Performance assessment of modified biosand filter with an extra disinfection layer

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ABSTRACT

Biosand filters (BSFs) have been used widely as an efficient, inexpensive, and appropriate point-of-use technology. Several organizations are promoting filters without adequate testing, which may not lead to sufficiently safe devices. The objective of this study was to evaluate the performance of a modified biosand filter (MBSF) with an extra disinfection layer (brass or zero valent iron (ZVI)) and three layers of underdrain in a range of parameters including *Escherichia coli*, total coliform, turbidity, pH, and dissolved oxygen. On average, a 91.29% reduction (log 1.43) in total coliform, 98.7% reduction (log 2.6) in *E. coli* and 88.71% reduction in turbidity were observed for the control. There was a 90.11% reduction (log 1.41) in total coliform, 98.2% reduction (log 2.25) in *E. coli*, and 88.5% reduction in turbidity for MBSF brass. A 96.93% reduction (log 1.81) in total coliform, 97.33% reduction (log 2.36) in *E. coli* and 91.5% reduction in turbidity for MBSF ZVI were observed. Adding brass as a disinfection layer in MBSF did not improve bacteria and turbidity removal rates. Adding ZVI as a disinfection layer gave better turbidity and total coliform removal relative to control and MBSF brass. Water quality remained within drinking water standards for all filters.

Key words | brass, disinfection layer, modified biosand filter, zero valent iron

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INTRODUCTION

Inadequate water quality, which supports endemic transmission of pathogenic organisms and high rates of morbidity and mortality, is a serious problem in underdeveloped and developing countries. Therefore, appropriate technologies are needed for disinfection of drinking water to enable safe use. However, since large municipal infrastructures are often unavailable, the technologies must be inexpensive and operate at the level of a small community or single dwelling. Biosand filters (BSFs) have been used widely as an efficient, inexpensive, and appropriate technology for removing particles and microbial hazards from filtered water at household level in developing countries and rural communities (Duke *et al.* 2006; Murphy *et al.* 2010; Ngai *et al.* 2014).

BSFs use biological and physical removal mechanisms. The biological layer, composed of algae, bacteria, diatoms, zooplankton and particles settled above the sand, breaks down organic particles in the water biologically and strains out very small particles from water (Devadhanam Joubert & Pillay 2008; Juarez *et al.* 2008; Kubare & Haarhoff 2010). These microbial communities are capable of metabolizing contaminants by mediating oxidation reduction reactions (Zhu *et al.* 2010).

Laboratory scale BSFs provide significant improvement in water quality, with removal of up to 95–99% for fecal coliform contamination, up to 99% for total coliform, up to 96–98.5% for *Escherichia coli* (*E. coli*), and up to 88–92% for turbidity (Duke *et al.* 2006, Stauber *et al.* 2006; Campos & Outhwaite 2014; Ngai & Baker 2014).

Modified BSFs with an additional adsorbent medium such as a biomass layer or metal particles have been investigated through several studies. Metal and metal oxide nanoparticles containing magnesium oxide, copper, iron and silver exhibit antimicrobial properties or growth-inhibiting activity. The

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germicidal property of those metals is due to an oligodynamic effect. When metal ions are released into bacterial cells, they bind to DNA, enzymes and cellular proteins, causing physical disruption of cell structures and disturbances of permeability and respiration. Metal ions damage DNA or enzymatic proteins and cause death (Yamanaka *et al.* 2005; Lee *et al.* 2008). Hydroxyl radicals in the solution are responsible for their lethal action (Santo *et al.* 2008). The germicidal property of copper has been investigated, with short-term storage (6 hours) in a brass water storage vessel decreasing the amount of *E. coli* in contaminated water (Tandon *et al.* 2005). In another study, copper immersed as a plate in raw water eliminated *E. coli* and total coliform content by more than 98% in about 90 minutes, while copper and zinc plates reduced these contents to zero levels within the same time interval (Varkey 2010). *E. coli* in raw water was completely destroyed in 600 μm clay pot water filters with copper mesh, whereas a 900 μm pot reduced it by 99.4%. The 600 μm and 900 μm pots reduced the total coliform concentration by 99.3% and 98.3%, respectively (Varkey & Dlamini 2012). A strong bactericidal effect of zero valent iron particles (ZVI, nano-Fe^0) was also investigated. Nano-Fe^0 under de-aerated conditions gave 0.82 log inactivation/mg/L nano-Fe^0· h for *E. coli* (Lee *et al.* 2008). Tellen *et al.* (2010) showed that introducing ZVI into the BSF media reduced 99% of total coliform, fecal coliform and fecal streptococci. In another study, iron oxide-coated sand-modified BSF was used; the mean bacterial removal was 99.3% and turbidity removal was >90% (Ahammed & Davra 2011).

