

The impact of loading frequency and copper as a biocide on biosand filter performance

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ABSTRACT

Biological sand filters (BSFs) can appropriately serve as point-of-use water treatment in developing nations. This study examined the benefit of adding copper to a BSF, and evaluated the impact of its addition in relation to extended pause times. Four 70-L BSFs were created – copper was incorporated in the packing of the two BSFs labeled Filter 1 and Filter 3. Filters 1 and 2 were loaded daily while Filters 3 and 4 were watered every third day. Source water was taken from the Ocmulgee River in Macon, Georgia. To investigate variation due to watering frequency and biocidal addition, BSF performance was quantified using coliforms, turbidity, solids, dissolved oxygen, pH, and copper analyses. *E. coli* removal efficiencies for Filters 1, 2, 3, and 4 averaged 90, 77, 87, and 80%, respectively. Paired *t*-tests at $\alpha = 0.05$ indicate that effluent coliform concentrations from filters watered daily were significantly impacted by the presence of copper. Filters loaded every third day showed no significant performance effect from copper addition on coliform removal efficiency. Similar paired *t*-tests at $\alpha = 0.05$ for turbidity, solids, and COD showed no significant difference between filter performance.

Key words | appropriate technology, biological sand filter, loading frequency, metallic biocide, point-of-use filtration

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INTRODUCTION

In many regions in developing nations, the lack of clean drinking water is intrinsically linked to the cycle of poverty due to its high impact on the health and welfare of a community. Studies performed by Tiwari conclude that the average child drinking untreated river water has a 2.2 times greater risk of contracting diarrhea than a child drinking water treated by a biological sand filter (BSFs) (Tiwari *et al.* 2009).

BSFs are an adaptation of traditional slow sand filtration (SSF), which has been used for over two hundred years in mainstream water treatment (Elliott *et al.* 2008). According to Huisman & Wood (1974), SSF is the most primitive, yet effective and practical method of water treatment available. SSF performs mechanical and physical filtration through its layered media, but also through a highly effective biological layer called the *shmutzdecke*. Literally translated as ‘filth cover’ or ‘dirty layer’, the *shmutzdecke* forms as microorganisms in the source water settle and populate the filter,

creating a slimy layer that aids in the capture of small particles. Located predominantly on the top 5–7.5 cm of the sand bed, where it has optimal access to oxygen and nutrients, the biological layer helps heighten the filter’s efficiency the longer it is operated, reducing the pore volume and aiding in the collection of increasingly smaller particles (Huisman & Wood 1974; Lea 2008; CAWST 2009).

While SSF is highly effective and useful for communities with water distribution systems, the BSF harnesses the primary concepts of SSF into a smaller filter that is capable of being used in rural areas without centralized water treatment. Classified as a point of use (POU) unit, the BSF is simple to create, use and maintain. To create drinking water with a BSF, a user merely collects source water and pours it into the filter when they desire treated water. The widely-accepted contemporary BSF design is accredited to Dr. David Manz, the co-founder of the Center for Affordable

Water and Sanitation Technology (CAWST). As of March 2011, CAWST estimates they have aided in the improvement of water quality for over three million people worldwide (CAWST n.d.).

In field and laboratory studies, BSFs have achieved 2–4 log removal of pathogenic organisms, a high removal rate for such a simple process (Duke *et al.* 2006). A basic BSF consists of seven key parts: filter body, outlet tube, diffuser, lid, sand, a separating layer, and a drainage layer. CAWST identifies the use of a concrete body, whereas many NGOs have begun encouraging plastic bodies, which increases the cost marginally, but also eases construction and transport of the filters to the user's home. Key operating parameters which have been identified to ensure high treatment efficiency for BSFs include the quality of the influent water source, the development of the *schmutzdecke* or bio-layer, the filter loading rate, the pause period between adding water to the filter, and the standing water level above the top of the filter media (CAWST 2009). CAWST recommends a loading rate of 400 L/hr/square meter (CAWST 2009). Commonly accepted flowrates vary from 0.6 to 1.0 L/min (Baker & Duke 2006; Elliott *et al.* 2008; AquaClara International 2009) and AquaClara International (ACI) recommends a 12–24 hr pause period (AquaClara International 2009).

