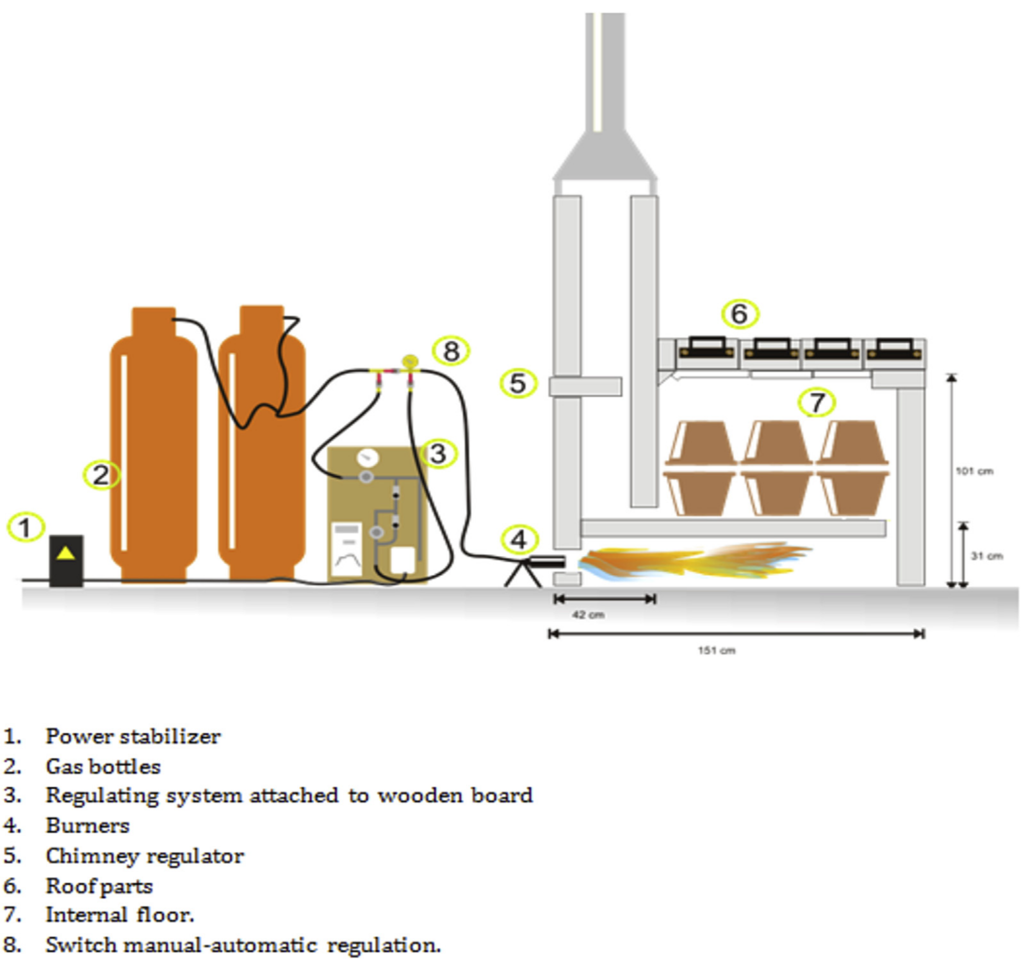

Fig. 1. Pilot factory with gas fired temperature-controlled kiln for the production of batches (6 filters) of reference and high flow rate pot filters.

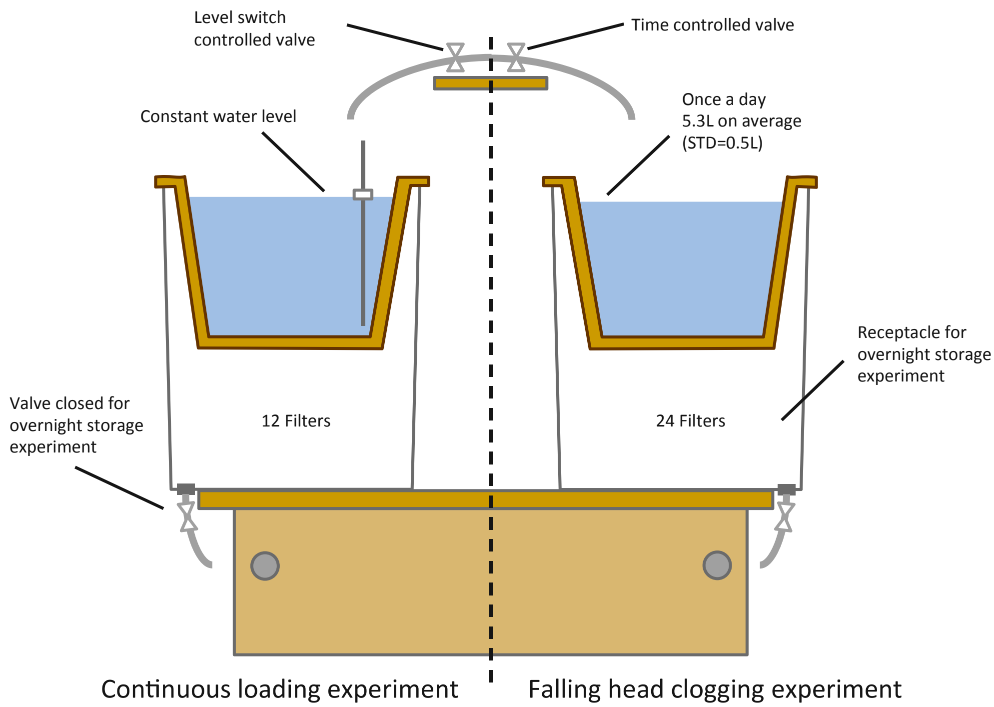

Fig. 2. Experimental set-up for (right) falling head clogging experiment and (left) continuous loading experiment. Receptacle and valve for overnight storage experiment are also indicated in the figure.