BSFs have been built in 59 countries by 500 organizations, giving a total of over 650,000 filters providing safe drinking water to more than 4 million people (Ngai *et al.* 2014). Numerous versions of the BSF (different filter height configuration, coarser/finer sand mixtures, hydraulic loading, depth of the materials, etc.) or modified BSFs with additional media have been proposed by different organizations claiming improved disinfection features, but without adequate testing. Many of these technologies involve compromises in materials and methods that may not lead to sufficiently safe practice.

The first aim of this study is to quantitatively assess the performance attributes of a modified biosand filter (MBSF) with a granulated brass/ZVI disinfection layer with three layers of underdrain inspired by a nonprofit corporation BSF design. The second objective is to analyze whether brass/iron corrosion yields metals (copper and zinc or iron) at concentrations high enough to be of health concern.

MATERIALS AND METHODS

Selection of disinfectant (batch reactor test)

Brass and ZVI as metal filings were chosen as disinfectants, because of their availability in most of the developing and under-developed countries. A batch reactor test was performed to analyze the germicidal effect of brass. A total of six flasks (including one control without brass) with duplicates were prepared. One gram of brass and 250 ml of natural water spiked with 400 CFU/ml *E. coli* was mixed and shaken at 200 rpm and tested at different time intervals (0, 15 min, 30 min, 1 hour, 2 hours, 5 hours) for total coliform and *E. coli*. The germicidal effect of ZVI was observed by other studies (Lee *et al.* 2008; Tellen *et al.* 2010; Ahammed & Davra 2011).

Filter setup

Three filters with duplicates were designed. The control BSF filter was filled with gravel, pea gravel, coarse sand, and fine sand. The MBSFs were constructed in the same order as the filtration media, with a granulated brass or ZVI disinfectant layer between fine sands.

PVC columns of 85 cm height with 14.9 cm inner diameter were used as laboratory scale filter columns for this experiment. Sand was purchased commercially and sieved. The sand was washed and dried and then placed inside the filter columns in successive layers of 5 cm stone (25 mm) overlying the collection pipe, 5 cm pea gravel (12.5 mm) as a drainage layer, 5 cm coarse sand (3.35 mm) as a separation layer, 5 cm fine sand mixed with brass or iron particles (with effective size $D_{10} = 0.3$ mm, $D_{60} = 0.71$ mm and uniformity coefficient $D_{60}/D_{10} = 2.33$; Ngai & Baker 2014) as a disinfection layer, and 40 cm fine sand as filtration media as shown in Figure 1. The design of this three-layer underdrain and disinfection layer between sand layers was inspired by the Aqua Clara water purification

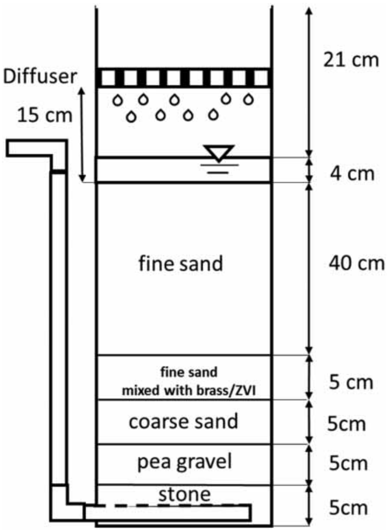

Figure 1 | Modified filter set up.

reactor design. For the control filter, the same order of layers was followed (5 cm stone, 5 cm pea gravel, 5 cm coarse sand and 45 cm fine sand), but without any disinfection layer. PVC pipe with 1.27 cm inner diameter was used as an outlet tube which was raised 5 cm above the height of the filter media. A diffuser with approximately 2 mm diameter holes was placed 15 cm above the filter media. Standing water was maintained 4 cm above the filter media during the pause period. The volume of the filled column was 20 L (sand + gravel + water) with a void space of 4 L. Water was present inside the filter before loading to avoid air spaces. The porosity/void fraction of the sand was 0.4. Filters were run intermittently twice a day (with 12 hours pause period) with 8 liters of local natural water spiked with *E. coli* for 3 months (including maturation period). Filters were operated by charging water into the reservoir to provide a maximum loading head of 17 cm. Initial flow rates in each column with the first charge were approximately 0.14 L/min for MBSF brass (0.5 m/h), 0.136 L/min for MBSF ZVI (0.47 m/h) and 0.13 L/min (0.45 m/h) for the control, which were in the prescribed range (0.16–1.1 m/h) (Elliott *et al.* 2008; Ngai & Baker 2014). Flow rates were measured daily. The water temperature was 24–26 °C during the testing period.

