The effect of increasing grain size in biosand water filters in combination with ultraviolet disinfection

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ABSTRACT

With sand less than 0.70 mm often difficult to source in the field, it is of interest to study larger grained sand for use in biosand water filters (BSF). This study examined how sand grain size affects biological sand water filtration and how the combination of biological sand filtration and ultraviolet (UV) disinfection affects drinking water quality. Two BSFs were built: a control with maximum grain size, \( d_{\text{max}} = 0.70 \) mm and an experimental with grain sizes ranging from 0.70 mm to \( d_{\text{max}} = 2.0 \) mm. Untreated water was passed through each BSF daily. Results show Escherichia coli and turbidity removal characteristics of the control and experimental BSFs were not significantly different from one another. Both BSFs produced water that met World Health Organization (WHO) drinking water guidelines for turbidity, and although E. coli reduction was over 98% for each BSF, a high initial bacteria concentration resulted in effluent levels above WHO guidelines. Subsequently, effluent from each BSF was placed in clear plastic bottles under UV light, after which water from each BSF met E. coli guidelines. The data yielded promising results for using larger sand in BSFs, but longer duration studies with more data points are needed.

Key words | biosand water filter, developing countries, disinfection, grain size, water quality

INTRODUCTION

The need for low-cost, sustainable methods to purify drinking water is paramount in many parts of the globe, and availability is often well short of demand. Over 1 billion people in developing countries do not have access to clean drinking water (WHO 2002). Further, the United Nations Children’s Fund (UNICEF) estimates 1.2 million children under the age of five die from diarrhea caused by waterborne pathogens each year (UNICEF 2012). In rural areas of developing countries or where municipal drinking water delivery systems are nonexistent, in poor repair, or unreliable, point-of-use water treatment methods can be an effective means of improving drinking water quality. When clean drinking water is available in developing countries, access typically involves long wait times and high cost (UNICEF 2012), both issues that point-of-use systems may be able to address.

Biosand water filtration

The point-of-use biosand filter (BSF) technology has been in existence for over 20 years and the Center for Affordable Water Sanitation Technology (CAWST) in Calgary, Canada is an international champion for the technology. Previous laboratory and field studies have observed BSF effluent with Escherichia coli and other bacteria removal rates greater than 90%, sometimes over 99% (Duke et al. 2006; Earwaker 2006; Stauber et al. 2006, 2012a, b; Baumgartner et al. 2007; Stauber 2007; Elliott et al. 2008; Jenkins et al. 2011). Additionally, studies have shown an even wider range

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of turbidity reduction, from almost none to 98% depending predominantly on the quality of the influent (Duke et al. 2006; Eerwaker 2006; Stauber et al. 2006, 2012a, b; Stauber 2007). The CAWST BSF version 10 manual recommends using sand with maximum grain size \( d_{\text{max}} = 0.70 \) mm or less as filter media (CAWST 2010), but sand grains this small can be difficult to locate or isolate in many developing countries. Manufactured sieves with 0.70 mm openings are not universally available worldwide, and often need to be imported, which can be difficult, or improvised, which can be unreliable. More common in developing countries, window screens and mosquito nets have larger openings (1.8 mm for window screens and 1.2 mm for mosquito nets, typically); performance of BSFs using sand media from these alternative sieve materials, however, is unknown. Previous research has been done on sand grain size and its effects on the performance of BSFs and other slow sand filters. Jenkins et al. (2011) explored the effect of two different effective sand sizes (ES = 0.17 mm and 0.52 mm) on the removal of fecal coliform and the MS2 virus in addition to turbidity reduction over a ten-week period. The smaller grained BSFs had a reduced flow rate which increased the sand’s ability to mechanically trap particles. They concluded that sand grain size is a critical factor in the performance of BSFs and data indicated that the smaller grained BSFs significantly or near significantly improved bacteria removal from water when compared with the larger grained BSFs. Further, the smaller grained BSFs outperformed the larger grained BSFs in turbidity reduction. Findings that finer grained sand outperformed coarser grained sand in total coliform and Cryptosporidium parvum oocyst removal have been made in two additional separate studies (Bellamy et al. 1985; Logan et al. 2001).