Copper is highly effective as a biocide against bacteria and fungi due to its ability to interfere with cellular life processes including membrane permeability, protein production, and DNA coding. Studies suggest that copper discourages cell viability by disrupting the integrity of proteins and lipids within a cell through displacement of essential metals, damage of nucleic acids and catalyzing the creation of H₂O₂ through copper's redox cycle between Cu⁺¹ and Cu⁺² (Borkow & Gabbay 2009). Other metals including zinc and nickel are capable of similar antimicrobial actions, but are not as effective as copper (Borkow & Gabbay 2009).

A number of non-profit organizations have designed their own BSFs and distribute them worldwide, including CAWST, Hydrad, and ACI. Of note is ACI's BSF construction, which uses brass (an alloy of copper and zinc) as a biocide. While ACI uses a copper alloy in their recommended process, the set of experiments outlined in this document only focus on copper. In combining copper and

zinc to manufacture a brass alloy, arsenic, lead, and an array of other materials are often added to prevent dezincification (Davies 1993). Several of these supplements, namely arsenic and lead, can be very harmful to humans if ingested. Thus, pure copper was substituted for brass in order to evaluate copper on its own disinfection merits without the complicating matter of arsenic or secondary material contaminations.

The focus of this study was to determine the effect of user compliance on BSF performance and the net benefit of a metallic biocide addition in the filtration units. More specifically, experiments were conducted:

1. To investigate the effect of pause time on filter performance; and
2. To quantify the benefit of using a metallic biocide in a BSF.

METHODOLOGY

Filter design and construction

Four BSFs were created. Two filters were constructed according to traditional CAWST BSF construction – a 70-L plastic container filled with 6.4 cm gravel, 6.4 cm coarse sand, and 38 cm fine sand. The remaining two filters, following ACI's instruction, contained 155 g of chipped copper mixed in with the bottom 2.5 cm of the fine sand layer, yielding a filter bed characterized by 6.4 cm gravel, 6.4 cm coarse sand, 2.5 cm fine sand mixed with copper, and 35.5 cm fine sand. Figure 1 shows a schematic of the two filter configurations.

Manufactured by manual milling, the copper metal shavings were approximately rectangular in shape and produced as uniformly as possible. The metallic chip size was estimated by measuring 30 randomly selecting milled pieces with a Fowler digital caliper (accuracy: 0.02 mm and resolution: 0.01 mm). The length of copper chips ranged from 1.0 to 13.3 mm; the average width and thickness of the rectangular chips produced was 3.3 and 0.12 mm, respectively. Construction-grade sand was sifted twice to identify two gradations – the fine sand, $d_p < 0.84$ mm, and the coarse sand, $d_p = 0.84$ –3.3 mm. PVC piping (2.54 cm) was used for the

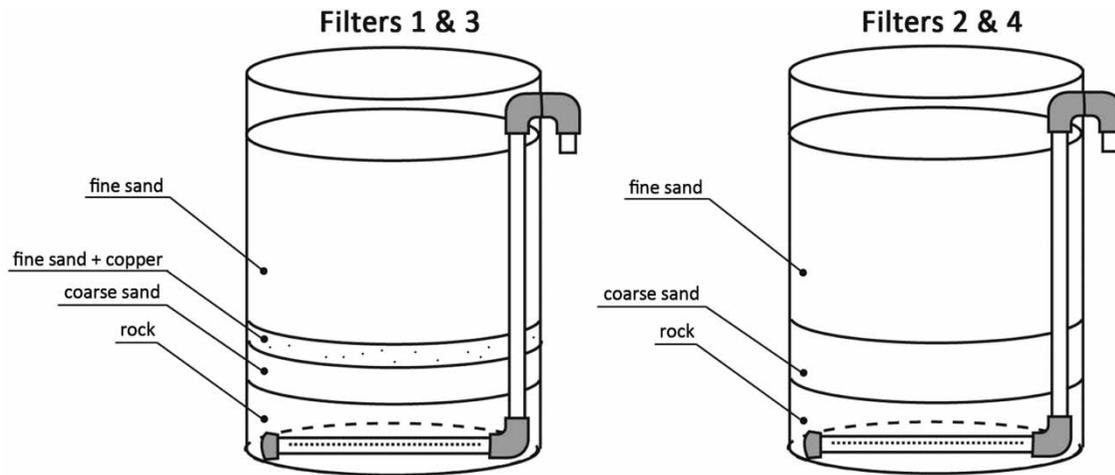


Figure 1 | Filters were constructed according to AquaClara standards. Filters 1 and 3 included copper while Filters 2 and 4 did not.

outlet pipe. The 2.54 cm pipe at the bottom of the filter was milled to have 14 holes, 16 mm in diameter, down the length on two sides, to serve as points for water collection into the outlet pipe. This perforated pipe was capped on one end and the other end was connected to the outlet.