The brass disinfectant layer was composed of reagent grade granular copper (copper metal foils 0.127 mm thick, Fisher brand) and zinc (20–30 mesh size, Fisher brand) (1/1 volume mixed, approximately 21 g). The ZVI used for this study was commercial iron particles (ETI8/50) obtained from Peerless Metal Powders and Abrasive. Iron particles were sieved (0.84 mm) and (15% volume basis, approximately 39 g) added to fine sand and mixed based on previous studies (Pachocka 2010; Shi *et al.* 2012).

Disinfection layer depth

To determine the effective disinfection layer depth for MBSF brass, four columns with duplicates were set. Brass as a disinfection layer was placed 36 cm, 18 cm, and 4 cm below the top of the filter media, respectively, for three filters. The fourth filter was used as control without a brass layer. Filters were run intermittently twice a day (every day) with natural water spiked with *E. coli* for 6 weeks. After the maturation period, the number of total coliforms in the water was determined before and after filtration for every 6 days.

Water and microbiology

A local water source (Doan Brook, Cleveland, OH, USA) was used to test the filters. Characteristics of the natural water are shown in Table 1. Doan Brook had relatively low levels of contamination. To simulate developing country conditions, the local natural water was spiked with *E. coli* (ATCC 25922). A new culture of *E. coli* was grown before

Table 1 | Characteristics of the natural water

Doan Brook characteristics	Value
Specific conductance (micro ohm)	1,360 ± 31 (10)
Turbidity (NTU)	6.82 ± 4.59 (53)
TS (mg/L)	897 ± 216 (5)
TVS (mg/L)	760 ± 159 (5)
TFS (mg/L)	137 ± 72 (5)
Total alkalinity (as mg/L $CaCO_3$)	127 ± 7.6 (5)
Hardness (mg/L as $CaCO_3$)	256 ± 23 (5)
BOD_7 (mg/L)	110 ± 21 (5)
Total iron (mg/L)	0.6 ± 0.02 (8)
Zinc and copper (mg/L)	0 (8)

Values represent mean ± standard deviation. Values in parentheses represent the number of samples analyzed.
TS: total solids; TVS: total volatile solids; TFS: total fixed solids; BOD_7: biochemical oxygen demand.

each experiment. A single colony was picked and inoculated to a sterile tube containing 40 ml of tryptic soy broth. The tube was incubated at 37 °C overnight. The culture was centrifuged at 1,000 × *g* for 10 min causing *E. coli* cells to settle. The supernatant was discarded. The cells were diluted, enumerated and stored at 4 °C until the experiment. Feed water was collected from Doan Brook every day. A daily spike suspension of *E. coli* was added to feed water to obtain the desired initial *E. coli* concentration (10,000 ± 250 CFU/100 mL) before charging the filters. The number of coliforms (*E. coli* and total coliform) in the water was determined before and after filtration.

Bacterial and physicochemical analysis

Grab samples were collected from exit pipes daily (weekdays) and tested immediately for pH and dissolved oxygen (DO). Composite samples were tested: on a daily (weekdays) basis for flow rate, turbidity and effluent concentration of metals; a triweekly basis for *E. coli*; and a weekly basis for total coliform. Sterile containers were placed at outlet tubes and filled with effluent water until the filtration was complete (approximately 28–30 minutes). The samples were well mixed before analysis. Enumeration of viable *E. coli* was conducted by plate count test using LB plates. Total coliform test was performed using the guidelines from *Standard Methods for the Examination of Water and Wastewater* 9222 D (Membrane filtration method) for total coliform. Turbidity was measured using a Monitek TA1 nephelometer. pH was measured using an Accumeter model 10 pH meter. DO was examined using an Accumet excel XL40 DO meter. Specific conductance was measured using a YSI Model 35 Specific Conductance Meter and Conductivity Cell. Alkalinity and hardness were determined using titration. Solids were analyzed using gravimetric analysis. Iron, zinc and copper were determined using a flame atomic absorption spectrometer, Varian FS220.

Data analysis

The experiments were duplicated and the average values were taken as data points per time point. Arithmetic mean and standard deviation were calculated for all data. Percentage reduction was calculated using effluent and influent water ((influent–effluent)/influent × 100). Log reduction was calculated in addition to percentage reduction for *E. coli* and total coliform removal. Student's *t*-test (two-tailed) was used to determine if the modified filters showed significant reduction for water quality parameters compared with the control.

RESULTS AND DISCUSSION

Metal concentrations in effluent

Effluent samples from each filter were analyzed for metals for 3 months to determine if brass or iron corrosion yields metals (copper and zinc or iron) at concentrations high enough to be of health concern. The mean copper concentration was 0.024 ± 0.05 mg/L, zinc was 0.24 ± 0.22 mg/L and total iron was 0.10 ± 0.1 mg/L for MBSF brass. The mean copper and zinc concentrations were both 0 mg/L and total iron was 0.08 ± 0.014 mg/L for MBSF ZVI, shown in Figure 2. Metal concentrations in effluents were below WHO drinking water standards (copper: 2 mg/L; iron: no guideline; and zinc: 3 mg/L; WHO 2008). Influent had 0.6 ± 0.02 mg/L total iron concentration. Copper and zinc concentrations were zero in the influent. Based on these results, it was concluded that metals corrosion/leaching would not be a concern in terms of adverse health effects.