Table 1
Number of filters per rice husk cohort, in brackets is the number of filters which have not been pained with Ag.

Rice husk cohort	Falling head experiment total # (no Ag)	Continuous loading experiment total # (no Ag)
Reference (9.7 kg)	10 (2)	–
11 kg	–	4 (0)
12 kg	6 (2)	2 (o)
13 kg	–	4 (0)
14 kg	6 (2)	2 (0)
TOTAL	22	12

plastic receptacle (22 L). To reduce the dead volume in the receptacle and to minimize the residence time of the water after filtration, a custom-made ¼” thread connection (FESTO) was fitted in the bottom of the buckets with a tube and ball valve (FESTO). The first 2 L of produced water were always discarded, and the water samples were collected from the subsequent filtered water. LRVs for *E. coli* and MS2 bacteriophages were obtained by spiking high concentrations of these indicator organisms to the challenge water.

When the flow rate dropped below 1 or 2 L h^{-1} for the falling head or continuous loading experiment, respectively, the filter was emptied and scrubbed using a hand brush, following the protocol of scrubbing the inside three times and the outside once. The filter was rinsed with chlorine-free tap water after each scrub. The flow rate was determined before and after scrubbing, as well as before each spike event. This was done by loading the filters with water to 18–19 cm from the bottom of the filter element and operating with a constant water level. Depending on the flow rate, the water was collected for 5–50 min and measured twice using a volumetric beaker (2 L).

2.2.1. *Falling head clogging experiment*

The objective of this experiment was to simulate normal ceramic pot filter operation by a household in order to assess (i) water yield of high flow rate pots and (ii) microbial removal efficiency of high flow rate pots. For 16 weeks, the filters (n = 22) were filled daily with an average of 5.3 L (STD = 0.5) water. This daily volume was based upon the practical limitation that this was the maximum volume that could be treated by the slowest flowing filters. Two additional reference filters were loaded with filtered chlorine-free tap water. All other filters were loaded with natural challenge surface water from the canal Schie, running through the city of Delft, with an average Total Suspended Solids (TSS) of 14.9 mg.L^{-1} (STD = 6.1), temperature of 9.2 °C (STD = 5.7), and pH of 7.9 (STD = 0.1) (Kruithuisweg, Delfland Water Board). On average, 94 (19–290) CFU.100 mL^{-1} *E. coli* were measured.

The filters were scrubbed when the flow rate fell below 1 L h^{-1}, and no other maintenance was performed. The network of tubes used for the automatic daily loading of the falling head filters was calibrated at the beginning and end of the experiment. The loading of every individual filter was registered, and an average of the two calibrations was used for calculating the total water load over time. The total throughput of each of these 22 filters was 638 L (STD = 29) on average. LRVs for *E. coli* were determined after 0, 60–85 L, 125–160 L and 240–320 L throughout; LRVs for MS2 were determined after 375–423 L and 575–695 L throughput.

2.2.2. *Continuous loading experiment*

In this experiment, high flow rate filters (n = 12), with 11 kg, 12 kg, 13 kg and 14 kg rice husk content, were continuously loaded with challenge water from the same water body as the falling head experiment. However, in this follow-up experiment the filters were operated with a constant water level for a period of 35 days, which was automatically regulated with an electronic float switch. The total throughput for each of these filters was therefore much higher, on average 2,413 L (STD = 734). In order to examine the influence of scrubbing, the filters were scrubbed and cleaned before the discharge reached the minimum of 2 L h^{-1}. It is hypothesized that such an intensive and constant operational mode should result in better theoretic description of the (ir)reversible clogging mechanisms. The filters in this experiment were all painted with Ag.

2.2.3. Overnight storage experiment with Ag-painted filters

In order to assess the effect of receptacle storage time on *E. coli* inactivation, samples were taken directly (like in all experiments), but also after overnight storage in the post-filtration receptacle. The spike of *E. coli* was performed similarly as in the other experiments, but now after taking the first, direct sample, the valve at the base of the receptacle was closed in order to allow water to accumulate. The next morning, a second sample was taken from the receptacle tap. These experiments were executed three times: (1) at the end of the falling head clogging experiment (throughput 320 L), (2) at the start of the continuous clogging experiment and (3) at the end of the continuous clogging experiment (throughput >1700 L). This experiment was executed for the filters with Ag application ($n = 18$), and 3 filters without Ag application were included as references (9.7, 12 and 14 kg). Ag concentrations in the filtrate were determined by ICP-MS analyses.

2.3. E. coli and MS2 stock preparation

E. coli (WR1) and *E. coli* (K12) were used to prepare the spiking fluid. The WR1-type was chosen since it is commonly used for research in Dutch laboratories. The K12-type was also selected, since this type of *E. coli* is used in several other studies with CPFs (Van Halem et al., 2007; Oyanedel-Craver and Smith, 2008). For both *E. coli* types, a stock was prepared by growing a culture overnight in peptone water at 25 °C. The concentrated solution of *E. coli* (WR1) was diluted with sterile skimmed milk and immediately stored until use at −80 °C. The solution of *E. coli (K12)* was prepared the night before the day of spiking the filters. The MS2 stock was generated following the procedure according to ISO 10105−1.