To the contrary, one study determined larger sand grains (0.30 mm to \( d_{\text{max}} = 1.8 \) mm) removed more bacteria and bacterial spores than smaller sand grains (0.13 mm to \( d_{\text{max}} = 0.37 \) mm) (Hijnen et al. 2007). While a noteworthy result, this study was conducted on large-scale slow sand filters, not point-of-use BSFs. More importantly, the authors acknowledge the difference in effectiveness could have been attributed to different chemical make-up of the sand between the two filters. To further explore sand grain size’s effect on BSF performance, the current study compared an experimental BSF with sand grains between 0.70 mm and \( d_{\text{max}} = 2.0 \) mm with a control BSF with \( d_{\text{max}} = 0.70 \) mm. E. coli and turbidity reduction were measured.

**Ultraviolet disinfection**

Another longstanding means of purifying drinking water used in developing countries is solar disinfection (SODIS), wherein ultraviolet (UV) light from the sun damages waterborne pathogens to the point where they can no longer reproduce. SODIS is also one of many forms of disinfection that sand grain size is a critical factor in the performance of BSFs and data indicated that the smaller grained BSFs significantly or near significantly improved bacteria removal from water when compared with the larger grained BSFs. Further, the smaller grained BSFs outperformed the larger grained BSFs in turbidity reduction. Findings that finer grained sand outperformed coarser grained sand in total coliform and Cryptosporidium parvum oocyst removal have been made in two additional separate studies (Bellamy et al. 1985; Logan et al. 2001).

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Like biosand water filtration, much laboratory research and field studies have been done about SODIS. Despite the fact that SODIS-only experiments have shown 3-log reductions or more of bacteria (Dejun et al. 2007; Hirtle 2008), an analysis of 39 data sets from previous disinfection and filtration trials in developing countries concluded that SODIS-only purification has little, if any, long-term public health benefits (Hunter 2009). This, however, could have been due to a variety of reasons that should not lead to the rejection of SODIS technology altogether, including improper implementation, equipment problems, poor study design, reporting bias, or simply the users no longer utilizing the technology at all.

Hirtle (2008) studied various pretreatments to increase SODIS efficiency. Her results showed passing water through a roughing filter consisting of a 17 cm column of coarse sand reduced turbidity by 93% and E. coli by 0.55-log. Once the filtered water was placed in the sun, SODIS was significantly more effective in further reducing E. coli than without pretreatment. One limitation she discovered, however, was that despite the effectiveness of SODIS when turbidity was below 30 NTU, water needed to be consumed immediately if turbidity was above 10 NTU because of the regenerative properties of bacteria in turbid water. Wilson (2010) also experimented with filtration as a pretreatment to SODIS. Using a 0.45 \( \mu \)m screen, she was able to virtually eliminate turbidity which enabled a greater amount of UV light to be absorbed. In the current study, untreated water was first filtered through a BSF, and then subjected to UV disinfection. E. coli was used as the water quality indicator.
Objectives

One research goal of this study was to determine whether sand grains above the CAWST recommended $d_{\text{max}} = 0.70 \text{ mm}$ could be used in a BSF to improve drinking water quality and make the water safe enough to drink. The effective grain size in the experimental BSF used in this study differed more dramatically from the CAWST BSF manual’s recommendation than any previous BSF study that measured $E. coli$. Since BSFs use mechanical trapping, adsorption, predation and natural death to remove bacteria from contaminated water, a BSF with larger sand grains would be expected to rely more on predation and natural death and less on mechanical trapping for bacteria removal. Furthermore, another aim of this research was not only to measure percentage reduction of $E. coli$ and turbidity, but also to compare post-treatment water quality with international drinking water guidelines established by the World Health Organization (WHO).