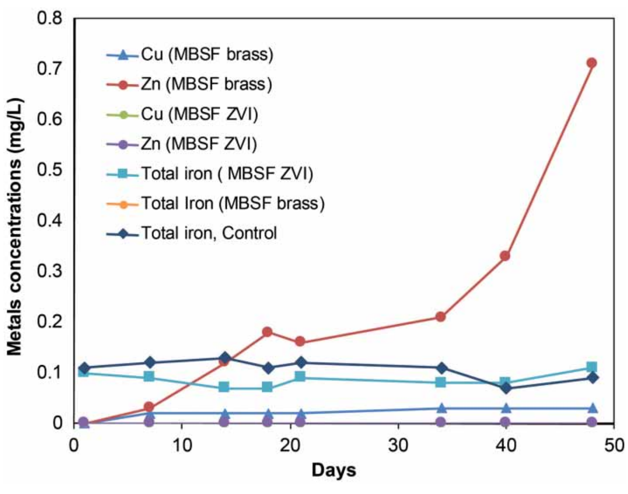

Figure 2 | Filter effluents metal concentrations.

Brass's germicidal effects

Based on a batch reactor test, brass showed 99.5% reduction of total coliform after 30 minutes and 67% reduction of *E. coli* after an hour as shown in Table 2. When contact time was increased, removal efficiency increased as well. According to the batch reactor test results, the brass germicidal effect was confirmed and filters were set.

Disinfection layer depth determination

The average removal efficiency for total coliform was as follows: filter 1 (36 cm), 70.4%; filter 2 (18 cm), 62.18%; Filter 3 (4 cm), 68.3%; and filter 4 (control) 60.31%. Based on these results, placing a brass layer at the bottom gave the best reduction rate. Tellen *et al.* (2010) suggested that mixing biocide with 5 cm of sand and locating it close to the bottom of the filter gives higher pathogen removal. Also Shi *et al.* (2012) showed that placing iron particles at lower depths gives better removal efficiency for MBSF ZVI. Therefore, disinfection layers were placed at lower depths for MBSF brass and MBSF ZVI filters.

Flow rate

The average flow rates were 0.07 L/min for the control, 0.052 L/min for MBSF ZVI and 0.09 L/min for MBSF brass throughout the study. A decline in flow rate over time was observed due to filter maturation, fouling (because of large-size pathogens, parasites, cysts trapped between sand particles) and increment of head-loss of the system for the control, MBSF brass and MBSF ZVI as expected, shown in Figure 3. In this study, hydraulic flow rates were within the acceptable range stated by Elliott *et al.* (2008) as discussed in the filter setup section above. The sequence of average flow rates was observed as MBSF brass > control > MBSF ZVI. The flow rates depend on sand depth, quality of raw water and sand grain distribution. ZVI with 0.84 mm particle size might have partially plugged the pore spaces of sand on the filter media, resulting in lower flow rates (Tellen *et al.* 2010; Ngai & Baker 2014). The brass particles had smaller particle size (0.127 mm), which might not have affected the pores. This could explain the different flow rates for each filter. A summary of average and standard deviations and minimum and maximum values for all water quality data is presented in Table 3.

Table 2 | Batch reactor results

	Time (h)				
	0.25	0.5	1	2.5	5
Total coliform % removal	0	99.5	97.5	93.1	99.79
E. coli % removal	0	61	70	82	91

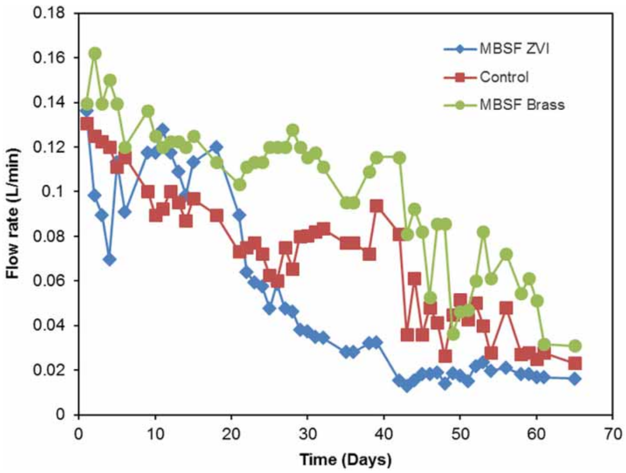

Figure 3 | Filters' effluents flow rates.