2.4. Spiking of E. coli and MS2 phages

During the falling head experiment, the filters were spiked four times with *E. coli* (week 1, 3, 6 and 7) and twice with MS2 (week 10 and 16). During the continuous loading experiment, the filters were spiked in week 1 and 5. The *E. coli* or MS2 stock solution was prepared in a 210 L vessel filled with surface water and stirred (150 RPM) to prevent settling. The influent concentration was sampled in triplicate: two before the spiked water was distributed and one after the spiking was done. All filter elements were first emptied beforehand to discard the remainder of the water load of the day before then filled with the spiked water. The first 2 L throughput of each filter was collected and discarded to displace any remaining water in the filter pores. Subsequently, a 250 mL sample was collected using a sterile bottle prepared with 0.5 ml sodium thiosulfate (0.06 M $Na_aSO_3 \cdot 5H_2O$) and nitrilotriacetic acid (NTA) (0.13 M $C_6H_6NNa_3O_6 \cdot H_2O$) solution. The time between the filling of the filters and the sampling of the 250 mL varied depending on the flow rate of the filter element between 30 and 180 min. The actual storage time in the receptacle was <5 min. The samples were refrigerated before analysis on the same day.

2.5. E.coli and MS2 analyses

E. coli analyses were performed according to NEN-EN-ISO 9308−1 (ISO, 2000). *E. coli* was enumerated by filtering undiluted and diluted samples through 47-mm diameter, 0.45 mm pore size mixed cellulose ester filters in standard, disposable filter funnels (Millipore). After filtering, the membranes were incubated on membrane lauryl sulfate agar (Oxoid). The plates were incubated for 24 h at 37 °C. After Incubation, the plates were visually inspected for yellow (lactose-fermenting) colonies, indicating coliforms that are potential *E. coli*. The yellow colonies were confirmed for *E. coli* by indol and oxidase tests. The *E. coli* concentrations were expressed as colony forming units (CFU) per unit volume of water.

MS2 bacteriophages analyses were performed according to NEN-EN-ISO 10705−1 (ISO, 1995). MS2 bacteriophages were enumerated on tryptic yeast glucose agar (TYGA) using the double agar layer technique. The samples were mixed with a small volume of semisolid TYGA. A culture of host strain (Salmonella WG49) was added and plated on a prepared TYGA plate. Plates are read for visible plaques after 24 h incubation at 37 °C. Simultaneous examination of parallel plates with added RNase for confirmation by differential counts was carried out. The results were expressed as the number concentration of plaque-forming particles (PFU) per unit volume of water.

3. Results and discussion

3.1. Clean filter performance

The high flow ceramic pot filters were produced by increasing the amount of burnt material, i.e., increase of rice husk content, from 9.7 kg to 11, 12, 13 or 14 kg per batch of six filters. Fig. 3 depicts the relation between rice husk content and initial flow rates of the ceramic elements. The initial flow rate was measured after complete saturation of the material in order to exclude the influence of trapped air.

Results show that the flow rate can indeed be increased with higher rice husk content. The average flow rate of the reference filters was 3.6 L h^{-1}, this increased to 6.4, 13.3, 15.5 and 19.1 L h^{-1} for filters produced with 11, 12, 13, and 14 kg rice husk content, respectively. Note that even under the highly controlled manufacturing conditions, the flow rate variation within filter batches was considerable, particularly for the 13 and 14 kg rice husk content filters.

In Fig. 4, the initial LRVs for *E. coli* are depicted in relation to the initial flow rate per filter. LRV of *E. coli* was <1 for all high flow filters. The regular filters had a variable removal between 0.6 and 3.1 LRV, which was, on average, considerably better than the high flow filters. It should be noted that the samples were taken directly after filtration, so potential inactivation of *E. coli* during receptacle storage was excluded. This may explain why the overall *E. coli* LRV was lower in this study than previously reported in equivalent studies with ceramic pot filters (Van Halem et al., 2007; Oyanedel-

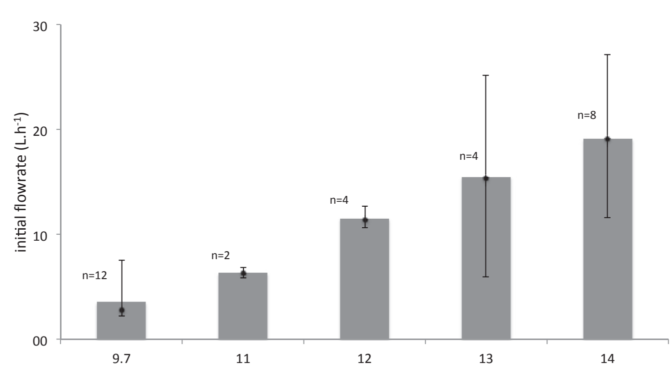

Fig. 3. Relationship between initial, clean filter flow rate and rice husk content of 9.7 (regular), 11, 12, 13, and 14 kg.

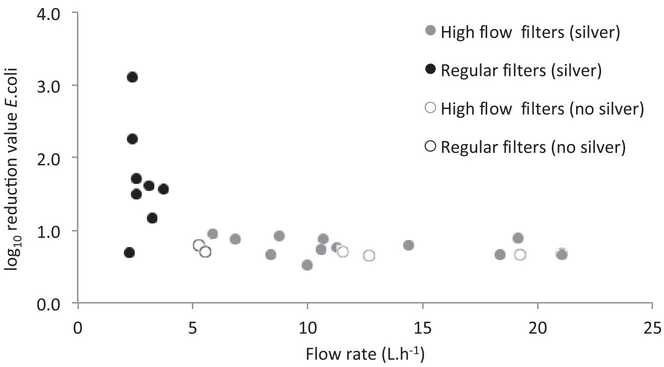

Fig. 4. Clean filter $\log_{10}$ reduction values for *E.* coli per initial flow rate.