Lastly, the effectiveness of biosand filtration as a pre-treatment to UV disinfection was explored. Contaminated water was filtered through each BSF and samples of the effluent were placed under UV light to disinfect. The use of a BSF as a pre-treatment for UV disinfection, unlike previously mentioned pre-treatment filtration methods, would introduce the added benefits of a biological layer to the filtration process. A literature review did not uncover studies using biosand water filtration and UV disinfection in series, and therefore this project which paired these two viable water purification techniques for developing countries may be the first.

Based on previous research mentioned above, the following three hypotheses were devised:

- the BSF with the smaller effective size would reduce $E. coli$ and turbidity more than the BSF with larger effective size;
- UV disinfection would further reduce $E. coli$ levels in the water that passed through each BSF; and
- the combination of biosand water filtration and UV disinfection would produce water quality meeting WHO guidelines, even using the experimental BSF.

METHODS

Materials

Two full-scale BSFs were constructed: one per the CAWST version 10 manual (the control BSF) and one using grain sizes from $0.70 \text{ mm}$ to $d_{\text{max}} = 2.0 \text{ mm}$ (the experimental BSF). The sand used for the filter media in both BSFs was sourced in Colorado, USA, and was angular quarry sand. Removing grains less than $0.70 \text{ mm}$ to create a minimum sand grain size in the experimental BSF was done to produce a more dramatic difference in effective size between the two BSFs and emphasize the effect of grain size on filtration. The $d_{\text{max}} = 2.0 \text{ mm}$ was slightly larger than the opening size of a typical window screen (approx. $1.8 \text{ mm}$) which would make the performance of the experimental BSF slightly more conservative than had a window screen been used to sieve its media. Sieve analysis determined the control BSF’s sand media had an ES = 0.19 mm and uniformity coefficient, UC = 2.1, both in accordance with the CAWST manual specifications. The experimental BSF’s sand media had an ES = 0.80 mm and UC = 1.5.

Per the CAWST manual, each BSF consisted of 10.0 cm of gravel that supported a 54.3 cm sand column. Based on the position of the outlet tube, 5.0 cm of standing water remained on top of the sand at all times. Only the grain size of the sand layer differed between the two BSFs.

Research design

To grow the biological layer, a 20 L solution of 10% raw wastewater and 90% dechlorinated tap water was introduced to each BSF daily for 21 days. The raw wastewater was gathered from a local wastewater treatment plant weekly and stored in sealed containers at 5°C until used. Prior to mixing with wastewater, the tap water was stored in 20 L buckets and left to naturally dechlorinate through evaporation over a 48 hour period, during which the water was agitated twice. Free chlorine in the tap water was measured using a CN-66 Test Kit made by the Hach
Company and shown to be consistently below 0.1 ppm. The raw wastewater was combined with the dechlorinated tap water and stirred for 10 seconds. Like in nature, the water quality of this mixture varied slightly from batch to batch. It was expected this manufactured water would be of poorer quality than many natural water sources in developing countries, but the intent was to be able to clearly demonstrate signiﬁcant reduction in bacteria between each treatment stage of this study, so a relatively high initial bacteria concentration was selected. With the dose volume larger than the BSF reservoir volume (12 L), water was added as quickly as the reservoir emptied until all 20 L was added.

Dose volume can have a large effect on the performance of a BSF (Baumgartner et al. 2007; Elliott et al. 2008). Smaller dose volumes are likely to cause bacteria to die naturally from lack of oxygen or light because some water will remain in the sand pore space and not get ﬂushed out from batch to batch. Therefore in practice, smaller doses (less than 70% of the media’s pore volume) will lead to better BSF performance, albeit yielding a smaller volume of treated water (Elliott et al. 2008). A 20 L dose volume was used in this study, as this mirrors WHO’s deﬁnition of basic access to water per capita per day (WHO/UNICEF 2000). WHO assumes per-capita drinking water consumption to be about 2 L per day, so a 20 L dose volume might service 10 people if used once per day solely for consumption. The 20 L dose was larger than the pore volume of either BSF in this study.