Turbidity

Influent and effluents from each filter were compared for turbidity. The average influent turbidity was 6.82 NTU. An 88.71% reduction with average 0.54 NTU effluent turbidity for the control and 88.5% reduction with average 0.6 NTU effluent turbidity for MBSF brass and 91.5% reduction with average 0.41 NTU effluent turbidity for MBSF ZVI were observed, shown in Figure 4. The two-tailed *t*-test was statistically significant (at the 0.05 level) between control and MBSF ZVI (*p*: 0.0087) and between MBSF brass and MBSF ZVI (*p*: 0.018) but not between control and MBSF brass (*p*: 0.69). Based on statistical analysis, MBSF ZVI gave slightly more turbidity reduction. The sequence of turbidity removal was observed as MBSF ZVI > control > MBSF brass which was similar to the residence time sequence observed as MBSF ZVI > control > MBSF brass.

Table 3 | Filter operating characteristics

	Influent	Control	MBSF brass	MBSF ZVI
Flow rate L/min (*n* = 55)				
Mean ± std dev	N/A	0.07 ± 0.03	0.052 ± 0.04	0.09 ± 0.033
Min–max	N/A	0.023–0.13	0.013–0.136	0.030–0.162
Turbidity (NTU) (*n* = 53)				
Mean ± std dev	6.82 ± 4.59	0.54 ± 0.3	0.6 ± 0.32	0.41 ± 0.23
Min–max	1–26	0.2–2.3	0.3–1.9	0.2–1
pH (*n* = 22)				
Mean ± std dev	7.74 ± 0.31	7.93 ± 0.08	7.97 ± 0.06	8.12 ± 0.19
Min–max	7.32–8.68	7.72–8.11	7.84–8.16	7.6–8.38
DO mg/L (*n* = 55)				
Mean ± std dev	8.12 ± 0.19	3.86 ± 1.13	3.81 ± 1.06	3.9 ± 0.98
Min–max	5.46–9.15	1.89–6.84	1.9–6.6	2.04–6.59

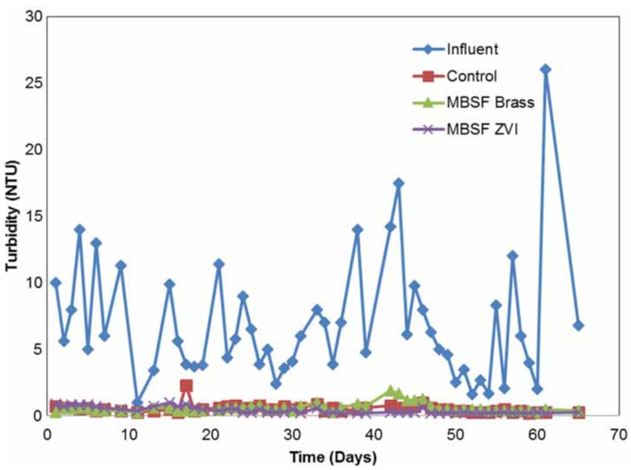

Figure 4 | Turbidity removal for influent and filter effluents.

Increasing residence time in filters increases bacterial removal and turbidity performance (Jenkins *et al.* 2011). Throughout the experiment, turbidity removals were almost constant for all filters. The range of the turbidity removal efficiencies for filters in this study was parallel with other studies performed for BSF and MBSF iron filters with the range of 70–98% (Elliott *et al.* 2008; Tellen *et al.* 2010; Ahammed & Davra 2011; Ngai & Baker 2014). Therefore, layers of underdrain did not affect the overall turbidity reduction percentage. All turbidity levels for all filters were below 3 NTU which was below the WHO drinking water quality standard (WHO 2008).

pH

The pH of the influent water varied between pH 7.3 and 8.6. Effluents from each filter showed a slightly increased pH. The average pH in the influent was 7.74 which was slightly increased to an average of 7.93 in the control, 7.97 in the MBSF brass and 8.12 in MBSF ZVI as shown in Figure 5. Slightly increased effluent pH may have indicated the dissolution of Cu^{2+}, Zn^{2+} and Fe^{3+} cations. Sand particles containing some monovalent ions (K^{+}, Na^{+}) react with water and cause the pH increment (Baig *et al.* 2011). Also

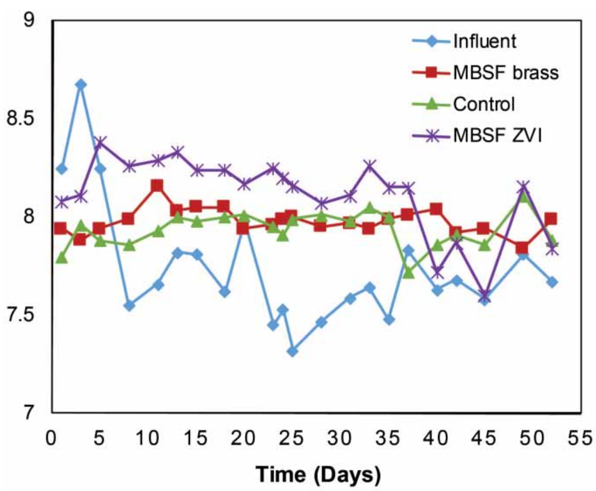

Figure 5 | pH variations for influent and filter effluents.

dissolution of natural carbonates from the sand can slightly increase the pH of the effluent (Elliott *et al.* 2006).