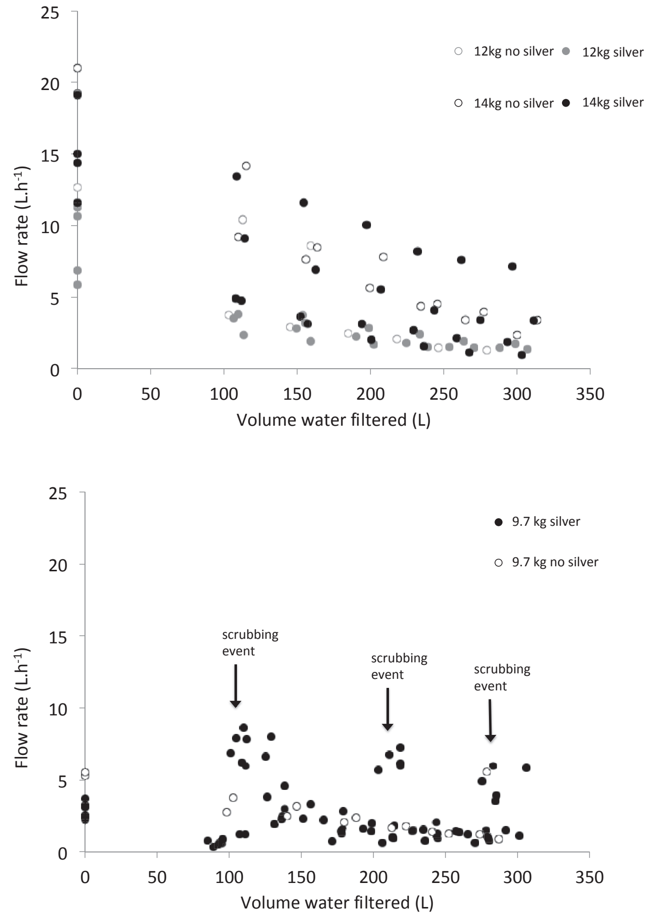

Fig. 5. Flow rate development during falling head experiment for high flow filters (top) and regular filters (bottom). Open circles represent filters without Ag application, closed circles represent filters with Ag application.

Craver and Smith, 2008; Lantagne et al., 2009; Simonis and Basson, 2011, Soppe et al., 2015). An effect of the Ag application directly on the ceramic element was not observed for the high flow filters (Fig. 4; grey open circles), whereas for the regular filters, the reduction was lowest for both filters without Ag (black open circles). The flow rate of filters without Ag was also slightly higher than the filters with Ag, which is consistent with previous research (van Halem et al., 2007; van der Laan et al., 2014; Mittelman et al., 2015). It should be noted that the focus in this study was on Ag-painted filters, as this is common practice in most ceramic pot filter factories. Therefore, as a reference, a smaller number of filters without Ag application were included in this study.

Amongst high flow filters the LRV did not vary much, whereas initial flow rates varied between 6 and 21 L h^{-1}. Apparently, a threefold increase in flow rate – and thus shorter residence time in the ceramic element – does not have an effect on the removal of *E. coli*. This confirms that mechanical screening is the main mechanism for *E. coli* removal (Bielefeldt et al., 2010) as opposed to processes like adsorption and diffusion into dead-end pores. Also, the uniform LRV between the high flow filters suggests that (effective) pore sizes are not increased by increasing the rice husk content from 11 to 14 kg. For clean filter performance, it may be concluded that regular filters, with a rice husk content of 9.7 kg per batch, have on average a higher LRV for *E. coli* than high flow filters. Nevertheless, the LRV was not consistent for the regular filters, as only 2 of the filters produced water with >2 LRV.

3.2. *Falling head clogging experiment*

In order to assess the long-term performance of the high flow pots, the filters were challenged with natural surface water in a falling head set-up. Fig. 5 shows the flow rate reduction for the regular filters and high flow filters for the first 320 L throughput. During the experiment, regular filters were scrubbed when flow rates dropped below 1 L h^{-1}, resulting in a sudden, temporary flow rate peak. Such peaks were not observed for the high flow rate pots, as flow rates of these filters did not drop below 1 L h^{-1}. Note that in this experiment, the water throughput, and thus also the yield of all filters, was equal. Hence, the filter clogging in all filters was caused by the same amount of foulants, e.g., suspended particles. In the high flow filters, these foulants accumulated in/on the ceramic element, whereas in the regular filters, the foulants were partially removed by the scrubbing events. It is worth mentioning that the variation between duplicate filters was large, both for flow rate and LRV, but this is inherent to the nature of locally produced ceramic pot filters (Lantagne et al., 2009; Soppe et al., 2015).

Fig. 6 shows that the LRVs for regular filters remained stable during 320 L of throughput, both for the filters without (top left) and with Ag (top right), where the filters with Ag showed a slightly better average removal of *E. coli*. The high flow filters, of the 12 and 14 kg rice husk cohort, systematically showed an increase in LRV of *E. coli* with an increasing throughput. This trend was observed for filters with and without Ag application, moving from <1 LRV in all filters to >2 LRV in half of the filters. Since these LRVs are nearing the WHO performance criteria for bacteria (1-star level, WHO, 2011), a follow-up continuous loading experiment was designed to learn what happens to the LRV beyond 320 L of throughput. It is perhaps not a surprise that the clogging of pores has a positive effect on the removal of *E. coli*, however, it is noteworthy that this is only observed for the high flow filters and not for the regular filters. Apparently, clean high flow filters – in contrast to regular filters – benefit from the (partial) blocking of pore channels that therefore aids in *E. coli* removal. It may therefore be concluded that clogged high flow filters are slightly better at removing *E. coli* than clean filters, while maintaining a higher flow rate than regular filters, i.e., no need for scrubbing.