Filter loading

To evaluate the importance of user compliance regarding pause time on filter performance, one set of filters (one containing copper, and one without copper) was watered daily, and the remaining set was watered every 3 days. As presented in Table 1, Filters 1 and 2 were watered daily, while Filters 3 and 4 were loaded every 3 days. Filters 1 and 3 contained copper and filters 2 and 4 did not. The filters were operated for 104 days.

Influent water was collected daily from the Ocmulgee River’s Spring Street boat ramp (latitude 32°50’ 45” N, longitude 083°37’ 40” W), located in Macon, Georgia. The source water was mixed and divided into four 20-L containers, ensuring consistent characteristics for the

influent to each BSF. Loading was completed in two batches; 10 L would fill the filter to the top of the free-board, at which point a sample was taken to evaluate the daily maximum flowrate. Immediately after the addition of the final 10 L of source water to the filter, a second sample was collected to test for the filter’s effluent water quality characteristics.

Three experimental water-loading schemes were tested. During Session 1, the ripening period, BSFs 1 and 2 were loaded with 20 L daily of river water, and Filters 3 and 4 received 20 L every third day. Session 2 is patterned after filter use following the assumed ripening time: 20 L twice daily for Filters 1 and 2, and 20 L twice every third day for Filters 3 and 4 (equating to 40 L per watering day per filter). Session 3 was marked by starvation of the filters. The filters were not watered for a week’s time, simulating the impact of extended pause periods in filter use. Table 2 outlines the filter watering schemes.

Table 1 | Filter performance was evaluated regarding pause time and copper addition

	24-hr pause time	72-hr pause time
Copper	Filter 1	Filter 3
No copper	Filter 2	Filter 4

Table 2 | Testing entailed three unique watering sessions, including periods of inoculation and starvation

Session	Days	Total daily volume (L)
One	1–78	20
Inoculation	55–58	20
Two	79–90	40
Three	91–98	0
One (resumed)	99–104	20

Source inoculation

During days 55–58 of Session 1, influent water was spiked with *Escherichia coli* (*E. coli*). With the highly contaminated influent, a high microbial removal efficiency was anticipated; literature predicted the possibility of 3- and 4-log removal (Duke *et al.* 2006; Stauber *et al.* 2006). A standard LB broth was prepared using Bacto-tryptone, yeast extract, and NaCl. A plate-scraping from an *E. coli* colony produced from a previous water sample was mixed into the broth and incubated for 24 h at 35 °C. The culture was serially diluted into the influent water.

Sampling and testing

Filtered samples were acquired at approximately 10 L of effluent volume, and water quality was tested based on five parameters: turbidity, pH, solids, coliform concentration (total and *E. coli*) and chemical oxygen demand (COD). Turbidity was monitored by a Hach Turbidometer Model 2100P, and pH was evaluated through use of a Hach EC10 pH combined meter and probe. Coliforms were evaluated using membrane filtration and Hach m-ColiBlue24 broth according to Standard Methods, 9222D (Greenberg *et al.* 1992). Solids analysis was conducted using Standard Method 2540D (Greenberg *et al.* 1992). Total COD was evaluated through the use of Hach COD Digestion Vials and a DR 2800 Portable Spectrophotometer.

Copper concentration was periodically monitored to evaluate potential toxicity due to the added biocide. Both influent and effluent waters from all filters were evaluated for copper, using HACH TNTplus for ranges of 0.1–8.0 mg/L and the DR 2800 Portable Spectrophotometer. Dissolved oxygen concentrations were also evaluated to determine the impact of the pause period. Samples were collected in 300-mL BOD vials at every 2 L of effluent. Dissolved oxygen was measured promptly through the use of a HACH Sension 8.