The longer the pause period between doses, the more effectively the BSF reduces bacteria (Baumgartner et al. 2007; Jenkins et al. 2011). Like smaller dose volumes, longer pause periods allow for more natural death of the bacteria. Since water does not continuously ﬂow through BSFs, there is a maximum practical limit to the pause period in order to maintain the health of the biological layer. The CAWST manual recommends a maximum of 48 hours; a 24 ± 2 hour pause period between doses was used in this study.

After the 21 day biological layer growth period, data collection began on 4 February 2013. Each day, 20 L of raw wastewater/dechlorinated tap water mixture was ﬁltered through a 297 μm sieve to help remove residual solids, and then poured into each BSF. Flow rate varied throughout the experiment, but averaged 0.19 L/min for the control BSF (min = 0.05 L/min, max = 0.39 L/min) and 0.60 L/min for the experimental BSF (min = 0.49 L/min, max = 0.71 L/min). A total of eight sample sets on each BSF were collected through 13 March 2013. As the ﬂow rate dropped, maintenance was conducted using the wet harrowing method; the control BSF was wet harrowed three times and the experimental BSF once. At least seven days passed from wet harrowing before taking the next sample; this seven-day period has been shown to be sufﬁcient to allow the biological layer to heal enough to only have a ‘modest effect’ on turbidity and bacteria removal (Jenkins et al. 2011). While a reduced ﬂow rate itself will not hinder BSF performance, it becomes unpractical if the user has to wait hours for a 20 L dose to ﬁlter through the BSF.

After the 20 L of inﬂuent was poured into each BSF and the pause period had passed, the ﬁrst 500 mL of efﬂuent was collected directly from each BSF’s outlet tube as the next day’s inﬂuent was poured. Precisely when the efﬂuent is taken has an effect on water quality (Baumgartner et al. 2007), especially when the dose volume is larger than the pore volume of the BSF. Taking the ﬁrst 500 mL of efﬂuent, versus a mid-dose sample, meant the water had been in the BSF for the entire pause period. Otherwise, the efﬂuent sample might contain a mixture of inﬂuent batches, making it diﬃcult to track and measure water quality throughout each stage of water treatment. The 500 mL sample was placed directly in a clear polyethylene terephthalate bottle that had been triple-rinsed with deionized water.

The bottles sat under monochromatic UV light with wavelength, λ = 365 nm for 24 ± 2 hours on top of a ﬂat surface coated in aluminum foil. Monochromatic lamps do not perfectly mimic natural sunlight (Wegelin et al. 1994), and generally lead to less bacteria inactivation than polychromatic sunlight (Berney et al. 2006); therefore, the UV disinfection results in this study would be more conservative than if natural sunlight or polychromatic lamps were used.

UV light affects various cell functions at diﬀerent levels of exposure (Bosshard et al. 2010), but past research has shown 3-log reduction of E. coli with approximately 2,000 kJ/m² of irradiation (Wegelin et al. 1994). This corresponds to a few hours of direct sunlight depending on
location and weather conditions. Three UVGL-25 handheld UV lamps placed three inches above the bottles were used in this study to produce an average irradiation of 1,820 kJ/m² as calculated using manufacturer’s specifications and validated with an Ideal Industries, Inc. 61–340 Multimeter and an Apogee SU-100 UV light sensor. While under UV lamps, the bottles were kept at room temperature, thus temperature was not expected to contribute to bacteria inactivation.

**Water quality testing**

It is widely understood that *E. coli* is a reliable indicator of fecal contamination (Wegelin *et al.* 1994; Baumgartner *et al.* 2007; Stauber 2007; WHO 2011). The *E. coli* concentration in the water was measured at three stages of this study: untreated water, BSF effluent and post-UV disinfection. To do this, IDEXX Laboratories, Inc. products were used. Colilert® was added to a 100 mL sample, stirred to combine, and placed into a Quanti-tray®/2000. The tray was sealed and incubated at 35.5 °C for 24–28 hours before the *E. coli* concentration was determined using the most probable number method. The *E. coli* concentration in the untreated water was measured after the 48 hour dechlorination process and the raw wastewater had been combined with the tap water, just before being poured into the BSFs. Because of the high *E. coli* concentration of the untreated water, a 100× dilution sample using a sterile buffer made from sodium dihydrogen phosphate prepared according to WHO guidelines (WHO 2011) was used. BSF effluent and post-UV disinfection samples were undiluted for *E. coli* testing.