In addition to *E. coli*, the removal of viruses was investigated by dosing MS2 bacteriophages to the challenge water. These tests were performed at the end of the falling head experiment, when all filters had clogged. Each filter was tested twice for the removal of MS2 bacteriophges, first directly after scrubbing (355–423 L throughput) and a second time after clogging again (575–695 L throughput). The LRV of MS2 bacteriophages was found to be low for all tested filters, and no relation was found between rice husk cohort and LRV. Regular filters had a LRV for bacteriophages

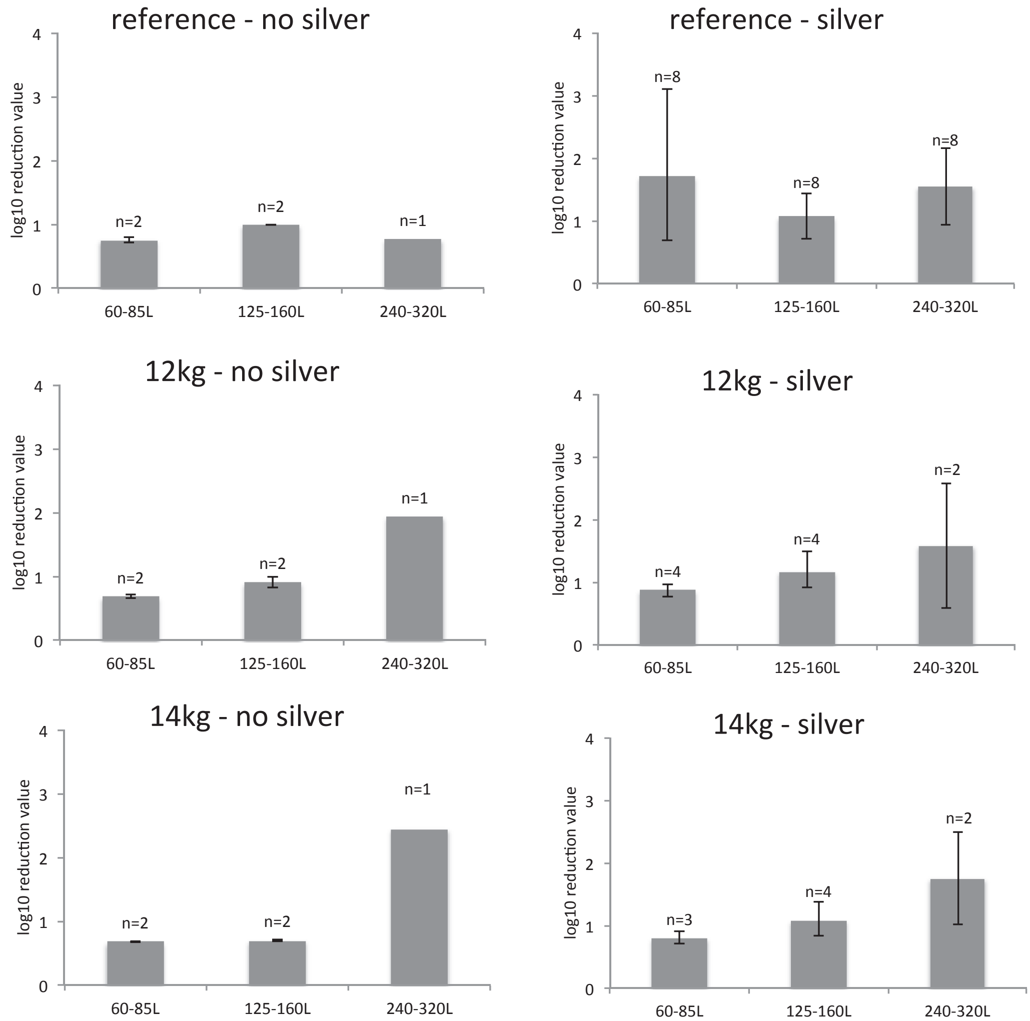

Fig. 6. LRV in relation to the throughput of water during the long-term falling head experiment without (left row) and with (right row) Ag application for the reference filers and high flow filters with either 12 or 14 kg rice husk.

between 0.2 and 1.5, and the LRVs for the high flow filters varied between 0.1 and 1.3.

Fig. 7 (left) shows that when plotting the results for the test directly after scrubbing, a clear relation can be observed between actual flow rate of the ceramic filter and the LRV of MS2 bacteriophages. The regular filters performed better in this test, though differences with the high flow filters were small. Viruses are much smaller than *E. coli*, and are thus not removed by ceramic pot filters due to mechanical screening alone but instead rely on processes like adsorption or diffusion into dead-end pores. The chance that a bacteriophage is removed by one of these processes increases with longer residence time, i.e., lower flow rates. These results therefore indicate that residence time in the supernatant water and/or ceramic element is an important parameter for MS2 bacteriophage

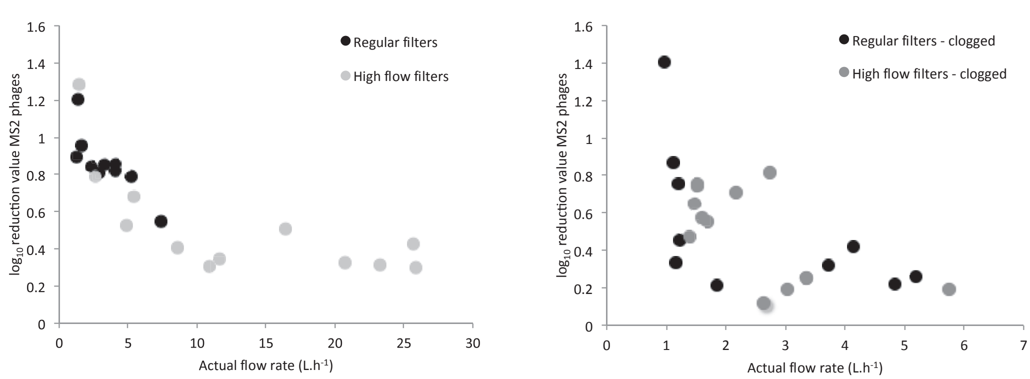

Fig. 7. MS2 bacteriophages removal immediately after scrubbing of clogged filters (left) and again clogged filter (right) related to actual flow rate.