DO

Average DO for influent was 7.8 mg/L. A decline in DO concentration over time was observed in all filters shown in Figure 6. DO concentrations in filter effluents decreased gradually until maturation time. Averages of 3.9 mg/L DO for MBSF ZVI, 3.86 mg/L DO for the control and 3.81 mg/L DO for MBSF brass were observed. The sequence of DO rates in filter effluents was observed as MBSF ZVI > MBSF brass > control. As Ahammed & Davra (2011) stated, MBSFs with an extra disinfection layer show more DO in effluent, indicating that a different mechanism is taking place compared with the control. After the 20th day (ripening of the biological layer), DO concentrations were stabilized, indicating that DO in the influent water was consumed by the biological layer up to 3–4 mg/L, which was similar to previous studies (Ahammed & Davra 2011; Kennedy *et al.* 2012; Young-Rojanschi & Madramootoo 2014, 2015). DO concentrations were always above 1.0 mg/L, indicating that aerobic conditions might become dominant throughout the filter bed. According to Young-Rojanschi & Madramootoo (2014), although the effluent DO concentration is significantly above 1 mg/L, anaerobic conditions may develop inside the filter. Aeration occurring at the filter outlet and within the collection flask, which was open to the atmosphere, might have caused higher DO concentrations in filter effluents.

E. coli reductions

An *E. coli* test was performed on a triweekly basis for a period of 3 months. *E. coli* reductions averaged log 0.36 (51.87%) for control, log 0.54 (67.15%) for MBSF brass and log 0.52 (66.2%) for MBSF ZVI from day 0 to day 20. The two-tailed *t*-test was statistically significant (at the 0.05 level) between control and MBSF brass (p: 0.021) and between control and MBSF ZVI (p: 0.028), but not between MBSF brass and MBSF ZVI (p: 0.71). Based on the statistical analysis, the extra disinfection layer gave slightly more *E. coli* removal during the ripening period, also noted by Ahammed & Davra (2011). *E. coli* removal percentages for filters during the ripening period were observed as MBSF brass > MBSF ZVI > control.

E. coli removal percentages from day 20 onward were observed as average log 2.6 (98.7%) reduction for control, log 2.25 (98.2%) reduction for MBSF brass and log 2.36 (97.33%) reduction for MBSF ZVI as shown in Figure 7 and Table 4. Removal performance increased with time (suggesting biofilm ripening). After 60 days, all filters gave slightly lower removal performance except MBSF ZVI which maintained significant results of log 3.7 (99.98%) *E. coli* removal. Adsorption, physical straining, natural die-off and predation are the principal processes to remove

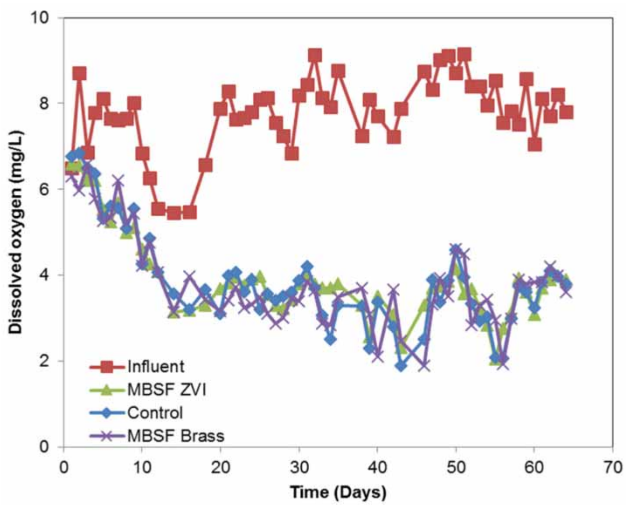

Figure 6 | DO variations for influent and for filter effluents.