RESULTS AND DISCUSSION

The two primary goals for this study were: (1) to determine the benefit of an added metallic biocide to a BSF and (2) to

evaluate the impact of non-compliance regarding filter pause time on the effectiveness of a BSF. Four filters were constructed for this experiment. Two filters followed ACI standards, and contained chipped copper as a biocide. The remaining two filters did not contain copper. Testing involved the monitoring of water quality parameters including coliforms, turbidity, and dissolved oxygen to determine the effectiveness of each BSF. A filter's effectiveness was determined by evaluating the effluent concentrations of given water contaminants in comparison to the influent and effluent from other filters. Due to the biocidal capacity of copper, coliform concentrations were of particular interest during the evaluation of filter performance. A 7 day moving average technique was used to smooth the data; when this process is used, it is noted on the corresponding figure caption.

Flow rates

Flowrate is a key operational parameter known to impact filter efficiency. In general for BSFs, lower volumetric flowrates yield higher removal, and as the *schmutzdecke* grows more dense, the filter flowrate decreases (Baker & Duke 2006; Elliott *et al.* 2008; AquaClara International 2009). Initial flowrates for each filter were 1.01, 1.05, 1.24, and 0.95 L/min for Filters 1–4, respectively. During Session One, flowrates for Filters 1 and 2 decreased by 0.268 and 0.360 L/h day, respectively. Flowrates for Filters 3 and 4 did not decrease significantly throughout Session One. Session Two yielded significant decreases in flowrates for all filters, suggesting a period of biological growth. Filters 1 and 3 represented the steepest declines in flowrate, marked by reductions of nearly 1 L/h day. Flowrate for Filters 2 and 4 declined by 0.5 L/h day. Following Session Three, flowrates for Filters 1 and 2 continued to decrease while Filters 3 and 4 did not. These trends suggest the growth and decay of the *schmutzdecke* due to increased and decreased filter loadings. On average, the flowrate for Filter 3 was 12 L/h faster than Filter 4. The flowrate for Filter 3 was always higher than those measured from all other Filters. Filter 1 was slower than Filter 2 by only 0.5 L/h. On the last day of the study (day 104), Filters 1–4 were characterized by flowrates of 0.69, 0.73, 1.0, 0.82 L/min, respectively.

Effluent volume at sample point

A 250-mL sample was taken from the effluent of each BSF on a daily basis. This grab sample did not accurately represent the quality of the composite 20 L of treated effluent produced. Characteristic curves on the filters identified an increasing concentration of coliforms as the effluent volume increased. As seen in Figure 2, the characteristic curve of Filter 1 on Day 33 of testing shows that the first liter of effluent had zero coliform colonies per 100 mL, but as the volume of water exiting the filter increased, so did the coliform concentration. A similar trend was also observed for turbidity. In the plot, the mean composite effluent volume at the point of daily sample collection is marked with a dotted line and the standard deviation is notated by the shaded box. Although these data are not presented for Filters 2–4, similar trends were observed.

Understanding that effluent coliform concentrations trended directly with the composite effluent volume emitted, it was pertinent to quantify the point in the filtration process at which the daily sample was drawn. If the sample was

taken early in the filtration process, the coliform measurements, in addition to any other parameters being sampled, would be biased toward the lower end of the true sample concentration. If taken too far towards the end, those same measurements would be biased high. In an effort to compensate for this trend, the daily effluent sample was routinely taken as soon as the last of the influent was poured into the filter, at a composite effluent volume of approximately 10.4 L. Table 3 provides the means and standard deviation of the composite effluent volume at which the daily samples were taken for the filters.