removal – possibly in combination with potential biofouling in the clogged pores. When the filters were clogged again, this relationship between actual flow rate and MS2 LRV was no longer as apparent (Fig. 6, right), potentially due to the smaller variation in actual flow rates after clogging (between 1 and 6 L h^{-1}). However, the LRV for filters with a flow rate >3 L.h^{-1} remained consistently <0.4, so the distinction between regular and high flow filters was no longer observed.

3.3. Continuous loading of high flow filters

The falling head clogging experiment has shown that, once clogged, high flow filters have the potential to produce more water of slightly better quality compared to regular filters. However, in that experiment, the water loading was equal for all filters, so it was not possible to determine whether high flow filters have the potential to produce a higher *water yield* over their lifetime, or have a longer lifespan based on a minimal acceptable flow rate. In order to investigate the net increase in cumulative water yield for the high flow filters, a second experiment was performed with continuous loading of these filters. During this experiment, the clogging of filters was intensified compared to the falling head experiment, resulting in a faster build-up of resistance. After 400 h of continuous loading, the water yield per rice husk cohort was 1.5 m^3 < 2.0 m^3 < 2.4 m^3 < 2.9 m^3 for 11, 12, 13 and 14 kg, respectively. Hence, the higher the rice husk content, the higher the water yield per filter. From the flow rate and shape of the filter, it is possible to calculate the hydraulic conductivity (Elmore et al., 2011) of a filter. The inverse of hydraulic conductivity (K) is the resistance of the filter. As expected, the filters with the highest rice husk content, and therefore the highest porosity, showed the lowest clean filter resistance. However, when filters are in use, the total filter resistance consists of three components: (1) R_f, the resistance of the ceramic element itself, which is the inverse of the hydraulic conductivity, (2) R_c, the resistance caused by reversible clogging of pores and cake layer formation and (3) R_p, the irreversible blocking of pores. The sum of these three components is equivalent to the total resistance of the filter. Fig. 8 illustrates how resistance is built-up during filter use for one specific high flow rate filter with 12 kg rice husk content. During water production, the resistance slowly increased, i.e. the flow rate decreased, while after scrubbing, a decrease was observed. The filters were always scrubbed before the flow rate reached a minimum of 2 L h^{-1}. After a scrubbing event, all reversible clogging is erased (e.g., cake layer) and therefore the total resistance then depends only on the clean filter resistance plus the irreversibly clogged pores (R_f+R_p). The build-up of R_p at the end of the continuous loading experiment was different for each rice husk cohort, where the filters with a higher rice husk content had the least irreversible clogging, resulting in the highest flow rate - after scrubbing - by the end of the experiment.

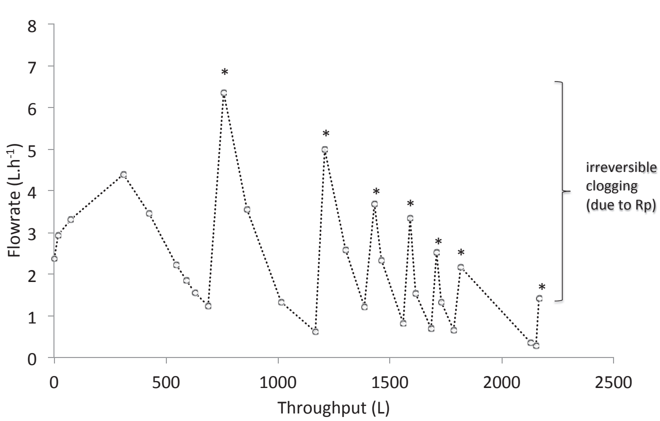

Fig. 8. Flowrate development caused by resistance build-up for a 12 kg pot filter (* indicates a scrubbing event).

In order to assess if these rigorously clogged high flow filters were achieving higher LRVs for *E. coli*, spikes were performed at the start and the end of the experiment for all filters. In the falling head experiment, it was found that clogged high flow filters were better capable of removing *E. coli* than new, clean filters. Fig. 9 shows that indeed the LRV for *E. coli* increased for all rice husk cohorts from just below 1 to average values between 2.3 and 3. At the same time, flow rates - before scrubbing - dropped in all rice husk cohorts to approximately 2 L h^{-1}. So although irreversible clogging (R_f+R_p) was lower for higher rice husk content filters, the total resistance before scrubbing (R_f+R_p+R_c) was very similar for all rice husk cohorts. Perhaps as a result, the *E. coli* LRVs were very similar between rice husk cohorts in the clogged filters. LRVs were consistently better than in the falling head experiment, which can be explained by the higher throughput that was achieved, i.e., more particle accumulation and subsequent irreversible pore clogging.