In addition to *E. coli*, turbidity is an important measure of water quality because particulates can provide a hospitable habitat for bacteria growth, shelter them from UV light, stimulate bacteria growth, and increase the residence time required for effective SODIS (Caslake *et al.* 2004; Hirtle 2008; WHO 2011). To measure turbidity, a PASCO® PASPORT PowerLink PS-2001 coupled with DataStudio software was used on a 5 mL sample. Turbidity of both the untreated water and BSF effluent were measured.

### RESULTS AND DISCUSSION

#### Findings

A *t*-test was used to check each hypothesis. When comparing effluent *E. coli* and turbidity between the two BSFs, there was no significant difference in performance of either water quality parameter (*p* ≫ 0.05 for both cases). This was unexpected, and differed from the hypothesis that the experimental BSF would not perform as well as the control. While the mean percentage reduction of both *E. coli* and turbidity was slightly greater in the control than the experimental BSF, the relatively small sample size (*n* = 8) was a large factor precluding statistical significance. Table 1 shows the average water quality measurements at each stage of testing for both BSFs.

The mean *E. coli* reduction was 98.7% (σ = 1.48 pp) for the control and 98.4% (σ = 2.45 pp) for the experimental BSF. Without sand grains smaller than 0.70 mm, the experimental BSF had larger void spaces, and its ability to mechanically trap was inferior to that of the control, thus a higher difference in *E. coli* reduction was expected. Reducing the impact of the grain size difference between BSFs, however, was the 24 ± 2 hour pause period. It is believed that natural death was the dominant means of killing *E. coli*, and since the pause period was the same for each BSF, this narrowed the gap in performance between them.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Control BSF</th>
<th>Turbidity (NTU)</th>
<th>Experimental BSF</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated water</td>
<td>39,400</td>
<td>19.9</td>
<td>42,700</td>
<td>18.3</td>
</tr>
<tr>
<td>BSF effluent</td>
<td>251</td>
<td>4.43</td>
<td>304</td>
<td>4.20</td>
</tr>
<tr>
<td>Post-UV disinfection</td>
<td>&lt;1</td>
<td>N/A</td>
<td>&lt;1</td>
<td>N/A</td>
</tr>
</tbody>
</table>
A shorter pause period may shift the dominant means of *E. coli* reduction away from natural death and more towards mechanical trapping in future studies.

Since the control required maintenance twice more than the experimental BSF, its effect on the results was explored. Wet harrowing temporarily damages the biological layer and reduces predation capacity; therefore, if performance in the control BSF was seen to decline immediately following wet harrowing, the insignificant difference between BSFs could have been attributed to the different maintenance frequencies. Figure 1(a), however, shows this was not the case. Wet harrowing did not cause declines in either *E. coli* or turbidity reduction beyond normal fluctuation from sample to sample. *E. coli* reduction remained relatively consistent throughout the experiment for both BSFs, but the control BSF actually experienced minor increases in *E. coli* reduction performance immediately after each wet harrowing effort. This also confirms the seven-day period after performing maintenance before taking the subsequent sample was sufficient for biological layer regrowth. As is the intention of wet harrowing, Figure 1 also shows that wet harrowing increased the flow rate of the control BSF significantly after each occurrence.