Dissolved oxygen

Dissolved oxygen concentrations in the filter effluent were evaluated to determine the impact pause period had on water quality. As shown by the characteristic curves provided in Figure 3, the dissolved oxygen concentration was related to its corresponding effluent volume. On average, oxygen concentrations in Filters 3 and 4 were 1 mg/L lower than those seen in Filters 1 and 2. This result was

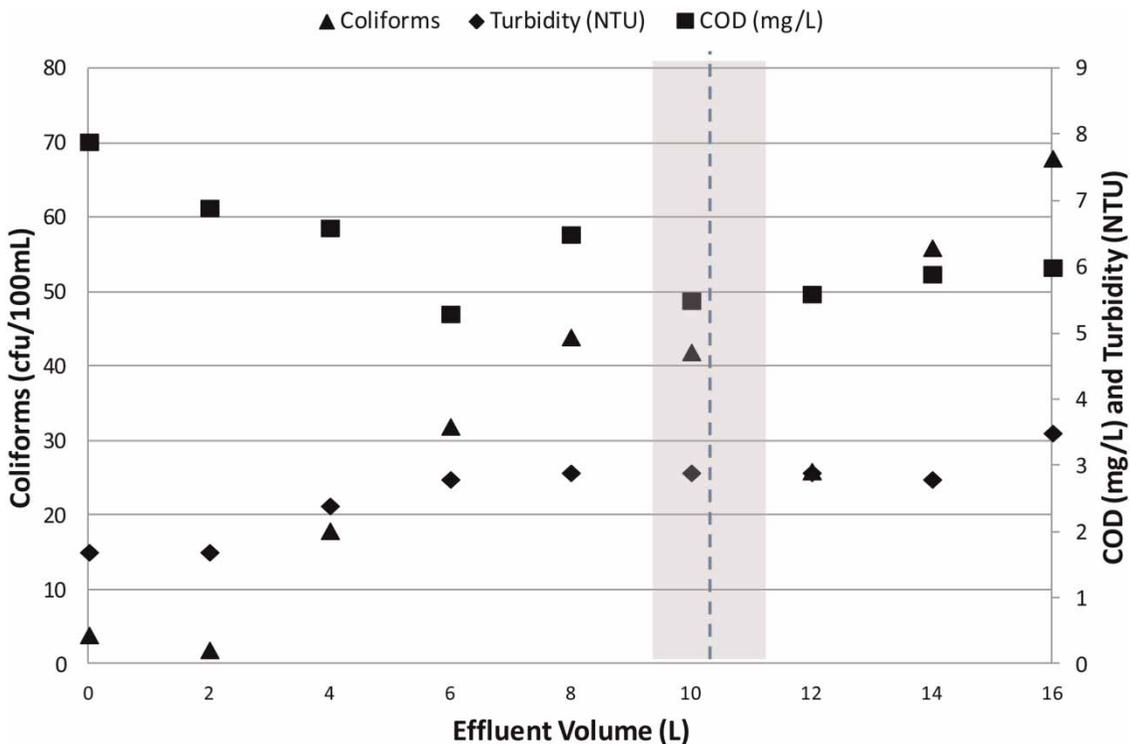


Figure 2 | A visual representation of the impact of point of sampling in relation to COD, turbidity and coliform measures for Filter 1.

Table 3 | Average composite effluent volumes at sampling point were similar for filters

	Filter 1	Filter 2	Filter 3	Filter 4
Average (L):	10.3	10.4	10.5	10.4
Std dev (L):	0.93	0.91	0.99	0.66

attributed to the more regular addition of water in Filters 1 and 2 versus the watering schedule for Filters 3 and 4. Not only was there no addition of oxygen-carrying fresh water to Filters 3 and 4 on a daily basis, but the longer residence time (pause period) allowed microorganisms to use more of the available oxygen. Also of note, after the week of starving the four filters, dissolved oxygen concentrations were above 4.0 mg/L O₂, greater than the recommended standard of 3.0 mg/L set by Huisman & Wood (1974).

pH

pH was not significantly impacted by the filtration process. The average influent pH was 7.08 ± 0.31 . Average effluent pH values from Filters 1, 2, 3 and 4 were 6.89, 6.91, 6.88, and 6.79 pH units, respectively.

Coliforms

Since copper is a biocide, its impact on filter performance was assessed by coliform enumeration. As seen in Figure 4,

the effluent coliform concentration peaks and valleys corresponded with influent coliform concentrations.