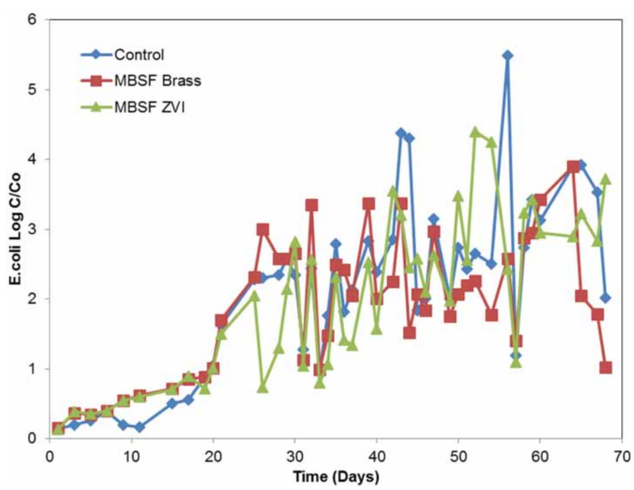

Figure 7 | *E. coli* reductions for filters.

Table 4 | Performance of filters

	Control	MBSF brass	MBSF ZVI
Turbidity (% removal) ($n = 53$)			
Mean ± std dev	88.71 ± 8.92	88.5 ± 6.4	91.5 ± 6.75
Min–max	41–98.5	68.75–98	60–99.23
***E. coli* log10 (*n*:47)**			
Mean ± std dev	2.6 ± 0.97	2.25 ± 0.74	2.36 ± 0.98
Min–max	0.96–5.48	0.99–3.89	0.73–4.39
***E. coli* % reduction**			
Mean ± std dev	98.7 ± 2.54	98.2 ± 2.84	97.33 ± 4.57
Min–max	89–99.9	89.8–99.98	81.5–99.99
Total coliform log10 (*n*: 8)			
Mean ± std dev	1.43 ± 0.76	1.41 ± 0.77	1.81 ± 0.66
Min–max	0.62–2.26	0.56–2.4	1.17–2.7
Total coliform % reduction			
Mean ± std dev	91.29 ± 9.46	90.11 ± 11.65	96.93 ± 2.97
Min–max	76.42–99.46	72.85–99.6	93.33–99.8

microbial populations from raw water. Adsorption resulted from attachment of small-sized pathogens to different surface charge substances. Bacterial cells possessing negative surface charges were attracted by positively charged surfaces such as brass and ZVI (Baig *et al.* 2011). The range of the *E. coli* removal efficiencies for filters in this study was parallel with other studies performed for BSF and MBSF iron filters with a range of 93–99% (Yamanaka *et al.* 2005; Stauber *et al.* 2006; Elliott *et al.* 2008; Ahammed & Davra 2011). Therefore layers of underdrain did not affect the overall *E. coli* reduction percentage.

The fundamental mechanisms of contaminant removal in ZVI columns are adsorptive size-exclusion and co-precipitation (Noubactep & Caré 2011). The two-tailed *t*-test (at the 0.05 level) was not significant between control and MBSF brass (p: 0.5), between control and MBSF ZVI (p: 0.5), or between MBSF brass and MBSF ZVI (p: 0.22). There was no significant difference in *E. coli* removal in the three filters after ripening time. The sequence of *E. coli* reduction was observed as control > MBSF brass > MBSF ZVI. No additional reduction of *E. coli* was observed in the filters with brass or ZVI addition compared with the control, so it cannot be concluded that bacteria removal was the result of antimicrobial activity of metal ions. Therefore, adding an extra layer of metal as a disinfection layer did not make any improvement in terms of reduction of *E. coli*.

Total coliform reduction

Total coliform test was performed on a weekly basis for a period of 8 weeks. Total coliform reductions averaged log 0.63 (62.5%) for control, log 0.66 (62.7%) for MBSF brass and log 0.86 (69.5%) for MBSF ZVI from day 0 to day 24. The two-tailed *t*-test (at the 0.05 level) was not significant between control and MBSF brass (p: 0.46), between control and MBSF ZVI (p: 0.37), or between MBSF brass and MBSF ZVI (p: 0.39). There was no significant difference in total coliform removal in the three filters during ripening time. The ripening process took 20 days, which was similar to that found by Kennedy *et al.* (2012). From day 24 onward, average log 1.43 (91.29%) reduction for control, log 1.41 (90.11%) reduction for MBSF brass and log 1.81 (96.93%) reduction for MBSF ZVI were observed as shown in Figure 8. The two-tailed *t*-test (at the 0.05 level) was statistically significant between control and MBSF ZVI (p: 0.02) and between MBSF brass and MBSF ZVI (p: 0.015) but not between control and MBSF brass (p: 0.61). Based on the statistical analysis, MBSF ZVI gave better total coliform removal after the ripening process. Removal performance increased