3.4. Overnight storage experiment with Ag-painted filters

The results presented so far were all collected from direct sampling after filtration, excluding the effect of storage time in the receptacle post filtration. In order to assess the influence of storage on the reduction of *E. coli*, the LRV was determined after overnight storage in a selection of Ag-painted filters during both falling head and continuous loading experiment. Fig. 10 shows the LRV for *E. coli*

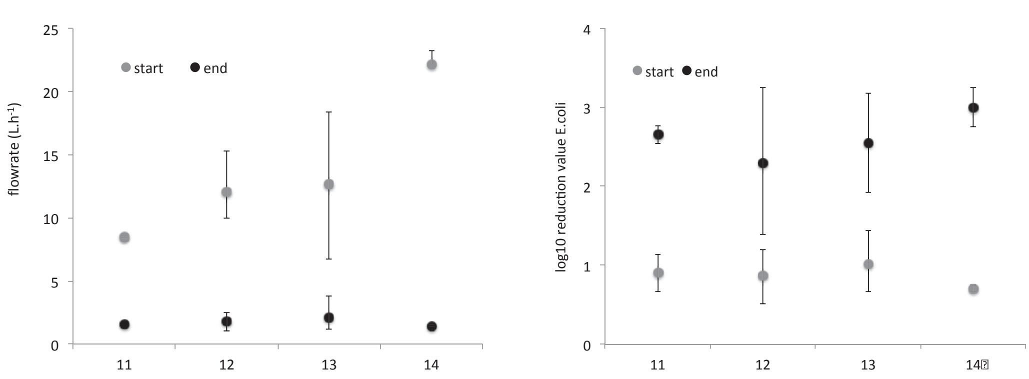

Fig. 9. Flow rate (left) and log10 reduction value (right) per rice husk content cohort (11, 12, 13 and 14 kg) at start and at end (400 h, >1700 L) of the continuous loading experiment. Flow rates were determined at the moment of the *E. coli* spike, which was before a scrubbing event, i.e. flow rates are lower than after scrubbing.

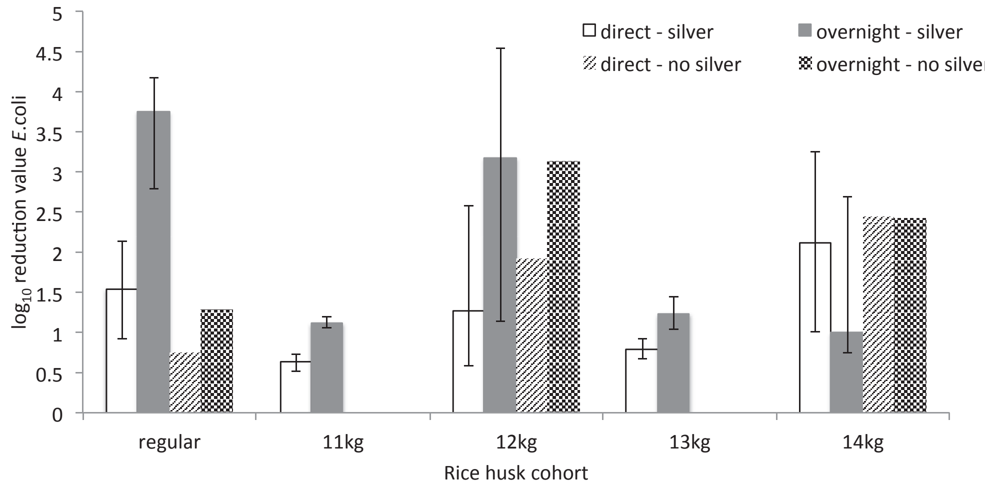

Fig. 10. *E. coli* LRV after overnight storage, throughput <300 L, black circles indicate result of sample taken from filter without Ag application.

per rice husk cohort both directly after sampling and after overnight storage in the receptacle. The regular filters showed a more than twofold increase in LRV after overnight storage. Also, the high flow filters for rice husk content 11, 12 and 13 kg clearly benefitted from overnight storage, though the cohorts of 11 and 13 kg had a lower LRV after overnight storage. The high flow filters with a rice husk content of 14 kg showed a decrease in LRV after overnight storage. However, this may be an inconsistency in the dataset, as LRVs were relatively high directly after sampling. The (single) reference measurements conducted for the filters without Ag (references) have also been included in Fig. 10; the regular filter without Ag does not show the same increase in LRV after overnight storage, highlighting the role of Ag. For the high flow filters (12 and 14 kg), the filters without Ag do not confirm this finding, indicating that the role of Ag might be somewhat different for these filters.

The reason for improved LRVs after overnight storage may largely be attributed towards residual Ag in the filtrate (Oyanedel-Craver and Smith, 2008; Bielefeldt et al., 2009; van der Laan et al., 2014; Mittelman et al., 2015). The efficacy of Ag as a disinfectant depends on the dose and contact time with the indicator organisms in the water, both during filtration and subsequent storage. One may argue that high flow filters provide a shorter contact time in the ceramics as well as in the receptacle, in the case that the receptacle is frequently emptied by end-users. In this study, only the effect of overnight storage was assessed; actual required contact times to achieve *E. coli* inactivation may have been shorter, i.e. minutes or hours. The dose was assessed based on the Ag concentration in the receptacle. When summarizing the Ag concentrations for filters loaded for <300 L, the Ag concentrations were on average 17, 14, 19, 12, and 20 μg/L for regular, 11 kg, 12 kg, 13 kg and 14 kg. So there was no clear difference in Ag dose observed between the different rice husk cohorts. Based on the results from this experiment, where no more than 300 L had passed the filter, it may be concluded that both regular and high flow filters benefit from overnight storage for inactivation of *E. coli*. However, the results for the regular filters were more consistent and reproducible.