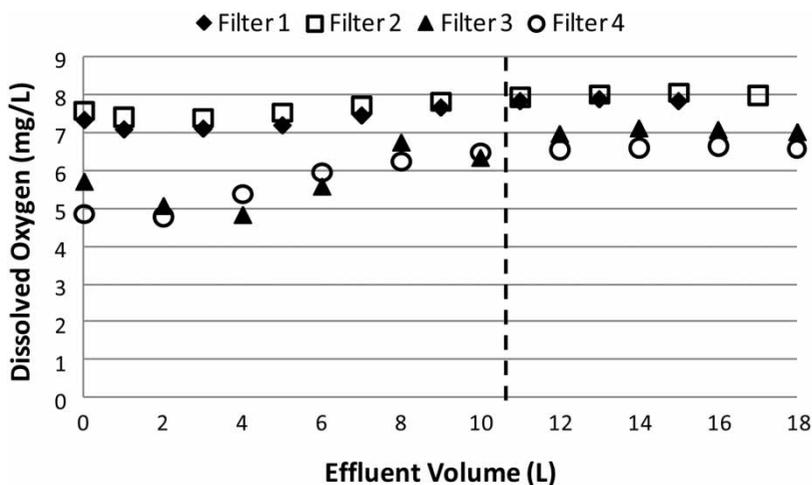
Also noted in Figure 4 are the significant points indicating different operating sessions. The inoculation point is signified by the dashed line at day 55. The shaded box represents the 14 day period (days 79–92) where the water filters were administered 40-L a day. The end of the starvation period is demarcated by a secondary dashed line at day 98.

Removal efficiencies compare the effluent water characteristics from a given day with the influent water characteristics from the previous day and were calculated as:

$$\text{Removal efficiency (\%)} = \frac{(c_i)_{t-1} - (c_i)_t}{(c_i)_{t-1}} \times 100$$

where $(c_i)_t$ is the concentration of the contaminant in the filtered effluent of the given day, and $(c_i)_{t-1}$ is the concentration of the contaminant in the influent of the previous day.

Regardless of copper addition, all filters performed effectively, reaching over 99.5% coliform removal efficiencies. *E. coli* removal efficiencies for Filters 1, 2, 3, and 4 averaged 90, 77, 87, and 80%, respectively. Similar removal efficiencies have been observed by other investigators (Duke *et al.* 2006; Stauber *et al.* 2006). Table 4 provides a performance comparison of the four filters used in this experiment with laboratory and field results found in literature.

**Figure 3** | Relationship between effluent volume and dissolved oxygen concentration. The dashed line represents the average composite volume at which daily sampling occurred.