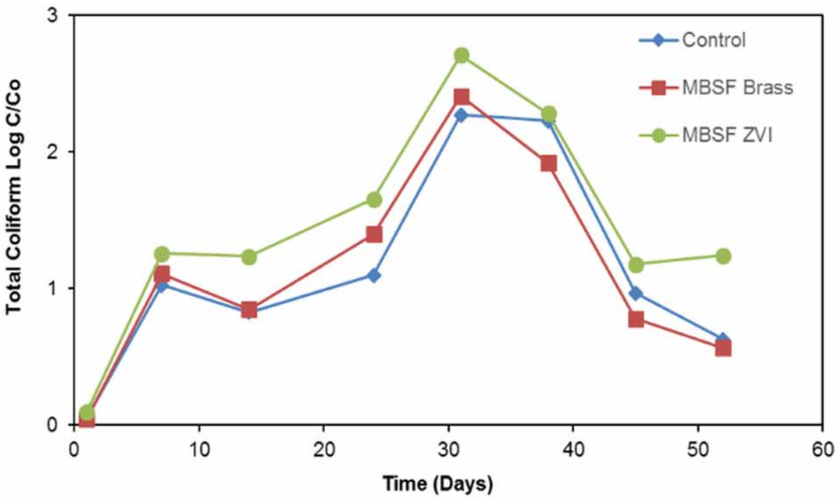

Figure 8 | Total coliform reductions for filters.

with time. All filters gave slightly lower removal performance after 40 days. All filters accomplished > 99% microbial reduction on multiple days throughout the experiment. The sequence of total coliform reduction was observed as MBSF ZVI > control > MBSF brass which was very similar to the turbidity removal and flow rate sequence. According to Jenkins *et al.* (2011), influent turbidity is highly significant for bacterial removal. According to Tellen *et al.* (2010), ZVI addition to BSFs improves performance over the control. Total coliform removal in MBSF ZVI was achieved due to both the germicidal effect of ZVI and biofilm formation, while total coliform removal in the control was achieved through biofilm formation (Tellen *et al.* 2010).

It may be highlighted that, although *E. coli* reductions were above 97% for all filters, the removal mechanism of total coliform with lower reduction rates for brass might be due to other factors. Brass as a disinfectant layer had not been used in BSFs before. Previous studies were batch reactor type studies with limited time intervals and direct contact with brass (Tandon *et al.* 2005; Varkey 2010; Varkey & Dlamini 2012). Mixing brass with sand or the short contact time (MBSF brass gave the highest flow rate and therefore the least residence time) in the filter may have affected the germicidal effect. According to Varkey & Dlamini (2012), the germicidal effect of copper is a function of time; longer contact times give greater pathogen removal. Another factor might be that brass is effective to remove only *E. coli*. *E. coli* is the major species in the fecal coliform group, which is one of the five general groups of bacteria that comprise the total coliforms. Natural die-off is another process that may have affected the total coliform reduction. Laboratory strain *E. coli* die-off rate could be higher than that of total coliforms because of death of the laboratory *E. coli*, which is not typically robust (Elliott *et al.* 2008). The range of the total coliform removal efficiencies for filters in this study was parallel with other studies performed for BSF and MBSF iron filters with a range of 90 to 99% (Elliott *et al.* 2008; Tellen *et al.* 2010; Ahammed & Davra 2011; Ngai & Baker 2014). Therefore, layers of underdrain did not affect the overall total coliform reduction percentage.

CONCLUSION

Physicochemical and biological tests were conducted to compare the performances of the MBSFs with a disinfection layer with the control for a 3-month period. Based on the results, using brass or iron as a disinfection layer would not be a health concern in terms of leaching. Turbidity in the filtered water was below the WHO acceptable level for drinking purposes. Slightly increased effluent pH and 3–4 mg/L DO consumption by the biological layer were observed for all filters. Different sizes of disinfection layer particles in filters caused the varied flow rates in filters because sand pores were filled by metal particles. During the filter ripening period, using a disinfection layer (brass or ZVI) increased *E. coli* removal percentage. This suggested that adding a disinfection layer could improve removal efficiencies during the ripening period for *E. coli*. After the ripening period, all three filters gave similar *E. coli* removal efficiencies. Therefore, adding an extra layer of metal as a disinfection layer did not make any improvement in *E. coli* reduction after the ripening period.

On the other hand, during the ripening period, there was no significant difference in total coliform removal in all three filters. After the ripening period, MBSF ZVI gave better total coliform removal. The different removal percentages for different pathogens suggested different removal mechanisms for each pathogen. The ranges of the turbidity, *E. coli* and total coliform removal efficiencies for filters in this study were parallel with other studies. Therefore, it was concluded that layers of underdrain did not affect the overall water quality. Adding brass as a disinfection layer improved neither the reduction efficiency of bacteria nor turbidity in MBSFs, although water quality remained within drinking water standards. Adding ZVI as a disinfection layer gave better turbidity and total coliform removal relative to the control and brass. Therefore, promoting brass as an extra disinfection layer for MBSFs to minimize the bacteria level in water may not be a sufficiently safe practice. This study only focused on bacteria removal with an extra disinfection layer in the MBSF. However, if viruses were considered, the conclusion may have been different.

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