The mean turbidity reduction was 75.4% (σ = 18.2 pp) for the control and 74.8% (σ = 13.1 pp) for the experimental BSF. Figure 1(b) shows the percentage turbidity removal, flow rate and wet harrowing schedule for each BSF. When comparing percentage turbidity removal directly before and after each instance of wet harrowing, maintenance improved the performance of both BSFs every time. The relatively low level of initial turbidity in the untreated water is believed to have contributed to the insignificant difference in performance between BSFs; a higher influent turbidity might have yielded a more pronounced difference in performance.

While not a focus of this study to observe performance difference at varying levels of influent water quality, it was noticed that for the seven samples across both BSFs (three from the experimental, four from the control) where untreated water turbidity was over 20 NTU, the BSFs reduced turbidity by an average of 81.9%. For the other nine samples (five from the experimental, four from the control) where the influent was less than 20 NTU, turbidity reduction averaged only 69.9%. This shows that the BSFs generally reduced a greater amount of turbidity, as measured by percentage reduction, when influent levels were higher. This agrees with past findings mentioned above.

As expected, UV disinfection significantly reduced *E. coli* from each BSF’s effluent. In every case, UV exposure virtually eliminated *E. coli*, reducing concentrations to below the quantifiable threshold for the test method used of 1 CFU/100 mL. Therefore, the bacteria levels were significantly reduced by both water purification processes in this study (biosand filtration and UV disinfection) for each BSF.
Finally, it was expected that the combination of biosand water filtration and UV disinfection would produce water quality meeting WHO guidelines, even for the experimental BSF. WHO drinking water guidelines suggest a target of zero *E. coli* (<1 CFU/100 mL for low health risk) and maximum turbidity of 5 NTU (WHO 2011). Both the experimental and control BSFs alone were able to meet WHO turbidity guidelines, on average, as five of eight samples from each BSF’s effluent were 5 NTU or less. Neither BSF alone, however, was able to meet *E. coli* guidelines. After UV disinfection, effluent from both BSFs produced water that met *E. coli* guidelines with all samples less than 1 CFU/100 mL.

A benefit of using the larger grained experimental BSF was observed; it required less maintenance over the short duration of this study, and maintained its flow rate much better than the smaller grained BSF. However, this could be because the untreated water was not pre-screened (with a 297 µm screen) during the 21-day biological layer growth period, which may have partially clogged the pore space in the control BSF. However, in practice when fine screens are not used and highly turbid water may exist, this benefit of larger sand grains with respect to flow rate and maintenance may be a consideration.

**Areas for further research**

This study demonstrates the potential for using larger grains as BSF sand media, but many questions for further research exist. Long-term effects of larger grained BSFs need to be determined to see if performance remains consistent over time. With larger pore spaces in the experimental BSF, silt could gradually become trapped in the sand at a depth below that removable with wet harrowing. When long-term maintenance is required, it is unclear if the wet harrowing method would be effective or if pore spaces throughout the sand column would be clogged to the point where the entire sand column needs to be replaced.

In this experiment, the water was left to sit inside each BSF for approximately 24 hours at a time, diminishing the effect of grain size and increasing the effect of natural death on *E. coli* inactivation. In developing countries, using the BSF once per day and pausing for 24 hours may not be practical. It might be of interest to shorten the pause period, and determine whether the difference in performance between the experimental BSF and the control is greater.

**CONCLUSION**

This study showed sand grains up to $d_{\text{max}} = 2.0$ mm reduced *E. coli* and turbidity nearly as well as the control BSF built according to CAWST specifications, and the difference may be insignificant. It also underscored the need for post-filtration disinfection to achieve *E. coli* associated with a low health risk for drinking. UV treatment was found to be extremely effective in reducing *E. coli* post-BSF filtration when the effluent was not very turbid. In conjunction with UV disinfection, biosand filtration produced water that met international drinking water guidelines with respect to *E. coli*, even with larger sand grains. These results may be of interest to BSF producers and users who find it difficult to locate or isolate sand grains less than 0.70 mm. The primary limitations in this study were a small sample size and using a monochromatic UV lamp to approximate SODIS in a laboratory setting. A longer duration study, with more data points and field testing would enhance this work.

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