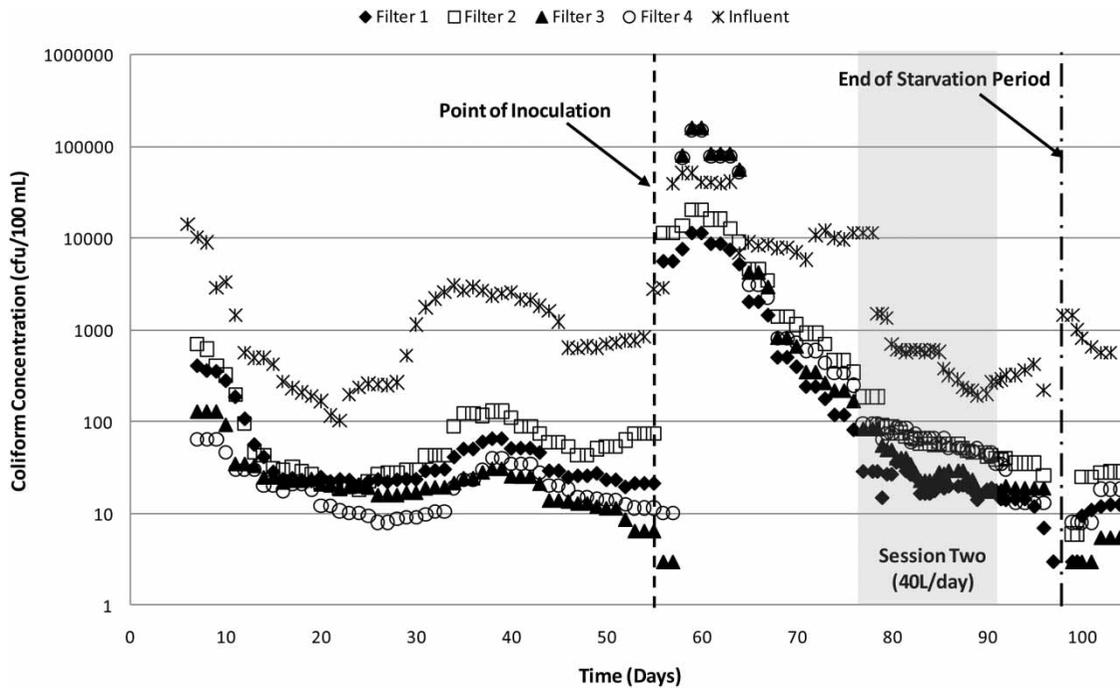


Figure 4 | Effluent coliform concentrations correlate with influent concentrations. Plot smoothed by a 7-d moving average.

Table 4 | Filter removal efficiencies were comparable to efficiencies seen in literature

Study	Study type	<i>E. coli</i> % removal ^a	Total coliform % removal ^a
Elliott <i>et al.</i> (2008)	Laboratory	50–99.99	N/A
Baumgartner <i>et al.</i> (2007)	Laboratory (12 hr pause time)	N/A	74.3–87.9
Baumgartner <i>et al.</i> (2007)	Laboratory (36 hr pause time)	N/A	70.0–85
Stauber <i>et al.</i> (2006)	Field	0–99.7	N/A
Stauber <i>et al.</i> (2006)	Laboratory	63–99	N/A
Collin (2009)	Field	>85	>95
Duke <i>et al.</i> (2006)	Field	N/A	98.5
Tiwari <i>et al.</i> (2009)	Field	N/A	94.4
Fiore <i>et al.</i> (2010)	Field	N/A	80
Earwaker & Webster (2009)	Field	N/A	87.9
Baig <i>et al.</i> (2011)	Laboratory	93	95
Filter 1 ^b	Laboratory	52–99.99	33.3–99.8
Filter 2 ^b	Laboratory	20–99.99	30–99.6
Filter 3 ^b	Laboratory	45–99.99	13.3–99.8
Filter 4 ^b	Laboratory	22–99.99	25.35–99.99

^aWhen a single number is presented, it represents the average removal observed.

^bFilters evaluated in this study.

N/A: No data were available.

Copper

Despite its benefit as a biocide and vital trace mineral involved in many functions in the human body, copper can be toxic if ingested in large quantities. To compare effluent copper concentrations of Filters 1 and 3, 95% confidence testing was performed. This statistical analysis yielded a confidence interval of 0.344–0.575 mg/L Cu for Filter 1 and 0.301–0.531 mg/L Cu for Filter 3. These results suggest that Filter 1 produces effluent with higher concentrations of copper than Filter 3, despite Filter 3's extended retention time.

To determine the significance of copper in the treatment process, the effluent coliform concentration and turbidity values from Filters 1 and 3 (the copper-bearing BSFs) were compared with the corresponding characteristics of Filters 2 and 4 (the non-copper-bearing BSFs). A one-sided paired *t*-test was conducted to analyze if Filter 1's performance regarding coliform concentration was significantly better than Filter 2's. Data from the inoculation period were exempt from this analysis. There was a significant difference between the values for Filter 1 ($M = 150.1$, $SD = 480.9$) and Filter 2 ($M = 322.5$, $SD = 1077$); $t(54) = 1.674$, $p = 0.05$. These results imply that Filter 1 removed potentially pathogenic material more effectively than Filter 2, presumably due to copper addition. Similar paired *t*-tests at $\alpha = 0.05$ for turbidity, solids, and COD showed no significant difference between filter performance.

The effect of copper on the performance of BSFs watered every third day was investigated. A paired-samples *t*-test was conducted to compare effluent water quality characteristics between Filter 3 and Filter 4. There was no significant difference between the coliform concentrations for Filter 3 ($M = 306.5$, $SD = 1,259$) and Filter 4 ($M = 257.9$, $SD = 929.2$); $t(32) = 1.6938$, $p = 0.05$. Similarly, paired *t*-tests for turbidity, solids, and COD showed no significant differences, except for the time period following starvation at day 98, at which point Filter 3 recovered more quickly than Filter 4. These results suggest that Filters 3 and 4 performed in a similar capacity despite the use of copper in Filter 3. A possible explanation relies on the impact of flowrate on water quality. Among the four filters, Filter 4 consistently represented the slowest flowrate while Filter 3 consistently yielded the fastest. A common

consensus across all literature reviewing BSFs emphasizes the impact of hydraulic loading and flowrate on filter efficacy (Baker & Duke 2006; Elliott *et al.* 2008; AquaClara International 2009).