Ag release into the filtrate depends on the water quality of the influent (e.g. pH), as well as on the amount of pore volumes that have passed the ceramic element. At the end of the continuous loading experiment with high flow rate filters (throughput >1700 L), the Ag concentrations in the filtrate had consistently dropped for all rice husk cohorts, varying between 2 and 7 μg/L. When repeating the overnight storage experiment with these clogged filters, the benefit of overnight storage was no longer so

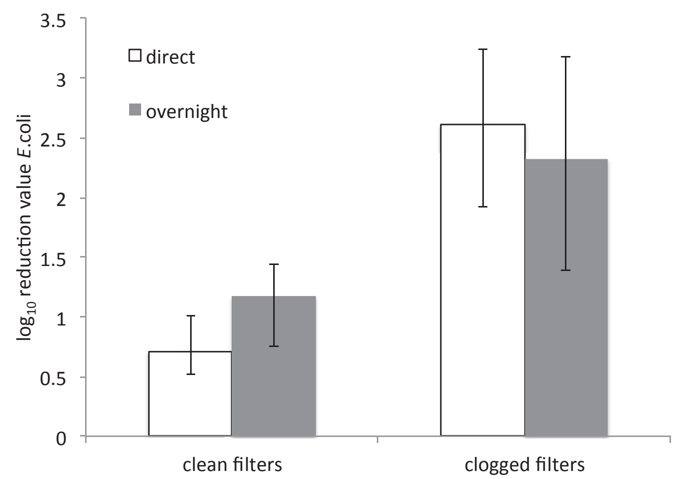

Fig. 11. *E. coli* LRV after overnight storage, in clean and clogged filters in the continuous loading high flow filters.

apparent (see Fig. 11, average of rice husk cohorts 11, 12 and 13 kg). This could mean that the contribution of residual Ag decreased or that the clogging of these filters had resulted in other removal mechanisms to dominate *E. coli* removal. The inactivation by overnight storage nicely complements the removal by mechanical screening: clean high flow filter elements have a poorer LRV of *E. coli* compared to clogged filters, but the effect of overnight storage is the opposite. In other words, overnight storage will add to the LRV as long as the ceramic element has not clogged sufficiently to achieve *E. coli* removal by itself.

3.5. WHO microbiological performance criteria

The World Health Organisation has defined criteria for the evaluation of Household Water Treatment (HWT) for their removal efficiencies related to the acceptable health risk based on tolerable burden of disease (WHO, 2011). The recommended microbial performance criteria consist of 3 levels, where 3-star is the highest protection level with very high pathogen removal, requiring $\geq$4 LRV for bacteria and protozoa and $\geq$5 for viruses. The 2-star level, or “comprehensive protection” requires $\geq$2, $\geq$3, and $\geq$2 LRV for bacteria, viruses and protozoa, respectively. A 1-star level is obtained if one of the individual 2-star criteria is met. Out of the 34 tested ceramic pot filters in this study, only 2 clean filters achieved the 1-star level for bacteria (regular filters, with Ag). All other clean ceramic pot filters evaluated in this study, either regular or high flow, failed to meet any of these performance classifications. Nonetheless, it has been observed that the *E. coli* LRV was improved both after overnight storage and after clogging of the ceramic element. After overnight storage, the regular ceramic pot filters (9.7 kg rice husk) achieved an *E. coli* LRV ≥ 3, but the high flow filters remained below 2. After clogging, however, the *E. coli* LRV of high flow filters increased to values between 2 and 3. This LRV for bacteria classifies as 1-star “targeted protection.” A 2-star classification was not achieved, as MS2 bacteriophages removal was below the set requirement of 3 LRV in all measured samples.

The total LRV of the ceramic pot filter system is composed of the sum of the LRV by the ceramic filter element *and* the LRV during storage in the receptacle. For *E. coli* LRV, regular filters seem to rely mostly on contact time with silver in the receptacle, whereas for high flow rate filters the contribution of the “clogged” ceramic element is dominant. Practically, both scenarios are difficult to manage for end-users as they may not know whether sufficient Ag is leaching into the receptacle or whether the filter is sufficiently clogged to promote *E. coli* LRVs. Nevertheless, it should be noted that clogging occurs rapidly, so this “clogged” condition may be considered representative for the majority of the filter's lifetime. Either way, based on the presented results this implies that users cannot safely drink the water from high flow filters directly upon purchase from the factory. Also, the rate and degree of clogging depends largely on the raw water quality and is therefore difficult to ensure in the wide range of application settings. It is therefore recommended to further investigate the engineering of high flow filters, for example by artificially clogging them with a standardized solution containing suspended particles with a specific size range. Additionally, it is encouraged to consider the storage time in the receptacle as an opportunity to reach higher LRVs and to further investigate how to achieve this benefit, e.g. (ceramic) additives in the receptacle.

4. Conclusion

High flow pot filters, produced by increasing the rice husk content, had a higher initial flow rate (6–19 L h^{-1}) as well as higher water yield. Initially, LRVs for *E. coli* of high flow filters was slightly lower than for regular filters. This disadvantage was, however, only temporary as the clogging in high flow filters had a positive effect on the LRV for *E. coli*. Since irreversible clogging occurred rapidly in all filters and could not be prevented with scrubbing, the “clogged” condition of high flow filters may be considered representative for the majority of its lifetime. Therefore, it can be carefully concluded that although regular filters perform better initially, after clogging the high flow filters have a higher flow rate as well as a higher LRV for *E. coli*. Nevertheless, the poorer performance at the start of a new high flow filter should not be neglected because the filters failed to meet the WHO microbiological performance criteria. Additional engineering of the high flow filters is required, for example an initial “pre-loading” in the factory. Also, it is recommended to further utilize residence time of the water in the receptacle for clean filter performance since additional *E. coli* inactivation was observed during overnight storage. This may be particularly useful for MS2 bacteriophages because both regular and high flow filters were unable to reach over 2 LRV. Interestingly, a relationship was found between the actual flow rate and MS2 bacteriophges LRV, indicating that residence time in the supernatant water and/or ceramic element is an important parameter for removal.

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