Filters 1 and 3 performed more effectively than Filters 2 and 4 during the 40-L watering period (Session Two). This trend could be attributed to the addition of copper or to the decreased flowrates observed in Filters 1 and 3. Further research is required to elucidate the relationship between copper addition, flowrates, and effluent quality.

Pause time compliance significance analysis

Key water quality characteristics, coliform concentration, solids, COD and turbidity, from Filters 1 and 2 were compared with the corresponding characteristics of Filters 3 and 4 to determine the effects of pause time. Filter 3 yielded lower coliform concentrations than Filter 1 for the first 55 d, but following the inoculation period, it did not recover as quickly as Filter 1 and retained a less efficient removal until the starvation period, when it recovered more readily than Filter 1. A paired-samples *t*-test was conducted to compare water quality characteristics between Filters 1 and 3 for the entire test period. There was no significant difference between the values for Filter 1 ($M = 195.1$, $SD = 1,259$) and Filter 3 ($M = 314.8$, $SD = 1,279$); $t(31) = 1.6955$, $p = 0.05$. Similar paired *t*-tests for solids, COD, and turbidity showed no significant differences. These results imply the use of copper is effective for a filter whether or not it is used in compliance with suggested pause times.

Filter 4 outperformed Filter 2 to provide better treatment of coliforms throughout the course of the experiment with the exception of the time period immediately after inoculation, similar to the relationship exhibited between Filters 1 and 3. To confirm this observation, a paired-samples *t*-test was performed between Filters 2 and 4. There was a significant difference between the values for Filter 2 ($M = 435.5$, $SD = 1,380$) and Filter 4 ($M = 264.7$, $SD = 943.2$); $t(31) = 1.6955$, $p = 0.05$, statistically confirming Filter 4 to be more effective than Filter 2 regarding coliform removal. Visual inspection of turbidity measurements for Filters 2 and 4 do not reflect one filter performing better than the other. Paired-samples *t*-tests for turbidity, COD and solids reflected the same conclusion,

representing no significant difference between the two filters aside from the coliform removal.

CONCLUSIONS

Studies performed in the laboratory (Baumgartner *et al.* 2007; Elliott *et al.* 2008; Baig *et al.* 2011) and in the field (Duke *et al.* 2006; Collin 2009; Earwaker & Webster 2009; Tiwari *et al.* 2009; Fiore *et al.* 2010) conclude that BSFs are highly efficient, capable of 3- and 4-log pathogenic removal. To further enhance the efficacy of treatment, designs suggested by ACI incorporate the use of a metallic biocide.

Testing outlined in this manuscript challenged the importance of daily watering and the presence of copper in BSFs. The performance of four filters – two built according to traditional BSF standards and two built according to ACI standards – was evaluated. Several water quality parameters were monitored for variation due to watering frequency and biocidal addition, including coliform, turbidity, and solids concentration. The filters were highly effective, reaching coliform removal efficiencies of over 99.5%. Paired *t*-tests were employed to determine whether treatment was significantly impacted by watering frequency or copper addition. At $\alpha = 0.05$, effluent coliform concentrations from filters watered daily appeared to be significantly impacted by the presence of copper, but filters watered infrequently were not. For the two filters loaded every third day, the BSF without copper often outperformed the copper-containing filter. This observation could be explained by Filter 4's flowrate, it was consistently much slower than its corresponding copper-laden Filter 3, confirming filter construction parameters that define filter efficiency as inversely proportional to hydraulic loading and flowrate. Filters 3 and 4 that were watered every third day did not accommodate peak coliform loadings as well as filters watered in compliance, regardless of copper concentration. The presence of copper had no impact on the removal of solids, turbidity, and COD, as paired *t*-tests between filters determined there was no significant difference. Additionally, the copper concentrations in the respective filters never exceeded the EPA or WHO

standards, even after an 8 day pause period, further supporting the inclusion of a metallic biocide in a sand filter.

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